Research on Permafrost Characteristics in Xining Region Based on Geophysical Methods

基于地球物理方法的西宁地区冻土特征研究

Author:

Wei Zhao (赵维)
Master of Geophysics
Email: zowieware@outlook.com
ORCID: https://orcid.org/0009-0006-8305-8129

Cover Statement:

This preprint has been submitted to a journal for peer review: [Journal Name, e.g., Journal of Geophysical Research]

Author Mastodon handle: [e.g., @weizhao@eartharxiv.social] (optional)

Data Availability Statement:

The permafrost distribution data used in this study are available from the National Cryosphere Desert Data Center (http://www.ncdc.ac.cn). Meteorological data were obtained from the China Meteorological Data Service Center (http://data.cma.cn).

Keywords: *permafrost, geophysics, electrical resistivity, ground temperature, Qinghai-Tibet Plateau*

Submission Date: June 12, 2026

Permafrost Degradation and Ecological Restoration Technologies in the Northeastern Margin of the Qinghai-Tibet Plateau: A Case Study of Xining and Surrounding Areas

Wei Zhao

Master's Candidate in Geophysics

[Institution Address]

ABSTRACT

The Qinghai-Tibet Plateau represents the highest-altitude and largest-area permafrost distribution zone in global mid-to-low latitude regions. Its northeastern margin, encompassing Xining City and surrounding areas, constitutes a critical transitional zone where seasonal permafrost and perennial permafrost interweave. Driven by the dual forces of global climate warming and anthropogenic engineering activities, permafrost degradation in this region has become increasingly severe, triggering a cascade of ecological consequences including thermal thaw slumping, retrogressive vegetation succession, and attenuation of water conservation functions. This paper systematically reviews the distribution patterns, thermodynamic characteristics, and degradation status of permafrost in the northeastern Qinghai-Tibet Plateau, and provides an in-depth analysis of the cascading impact mechanisms of permafrost degradation on alpine ecosystems. Based on typical ecological restoration practices such as the Muli Mining Area in Qinghai Province, this study summarizes key technologies including artificial permafrost layer construction, landform reshaping, and vegetation reconstruction. Furthermore, drawing upon cutting-edge methodologies such as physics-informed digital twin technology, this paper explores technical pathways for intelligent prediction of permafrost thermodynamic processes and dynamic assessment of ecological restoration effectiveness. Research findings indicate that the systematic restoration workflow of "permafrost survey - profile model construction - overlapping integration - surface water retention - vegetation recovery" can effectively promote ecological functional reconstruction in degraded permafrost regions. The digital twin framework integrating physical mechanisms with data-driven approaches provides scientific support for precise decision-making in permafrost ecological restoration. This study offers theoretical foundations and technical references for permafrost protection and ecological restoration in the marginal zones of the Qinghai-Tibet Plateau.

Keywords: Northeastern Qinghai-Tibet Plateau; Xining permafrost; ecological restoration; artificial permafrost layer construction; physics-informed digital twin; permafrost degradation

1. Introduction

Permafrost refers to rock or soil layers that remain at or below 0°C and contain solid ice, constituting an essential component of the cryosphere. The Qinghai-Tibet Plateau hosts approximately 1.06 million km² of permafrost, accounting for 54.3% of the total plateau area, making it the largest and highest-altitude permafrost region in global mid-to-low latitude zones. Permafrost serves not only as the fundamental material basis for plateau ecosystems but also as a critical influencing factor for regional hydrological cycles, carbon budget balance, and engineering safety. As an important carrier of shallow groundwater aquitards, permafrost layers regulate soil moisture transport and heat transfer, maintaining the stability and succession of unique ecosystems such as alpine meadows and marsh wetlands.

The northeastern margin of the Qinghai-Tibet Plateau represents a sloping transitional zone from the plateau to the Loess Plateau, characterized by significant elevation variations and complex, diverse terrain. Xining City, located at the core of this region in the Huangshui River Valley, has an average elevation of approximately 2,260 meters. Controlled jointly by plateau uplift and latitudinal zonation, seasonal permafrost is extensively distributed in mountainous and hilly areas surrounding Xining above 2,500 meters elevation, with sporadic perennial permafrost developed in certain high-altitude shaded slopes. This transitional permafrost system is extremely sensitive to environmental changes, representing a frontier region responding to global climate warming. Over the past four decades, the annual mean temperature of the Qinghai-Tibet Plateau has risen by approximately 0.3-0.4°C, with evident signs of permafrost degradation manifested primarily as ground temperature elevation, active layer thickening, permafrost disconnection, and talik expansion.

Permafrost degradation not only directly threatens the long-term stability of cold-region infrastructure such as the Qinghai-Tibet Railway and highways but also exerts profound impacts on regional ecosystems. Issues including declining vegetation coverage, retrogressive plant community succession, increased soil organic carbon release, and reduced biodiversity have become increasingly prominent. The frequent occurrence of thermal thaw slumping and thermokarst lakes further exacerbates ecosystem fragmentation and functional degradation. As a pilot demonstration zone for national ecological civilization, Qinghai Province bears the significant mission of consolidating the national ecological security barrier. Therefore, in-depth investigation of degradation mechanisms in the Xining permafrost region and exploration of scientifically effective ecological restoration pathways hold important theoretical value and practical significance.

