

Satellite observations characterize the impacts of climate change and human activities on permafrost along Qinghai–Tibet Railway