In recent years, domestic and international scholars have achieved a series of important advances in permafrost thermodynamic modeling, ecological restoration technologies, and intelligent monitoring methods. Particularly in the field of physics-informed neural networks and digital twin technology, researchers have achieved real-time prediction and inversion of permafrost thermodynamic characteristics through the integration of differentiable modeling with distributed sensing observations, providing new technical means for permafrost protection. However, existing research has primarily focused on permafrost engineering stability analysis, while systematic ecological restoration studies targeting permafrost degradation in the marginal zones of the Qinghai-Tibet Plateau remain insufficient. This paper takes the permafrost region of Xining and surrounding areas as the research object, integrating field investigations, engineering practices, and frontier technologies to construct a comprehensive framework encompassing permafrost degradation diagnosis, restoration technology integration, and intelligent effectiveness assessment, aiming to provide references for ecological restoration in similar regions.

2. Distribution Characteristics and Degradation Status of Permafrost in the Northeastern Qinghai-Tibet Plateau

2.1 Regional Permafrost Distribution Patterns

The northeastern margin of the Qinghai-Tibet Plateau, encompassing the eastern Qilian Mountains, northern slopes of the Bayan Har Mountains, and the Huangshui River basin, constitutes a critical transitional zone from perennial permafrost to seasonal permafrost regions. Permafrost distribution in this area is controlled jointly by elevation, latitude, and local topography, exhibiting significant spatial heterogeneity. According to the distribution patterns of mean annual ground temperature in perennial permafrost, elevation represents the dominant factor influencing permafrost development, with mean annual ground temperature decreasing as elevation increases. In the Bayan Har Mountains, the elevation lapse rate of mean annual ground temperature is approximately 0.6°C per 100 meters on northern slopes and about 0.4°C per 100 meters on southern slopes, with the north-south difference primarily attributed to mountain effects and asymmetric solar radiation distribution.

In the Xining surrounding area, seasonal permafrost is extensively distributed in mountainous and hilly regions above 2,500 meters elevation, with the freezing period generally extending from mid-November to late March of the following year, and maximum freezing depths reaching 1.5-2.5 meters. Sporadic perennial permafrost has developed in certain high-altitude shaded slope locations (such as Eling in the Qilian Mountains and Daban Mountain in Datong County), with mean annual ground temperatures slightly above -1.0°C and active layer thicknesses of approximately 1-2 meters. The lower boundary of perennial permafrost generally coincides with the -2.5°C to -2.0°C annual mean air temperature isotherms, displaying pronounced elevation-controlled characteristics.

Permafrost development in this region also exhibits significant aspect differentiation. Northern slopes receive less solar radiation and maintain higher soil moisture content, resulting in permafrost distribution boundaries 200-400 meters lower than southern slopes, with greater permafrost thickness and lower temperatures. Footslope areas, influenced by topographic water convergence, often form thicker peat layers and wetland ecosystems where permafrost develops relatively well. Conversely, southern slopes and ridge areas experience intense solar radiation and high evaporation rates, with permafrost predominantly occurring in island-like or discontinuous distributions with poor stability.

2.2 Permafrost Degradation Status and Driving Factors

Under the background of global climate warming, permafrost degradation in the northeastern Qinghai-Tibet Plateau has become increasingly severe. Monitoring data indicate that the annual mean temperature in this region has risen by approximately 0.3-0.4°C over the past four decades, with winter warming exceeding summer warming. Temperature elevation has led to overall ground temperature increases in permafrost areas, with continuous thickening of the active layer (the seasonally frozen and thawed soil layer). Research demonstrates that from the 1970s to the 1990s, ground temperatures in seasonal permafrost areas along the Qinghai-Tibet Highway rose by 0.3-0.5°C, while mean annual ground temperatures in continuous perennial permafrost areas increased by 0.1-0.3°C.

The primary driving factors of permafrost degradation include climate change and human activities. Regarding climatic factors, temperature elevation directly leads to decreased thermal stability of permafrost, increased thaw depth, and shortened freezing periods. Changes in precipitation and snow cover patterns further alter surface energy balance, accelerating permafrost degradation processes. Particularly, increased winter snow depth reduces winter surface cooling efficiency, exerting adverse effects on permafrost preservation.

Regarding human activities, Xining, as the largest city and economic center on the Qinghai-Tibet Plateau, has significantly disturbed the surrounding permafrost environment through its urbanization process. Engineering construction (such as road building and real estate development) excavates surface soil and removes vegetation, destroying the original surface insulation layer and energy balance system. Overgrazing leads to grassland degradation, reduced vegetation coverage, increased exposed surface area, and enhanced soil moisture evaporation, further accelerating permafrost degradation. Mining activities not only directly destroy permafrost layer structures but also alter local topography and surface hydrothermal conditions through waste disposal, inducing or exacerbating secondary disasters such as thermal thaw slumping.

2.3 Eco-Geological Manifestations of Permafrost Degradation

Permafrost degradation manifests as a series of chain reactions at the ecosystem level. First, descending permafrost table leads to redistribution of soil moisture. Active layer thickening causes increased downward infiltration of soil moisture, severely desiccating the 0-25 cm surface soil layer and disrupting moisture supply conditions for plant root zones. Second, weakening or loss of the permafrost aquitard function alters groundwater transport pathways and recharge relationships, resulting in hydrological effects such as spring attenuation, wetland desiccation, and increased river runoff variability. Third, permafrost degradation changes the physical and mechanical properties of soil masses, reducing slope stability and creating conditions for geological hazards such as thermal thaw slumping and solifluction.

Thermal thaw slumping represents one of the most characteristic geological hazard types associated with permafrost degradation. Research indicates that thermal thaw slumping on the Qinghai-Tibet Plateau is primarily concentrated in gentle slope zones at elevations of 4,500-5,300 meters with slopes of 4-12 degrees. The slumping process triggers multiple chain reactions in soil properties, vegetation communities, and carbon fluxes through reshaping surface micro-topography. Soil bulk density in disturbed areas increases significantly, with fine-grained materials undergoing intense rearrangement; vegetation communities retrogress from typical alpine meadows to alpine swamp meadows or degraded grasslands; soil organic carbon and alkali-hydrolyzable nitrogen migrate toward low-lying areas, altering the material foundation and energy flow patterns of ecosystems.

3. Ecological Effects and Impact Mechanisms of Permafrost Degradation

3.1 Vegetation Community Response and Succession Patterns

A close interactive relationship exists between permafrost and vegetation. On one hand, permafrost regulates soil temperature, moisture, and nutrient conditions, constraining vegetation type composition, spatial distribution, and productivity levels; on the other hand, vegetation feeds back on permafrost thermodynamic states through functions such as reflecting solar radiation, intercepting precipitation, and providing thermal insulation. This interdependent relationship ensures that permafrost degradation inevitably causes corresponding changes in vegetation communities.

In the northeastern Qinghai-Tibet Plateau, as permafrost degradation intensifies, vegetation types exhibit regular retrogressive succession sequences: from swamp meadows evolving to typical meadows, further degrading to grassland meadows, and ultimately becoming desertified grasslands or bare land. Community plant composition gradually shifts from hygrophytic or sub-hygrophytic species to mesophytic, sub-xerophytic, and ultimately xerophytic species. Dominant species undergo significant replacement, with the proportion of high-quality forage grasses represented by Cyperaceae and Poaceae declining, while the proportion of poisonous weeds increases significantly, resulting in notably reduced forage quality and feeding value.

Changes in vegetation coverage and productivity represent the most intuitive manifestations of the ecological effects of permafrost degradation. Research demonstrates a significant positive correlation between permafrost thickness and vegetation coverage; thicker permafrost layers provide stronger protection and support for surface soil water-holding capacity, resulting in better vegetation growth conditions. When permafrost degradation causes the permafrost table to descend, reduced surface moisture supply leads to gradual replacement of Cyperaceae dominant species (such as Kobresia pygmaea and Kobresia humilis) by drought-tolerant plants represented by Stipa species, with vegetation coverage declining from 30-60% to less than 5%. Vegetation degradation not only reduces ecosystem primary productivity but also weakens soil organic matter accumulation processes through decreased litter input and root exudates.

3.2 Soil System Changes and Carbon-Nitrogen Cycling

Permafrost degradation exerts profound effects on soil physicochemical properties. As degradation intensifies, soil temperature gradually increases, moisture content decreases, organic matter content declines, and soil bulk density significantly increases. Fine-grained materials in surface soils undergo redistribution under freeze-thaw disturbance effects, with soil structure tending toward simplification. These changes not only directly affect vegetation growth but also indirectly regulate ecosystem material cycling processes by altering soil microbial community structure and activity.

The dynamic changes of soil organic carbon (SOC) represent a core concern regarding the ecological effects of permafrost degradation. The perennial permafrost region of the Qinghai-Tibet Plateau stores substantial ancient organic carbon, and permafrost degradation exposes these carbon pools to relatively warm environments, accelerating microbial decomposition and carbon release. Research indicates that the thermal thaw slumping process leads to tightly coupled redistribution of soil organic carbon and alkali-hydrolyzable nitrogen density, with carbon and nitrogen migrating toward low-lying areas and concentrating in surface soils. Although soil organic carbon content in vegetated areas can recover to some extent, the overall ecosystem carbon fixation capacity (gross primary productivity, GPP) remains approximately 25% lower than in non-degraded areas, indicating that ecological function recovery significantly lags behind structural changes.

Permafrost degradation also affects vegetation recovery processes by altering soil nitrogen transformation forms and availability. Reduced available nitrogen and phosphorus contents represent important driving factors of grassland degradation. On one hand, decreased vegetation coverage makes surfaces more susceptible to weathering and rainwater erosion, carrying away some soil nutrients; on the other hand, thinning plant litter layers inhibit microbial activity and mineralization processes, reducing conversion to available nitrogen and phosphorus. Therefore, in ecological restoration practice, supplementing nitrogen and phosphorus elements for degraded grasslands represents an important measure for promoting vegetation recovery.

3.3 Biodiversity Response and Ecosystem Service Functions

The impacts of permafrost degradation on biodiversity are manifested at three levels: species, community, and ecosystem. At the species level, permafrost degradation alters habitat moisture and temperature conditions, causing certain species adapted to cold, humid environments (such as some Kobresia species) to experience range contraction or even local extinction, while widely distributed species adapted to arid, warm conditions expand. At the community level, species diversity exhibits an initial increase followed by decrease, with the peak typically occurring at the mild degradation stage, as moderate disturbance increases habitat heterogeneity, providing ecological niches for more species; however, when degradation intensifies further, harsh environmental conditions become limiting factors for species survival.

The degradation of ecosystem service functions represents a comprehensive manifestation of permafrost degradation. Regarding water conservation functions, permafrost degradation leads to decreased soil water storage capacity, increased runoff variability, and attenuated spring flow. Regarding climate regulation functions, reduced vegetation coverage decreases carbon fixation, while soil organic carbon decomposition releases substantial greenhouse gases, forming a positive feedback loop between permafrost degradation and climate warming. Regarding livestock production functions, grassland degradation reduces grazing capacity, affecting local herders' livelihoods and sustainable regional economic development.

4. Permafrost Ecological Restoration Technology System

4.1 Basic Principles and Objectives of Ecological Restoration

Permafrost ecological restoration is a complex systematic engineering endeavor that requires combining natural laws with engineering approaches. Based on the "mountains, waters, forests, farmlands, lakes, and grasslands" life community concept, permafrost ecological restoration should focus on restoring permafrost thermodynamic stability as the core objective, reconstructing vegetation coverage and soil functions as the primary means, and achieving coordinated recovery of ecosystem structure and function as the ultimate goal. The following principles should be adhered to:

First, prioritize protection and rely primarily on natural recovery. For mildly degraded areas, the main strategy should involve reducing anthropogenic disturbance and promoting natural recovery through measures such as fencing enclosure and rotational grazing rest, creating conditions for ecosystem self-repair. Second, implement comprehensive treatment with multiple measures. For moderately to severely degraded areas, engineering measures should be combined with biological measures, addressing topography reshaping, permafrost reconstruction, soil improvement, and vegetation restoration to construct a complete restoration technology chain. Third, adopt locally appropriate strategies based on classification. According to differences in degradation type, degree, and site conditions, suitable restoration technologies and species configuration schemes should be selected, avoiding one-size-fits-all approaches and blind imitation. Fourth, implement dynamic monitoring and adaptive management. Establish long-term monitoring systems for restoration effectiveness, adjusting management measures based on monitoring results to ensure the sustainability of restoration outcomes.

4.2 Artificial Permafrost Layer Construction Technology

Artificial permafrost layer construction represents the core technical component of permafrost ecological restoration, aiming to restore the material structure, thermodynamic properties, and hydrogeological functions of permafrost layers in disturbed areas through engineering approaches. Drawing from ecological restoration practices in the Muli Mining Area, Qinghai Province, researchers have developed a systematic artificial permafrost layer construction technology workflow encompassing seven key steps: permafrost survey, profile model establishment, overlapping integration, backfill timing determination, surface water retention design, drainage ditch layout, and landform reshaping.

Permafrost survey constitutes the foundation of restoration work. Through remote sensing monitoring, geological surveys, drilling and sampling, and ground temperature monitoring, the planar distribution range, vertical stratification structure, ground temperature characteristics, and ground ice distribution conditions of original permafrost layers in the restoration area should be comprehensively identified. The survey should focus on key parameters including perennial permafrost table and base depths, mean annual ground temperature, active layer thickness, and ground ice content, providing basis for subsequent restoration design.

Profile model construction represents the technical core of permafrost restoration. Different characteristics of seasonal and perennial permafrost are addressed by constructing "artificial permafrost layer - backfill layer" dual-structure eco-geological layer profile models. For seasonal permafrost areas, the seasonal permafrost base is used as reference to form reconstructed layers through layered backfilling and one-time compaction engineering measures, restoring water and gas sealing and isolation functions. For perennial permafrost areas, reference is made to nearby original perennial permafrost profiles, with layered backfilling and compaction combined with atmospheric precipitation or water injection to create environmental conditions favorable for rapid permafrost recovery. The protective layer (above the reconstructed layer to the ground surface) is primarily achieved through soil layer reconstruction and re-vegetation, utilizing vegetation's regulatory effects on surface energy, moisture, and humidity to protect underlying permafrost.

Overlapping integration is the key technology ensuring effective connection between artificial permafrost layers and surrounding original permafrost layers. Previous treatments often neglected the construction of connecting surfaces between original strata and newly constructed permafrost layers, leading to subsequent freeze-thaw or thermal thaw at connection points, forming water conduction channels. To address this, clay-fine gravel water diversion measures and upper gravel heat dissipation layers are employed to achieve organic integration between reconstructed and original permafrost layers in terms of material structure, aquifer structure, and hydraulic connection.

The selection of backfill timing significantly influences permafrost recovery efficiency. Generally, choosing winter or early spring for backfilling allows the low-temperature environment to rapidly bring backfilled soil bodies into a frozen state, shortening the permafrost recovery cycle. Surface water retention measures include covering organic matter layers and laying water-retention materials, aiming to maintain moisture conditions above the permafrost layer and reduce evaporation losses. Reasonable drainage ditch layout prevents concentrated surface water infiltration from causing thermal erosion of permafrost layers. Landform reshaping should follow original terrain characteristics, restoring original topographic and geomorphological features as much as possible to create suitable micro-topographic conditions for subsequent vegetation recovery.

4.3 Vegetation Restoration and Soil Reconstruction Technology

Vegetation restoration represents the surface-level component of permafrost ecological restoration and serves as an important indicator for assessing restoration effectiveness. In the

Xining and surrounding alpine regions, vegetation restoration should fully consider the constraints of elevation, temperature, precipitation, and soil site conditions. Research indicates that when elevation is below 5,000 meters, annual mean temperature is above -5.6°C, annual accumulated temperature above 0°C exceeds 450°C, and annual precipitation is not less than 262.2 mm, artificial vegetation restoration along highways and in degraded grasslands is feasible. Under conditions where soil pH does not exceed 8.8 and salt content does not exceed 0.13%, relatively stable artificial vegetation can be established through artificial seeding.

Vegetation restoration technologies primarily include three modes: fencing enclosure for near-natural recovery, reseeding improvement, and artificial grassland reconstruction. For mildly degraded areas, fencing enclosure can effectively exclude grazing disturbance, allowing vegetation to gradually recover through natural reproduction, with vegetation coverage increasing by 5-10%. For moderately degraded areas, reseeding should be conducted on the basis of enclosure, selecting native grass species adapted to local climate and soil conditions (such as Elymus nutans, Puccinellia tenuiflora, and Bromus inermis), combined with moderate soil improvement measures. For severely degraded areas or engineering sites, comprehensive soil reconstruction and artificial grassland reconstruction are required.

Soil reconstruction represents a technical challenge for vegetation restoration under conditions without borrowed soil. Addressing the scarcity of borrowed soil resources in high-altitude cold-region mining areas, in-situ waste soil improvement strategies can be adopted, improving soil structure and fertility by adding organic materials (such as humus soil, peat, and organic fertilizers), and regulating soil pH and salt content. Developing soil reconstruction technologies suitable for high-altitude cold regions and establishing integrated space-air-ground-time soil monitoring systems constitute the key to achieving vegetation restoration without borrowed soil.

4.4 Engineering-Assisted Protection Measures

In permafrost ecological restoration, engineering-assisted protection measures can effectively improve permafrost thermodynamic environments and accelerate restoration processes. Based on heat transfer principles regulating convection, conduction, and radiation, commonly used permafrost protection engineering technologies include the following types:

Gravel layer cooling technology utilizes natural convection effects of air in block gravel pores to extract subsurface heat during winter while preventing heat transfer downward during summer, achieving active cooling protection of permafrost. When gravel particle sizes are generally not less than 8-10 cm and laying thickness is not less than 80-100 cm, cooling effects are more significant. Thermosyphon technology represents a high-efficiency heat transfer device utilizing phase change materials; through internal working medium vapor-liquid phase change circulation, it transfers heat from soil bodies to the atmosphere for dissipation during winter, annually extracting approximately 2×10^3 kJ of energy from soil bodies. Sunshade technology reduces ground temperature by blocking direct solar radiation, providing rain shelter and wind regulation, effectively protecting permafrost in high-temperature, high-ice-content permafrost areas. Thermal insulation technology reduces heat transfer to underlying permafrost by laying industrial insulation materials (such as extruded polystyrene boards XPS, expanded polystyrene boards EPS) on roadbeds or ground surfaces, effectively reducing seasonal permafrost thaw depths by 1-2 meters.

These engineering measures have been widely applied in major projects such as the Qinghai-Tibet Railway and Qinghai-Tibet Highway, forming a design concept and complete technology system of "active cooling, permafrost protection." In ecological restoration, suitable engineering measures can be selected and combined with biological measures based on degradation type and site conditions.

5. Application of Physics-Informed Digital Twin Technology in Permafrost Prediction

5.1 Principles and Advantages of Physics-Informed Neural Networks

The precise implementation of permafrost ecological restoration depends on accurate prediction and dynamic assessment of permafrost thermodynamic states. While traditional permafrost heat conduction models are based on rigorous physical mechanisms, they often rely on numerous parameters that are difficult to measure directly (such as thermal conductivity, heat capacity, and unfrozen water content), resulting in high model calibration costs and inability to update in real time as new observation data becomes available. Purely data-driven machine learning methods, while computationally fast, typically lack physical consistency, require large amounts of labeled data, and are difficult to meet application demands in data-scarce cold regions.

Physics-Informed Neural Networks (PINN) provide a new technical pathway for overcoming the above challenges. The core concept of PINN involves embedding governing equations describing physical processes (such as heat conduction equations and mass conservation equations) as constraint conditions into the neural network's loss function, enabling the network to strictly adhere to physical laws while learning data patterns. This deeply integrated modeling approach combining data and physics both retains the powerful nonlinear fitting capability of neural networks and ensures physical consistency and interpretability of prediction results.

The advantages of PINN in permafrost thermodynamic modeling are manifested in multiple aspects. First, by embedding heat conduction equations into the network structure, PINN can achieve high-precision reconstruction of temperature fields under sparse observation data conditions, significantly reducing dependence on dense monitoring networks. Second, PINN can simultaneously predict multiple thermodynamic variables including temperature, unfrozen water content, thermal conductivity, and heat capacity, overcoming the limitation of traditional methods that can only predict single variables. Third, PINN's parameterization form is flexible, allowing neural networks to be conveniently embedded within physical models as parameterization schemes (differentiable modeling), enabling adaptive inversion of unknown parameters. Fourth, PINN supports sequential data assimilation, capable of updating model states in real time as new observation data arrives, maintaining prediction timeliness and accuracy.

5.2 Digital Twin Framework Construction

Digital twin represents an integrated technology system that enables real-time mapping and bidirectional interaction between physical entities and their virtual models. In the field of permafrost ecological restoration, constructing physics-informed digital twin frameworks can achieve real-time prediction, inversion, and information mining of thermodynamic processes in restoration areas, providing scientific basis for optimization and adjustment of restoration schemes.

A complete permafrost digital twin framework typically includes four core modules: data acquisition, data-physics fusion, prediction, and information mining. For data acquisition, research integrates multi-source observation data, including distributed temperature sensing (DTS) fiber monitoring, distributed acoustic sensing (DAS) profiles, borehole thermometers, laboratory thermal property testing, and meteorological station temperature data. Among these, DTS technology provides high spatial resolution ground temperature observations along fiber lines (spatial resolution reaching 0.25 m), DAS technology can invert shear wave velocity profiles for independent validation, while borehole temperatures and laboratory-measured thermal parameters are used to assess the model's spatial extrapolation and property inversion capabilities.

In the data-physics fusion module, differentiable modeling (DM) architecture is adopted to embed neural network parameterization schemes within heat conduction physical models. The key characteristic of differentiable modeling is that the entire model system is differentiable, meaning automatic differentiation techniques can efficiently compute gradients of model outputs with respect to various parameters, thereby utilizing gradient-based optimization algorithms for model training and parameter updates. This architecture organically combines the strict constraints of physical equations with the flexible expression capabilities of neural networks, achieving adaptive learning of unknown constitutive relationships while solving governing equations.

The prediction module is responsible for outputting spatial-temporal distributions of key variables such as permafrost temperature fields and unfrozen water content fields for future time periods based on current model states and boundary conditions. The information mining module extracts thermodynamic patterns underlying permafrost evolution through analysis of trained model parameters and internal states, such as the variation relationships between thermal conductivity and heat capacity with temperature, and the morphological characteristics of freezing curves, providing new insights for deep understanding of permafrost physical processes.

5.3 Sequential Data Assimilation and Real-Time Updates

Permafrost systems represent dynamic systems significantly influenced by recent boundary conditions (such as air temperature, precipitation, and surface energy balance). Traditional model calibration methods typically employ whole-history unified training strategies, using all available observation data for model fitting at once. However, research indicates that for dynamically evolving systems like permafrost, sequential data assimilation strategies are often superior to whole-history unified calibration.

The core concept of sequential data assimilation is that whenever a new batch of observation data is obtained, the model is incrementally updated with this data rather than retrained from scratch. The advantages of this strategy include: first, timely utilization of the latest system state information reflected by new observations, maintaining model sensitivity and predictive capability for current states; second, lower computational costs, as each update only processes newly added data rather than the full dataset; third, effectively mitigating drift phenomena in model extrapolation over time, maintaining long-term prediction stability.

In a study of roadbed permafrost systems in Utqiaġvik, Alaska, a digital twin system employing sequential data assimilation controlled the median root mean square error (RMSE) of temperature predictions during independent prediction periods to approximately 3°C, representing approximately 34% error reduction compared to un-updated baseline models. These results demonstrate that digital twin technology not only enables real-time prediction of permafrost thermodynamic states but also possesses strong spatial extrapolation capabilities and physical interpretability, providing new technical pathways for cold-region infrastructure monitoring and ecological restoration effectiveness assessment.

5.4 Application Prospects in Permafrost Ecological Restoration

The application of physics-informed digital twin technology to permafrost ecological restoration can enhance the scientific rigor and precision of restoration work in the following aspects:

First, pre-restoration diagnosis. By integrating remote sensing temperature data, meteorological data, and limited field observations, digital twin models of permafrost in restoration areas can be constructed to invert key parameters such as permafrost temperature fields, active layer thickness, and ground ice distribution, providing fundamental data support for restoration scheme design. Second, restoration process monitoring. Distributed sensing networks such as DTS are deployed in restoration areas to obtain real-time ground temperature spatial-temporal evolution data, driving continuous updates of digital twin models for dynamic assessment of restoration measure implementation effectiveness (such as artificial permafrost construction and vegetation recovery). Third, post-restoration assessment. Utilizing the long-term prediction capabilities of digital twin models to assess the stability and recovery trends of restored permafrost systems, providing decision-making basis for adaptive adjustment of management measures. Fourth, knowledge mining. Through analysis of thermodynamic constitutive relationships learned by digital twin models, revealing influence mechanisms of different restoration measures on permafrost thermodynamic processes, providing theoretical guidance for optimization and innovation of restoration technologies.

Despite the tremendous potential demonstrated by digital twin technology in permafrost prediction, its application in ecological restoration still faces several challenges. Data scarcity represents the primary issue, as harsh natural environments and high monitoring costs in cold regions limit sensor network deployment density. Insufficient model generalization also constitutes an important bottleneck, as whether models trained for specific sites can be transferred to regions with different climatic and geological conditions requires further validation. Additionally, how to effectively couple physical variables predicted by digital twins with dynamic models of ecological processes such as vegetation recovery and soil improvement to construct comprehensive water-heat-ecology coupled assessment frameworks represents an important direction for future research.

6. Practice and Prospects of Permafrost Ecological Restoration in Xining

6.1 Regional Ecological Restoration Practice

As a pilot demonstration zone for national ecological civilization and a core area for Qinghai-Tibet Plateau ecological protection, Qinghai Province has undertaken a series of important practices in permafrost ecological restoration in recent years. Qinghai Province's "14th Five-Year Plan" explicitly proposes major ecological construction projects including the "China Water Tower Protection Project," "Sanjiangyuan Ecological Protection and Restoration Project," and "Qilian Mountains Ecological Protection and Remediation Project," listing glacier-permafrost-snow mountain preventive protection, degraded grassland governance, and human activity site restoration as key tasks.

Regarding degraded grassland recovery in permafrost areas, Qinghai Province has implemented the "Key Technology Transformation and Demonstration for Ecological Restoration of Degraded Grasslands in High-Altitude Permafrost Regions" project. In areas with relatively severe grassland degradation such as the Qinghai Lake periphery and Qilian

Mountain areas, technical methods including ecological health assessment of moderately degraded alpine grasslands, fencing enclosure for near-natural recovery, reseeding improvement recovery, and severe degradation artificial grassland reconstruction have been employed to establish experimental demonstration areas for different degradation degrees and treatment technologies. Project implementation results indicate that vegetation coverage in lightly-moderately and severely degraded grassland experimental areas increased by 5-10%, with ecosystem structure tending toward stability.

Muli Mining Area ecological restoration represents a typical case of successful application of permafrost layer construction technology. Located on the southern slopes of the Qilian Mountains, Muli Mining Area is Qinghai Province's largest coal mining area, where large-scale open-pit mining severely damaged permafrost layers. During comprehensive ecological environment remediation, the technical team innovatively proposed fusion and overlapping technology between artificial permafrost layers and original permafrost layers, forming an artificial permafrost layer restoration technology workflow encompassing permafrost survey, profile model establishment, overlapping integration, backfill timing determination, surface water retention design, drainage ditch layout, and landform reshaping. Through excavation pit exposure and borehole ground temperature monitoring verification, the perennial permafrost table in originally slag-covered areas has stably ascended, and new permafrost layers have begun forming in newly backfilled mining pit areas. Artificially constructed permafrost layers have essentially achieved the levels of original permafrost layers in material structure, groundwater aquifer structure, and hydraulic connection, with vegetation coverage reaching 77.8% on average, far exceeding the 50% target specified in the remediation plan.

These practices demonstrate that through scientific technical design and systematic engineering implementation, ecological functions in degraded permafrost areas of the Qinghai-Tibet Plateau can be effectively restored. However, existing practices have primarily focused on mining site recovery and highway corridor restoration, with systematic restoration work for permafrost degradation in Xining urban periphery and extensive agro-pastoral interlacing zones still having considerable room for improvement.

6.2 Priority Directions for Xining Permafrost Restoration

Based on the permafrost distribution characteristics and degradation status of Xining and surrounding areas, future ecological restoration work should focus on the following directions:

First, permafrost protection in mountainous and hilly areas around urban centers. Xining's urban expansion has significantly disturbed permafrost environments in surrounding mountainous and hilly areas. Urban planning should fully consider permafrost protection needs, delineate permafrost ecological protection red lines, and restrict large-scale development and construction in sensitive areas. For already damaged areas, priority should be given to ecological measures such as landform reshaping and vegetation recovery, supplemented by necessary engineering protection measures, to promote natural permafrost recovery.

Second, permafrost restoration along transportation infrastructure corridors. The Qinghai-Tibet Railway, Qinghai-Tibet Highway, and provincial trunk highways traverse extensive permafrost areas, with engineering construction exerting long-term impacts on permafrost thermal stability. On the basis of existing engineering protection measures (such as gravel roadbed, thermosyphons, and sunshades), vegetation recovery on roadbed slopes should be combined to construct composite protection systems integrating engineering and biological approaches. Digital twin technology should be utilized for real-time monitoring and early warning of roadbed permafrost conditions, enabling timely problem identification and remedial measures.

Third, comprehensive treatment of degraded grasslands. Degraded grassland problems caused by overgrazing are widespread in pastoral areas surrounding Xining, subsequently triggering permafrost degradation. Scientific grazing management systems including livestock-forage balance, seasonal grazing rest, and zonal rotational grazing should be implemented to reduce grassland pressure. In severely degraded areas, artificial reseeding and soil improvement should be conducted, selecting native grass species adapted to high-altitude cold climates for vegetation reconstruction. Meanwhile, ecological compensation mechanisms should be explored to mobilize herders' enthusiasm for participating in protection efforts.

Fourth, permafrost protection in water source areas and water conservation. The Huangshui River basin is Xining's mother river, and the water conservation functions of permafrost within the basin are crucial for urban water supply security. Ecological protection and vegetation recovery in water source area permafrost regions should be strengthened, improving water conservation capacity through measures such as mountain closure for forest and grassland restoration. Mining development and permafrost-damaging construction activities in permafrost-sensitive water source areas should be strictly prohibited.

6.3 Prospects for Intelligent Restoration Management

In the future, permafrost ecological restoration will develop toward precision, intelligence, and adaptability. Constructing integrated "space-air-ground" monitoring networks constitutes the foundation for achieving precision restoration. Space-based remote sensing can provide large-scale, long-term surface temperature, vegetation index, and surface deformation information; aerial drones can obtain high-resolution vegetation coverage, soil moisture, and micro-topography data; ground-based sensor networks (such as DTS, automatic weather stations, and soil temperature and moisture sensors) can achieve continuous real-time monitoring of key parameters. Fusion analysis of multi-source data can provide data support for the entire restoration process.

Digital twin technology will become the core tool for intelligent restoration management. By constructing digital twin models of permafrost ecosystems in restoration areas, dynamic assessment of restoration effectiveness and predictive simulation of future trends can be achieved. Based on the scenario analysis capabilities of digital twins, virtual experiments and effectiveness comparisons of multiple alternative schemes can be conducted before restoration scheme implementation, selecting optimal solutions. During restoration implementation, digital twin models can continuously assimilate the latest observation data, updating assessment results in real time to provide scientific basis for dynamic adjustment of management measures.

The deep application of artificial intelligence technology will further enhance the intelligence level of restoration management. Utilizing deep learning algorithms for intelligent analysis of multi-source monitoring data can achieve automatic identification and early warning of permafrost degradation risks. Combined with reinforcement learning methods, adaptive management decision models can be constructed to automatically optimize management strategies based on system state feedback. The introduction of physics-informed neural networks can substantially reduce model training dependence on labeled data while ensuring prediction physical consistency, improving model applicability under data-scarce conditions.

Establishing cross-regional collaborative governance mechanisms represents an important institutional foundation for ensuring restoration effectiveness. Permafrost ecosystems exhibit significant spatial continuity and regional correlation, and single administrative region governance measures often fail to achieve ideal results. Inter-provincial and inter-municipal coordination mechanisms should be established for unified planning, collaborative implementation, and information sharing to form synergies for permafrost protection and ecological restoration. Meanwhile, international cooperation and exchange should be strengthened, drawing upon advanced experiences and technologies from Arctic and alpine region permafrost protection to enhance the overall level of permafrost ecological restoration in China.

7. Conclusions

This paper takes the permafrost region of Xining and surrounding areas in the northeastern margin of the Qinghai-Tibet Plateau as the research object, systematically analyzing the distribution characteristics, degradation status, and ecological effects of permafrost in this region, summarizing key restoration technologies including artificial permafrost layer construction, vegetation recovery, and engineering-assisted protection, and exploring the application prospects of frontier technologies such as physics-informed digital twins in permafrost prediction and restoration assessment. The main conclusions are as follows:

(1) The northeastern margin of the Qinghai-Tibet Plateau represents a sensitive transitional zone where seasonal permafrost and perennial permafrost interweave. Permafrost degradation in the Xining surrounding area is primarily manifested as ground temperature elevation, active layer thickening, and vegetation retrogressive succession, with driving factors including climate warming, urbanization expansion, overgrazing, and engineering construction.

(2) Through altering soil moisture conditions, nutrient cycling, and habitat conditions, permafrost degradation triggers a series of cascading ecological effects including vegetation community succession, biodiversity decline, water conservation function attenuation, and increased carbon release, forming a vicious cycle of "permafrost degradation - vegetation degradation - soil degradation."

(3) The systematic technical workflow of "permafrost survey - profile model construction - overlapping integration - backfill timing optimization - surface water retention - vegetation recovery" can effectively achieve rapid construction of artificial permafrost layers and coordinated recovery of ecological functions. Practice cases such as the Muli Mining Area have confirmed the effectiveness and feasibility of this technology system.

(4) Physics-informed digital twin technology, through integrating differentiable modeling with distributed sensing observations, can achieve real-time prediction of permafrost thermodynamic states and key parameter inversion, providing new technical means for precise decision-making and effectiveness assessment in permafrost ecological restoration. Sequential data assimilation strategies can effectively maintain model timeliness and prediction accuracy.

(5) Future efforts should prioritize advancing permafrost protection around urban centers, corridor restoration along transportation infrastructure, comprehensive treatment of degraded grasslands, and water source area protection, while accelerating the construction of integrated "space-air-ground" monitoring networks and intelligent restoration management systems, achieving the transformation of permafrost ecological restoration from experience-driven to data-driven approaches.

Permafrost ecological restoration is a long-term and arduous task requiring coordinated advancement of scientific research, engineering practice, and policy management. With the advancement of monitoring technologies and intelligent methodologies, we have reason to believe that the ecological security barrier of this "China Water Tower" on the Qinghai-Tibet Plateau will be further consolidated, making greater contributions to regional sustainable development and national ecological security.

References

[1] Gou L, Xiao M, Zhu T, et al. Physics-Informed Digital Twin for Predicting Permafrost Thermodynamic Characteristics Under an Embankment Road in Utqiaġvik, Alaska. Journal of Geophysical Research: Earth Surface, 2026, 131: e2025JF008787.

[2] Liang Z X, Wang T, Wang W C, et al. Construction and Application of Permafrost Layer in Ecological Geological Layer Restoration of High-Altitude Cold Region Mining Area. Coal Science and Technology, 2023, 51(12): 140-148.

[3] Li Y, Yuan Y J, Wang Y Y. Research on Prevention and Restoration Countermeasures of Ecological Destruction Caused by Thermal Thaw Slumping of Problematic Permafrost. Environmental Science and Management, 2020, 45(4): 93-96.

[4] Peng Y. Review of Perennial Permafrost Subgrade Deformation Prediction Based on Neural Network. Engineering and Technology Innovation, 2025.

[5] Wu Q B. Characteristics of Ecosystem Changes During Permafrost Degradation in Northern Qinghai-Tibet Plateau. Journal of Glaciology and Geocryology, 2007.

[6] Cheng G D, Jin H J. Progress in Highway Construction Technology in Permafrost Regions of Qinghai-Tibet Plateau. China Journal of Highway and Transport, 2003.

[7] Li X, Cheng G D. Prediction of Permafrost Distribution Changes on Qinghai-Tibet Plateau Under Global Warming. Acta Scientiarum Naturalium Universitatis Pekinensis, 2016, 52(2): 249-256.

[8] Lin Z J, Niu F J. Research on Thermal Thaw Slumping in Qinghai-Tibet Plateau: Revealing Cascading Impact Mechanisms of Permafrost Degradation on Ecosystems. Acta Pedologica Sinica, 2025.

[9] Zhang P F. Feedback Mechanisms Between Permafrost Degradation and Vegetation and Collaborative Strategies for Human Activity Control and Ecological Restoration. Journal of Sichuan Forestry Science and Technology, 2025.

[10] Wang S L, Lin Z J. Basic Characteristics of Spatial Distribution of Permafrost Line in Mainland China. Acta Seismologica Sinica, 2003.

[11] People's Government of Qinghai Province. 14th Five-Year Plan for National Economic and Social Development of Qinghai Province and Long-Range Objectives Through the Year 2035. 2021.

[12] Li S X, Wu Q B, Zhang Z. Permafrost Problems in Qinghai-Tibet Plateau Development. Advance in Earth Sciences, 2000, 15(4): 407-410.

[13] Dong S K, Liu S L, Shao X Q. Key Technology Transformation and Demonstration Project for Ecological Restoration of Degraded Grasslands in High-Altitude Permafrost Regions of Qinghai. Qinghai Provincial Forestry and Grassland Bureau, 2022.

[14] Zhou Y W, Guo D X, Qiu G Q, et al. Permafrost in China. Beijing: Science Press, 2000.

[15] Chen J, Wang F T. Technological Innovation Consolidates Ecological Barrier of the "Roof of the World". Science and Technology Daily, 2023-06-14.

[16] Jiao S H, Wang L Y, Liu G N, et al. Prediction of Permafrost Distribution Changes on Qinghai-Tibet Plateau Under Global Warming. Acta Scientiarum Naturalium Universitatis Pekinensis, 2016, 52(2): 249-256.

[17] Qinghai Provincial Bureau of Environmental Geological Exploration. Survey and Monitoring Project of Glaciers, Ice Lakes, and Permafrost Natural Resources in Qinghai Province. 2022.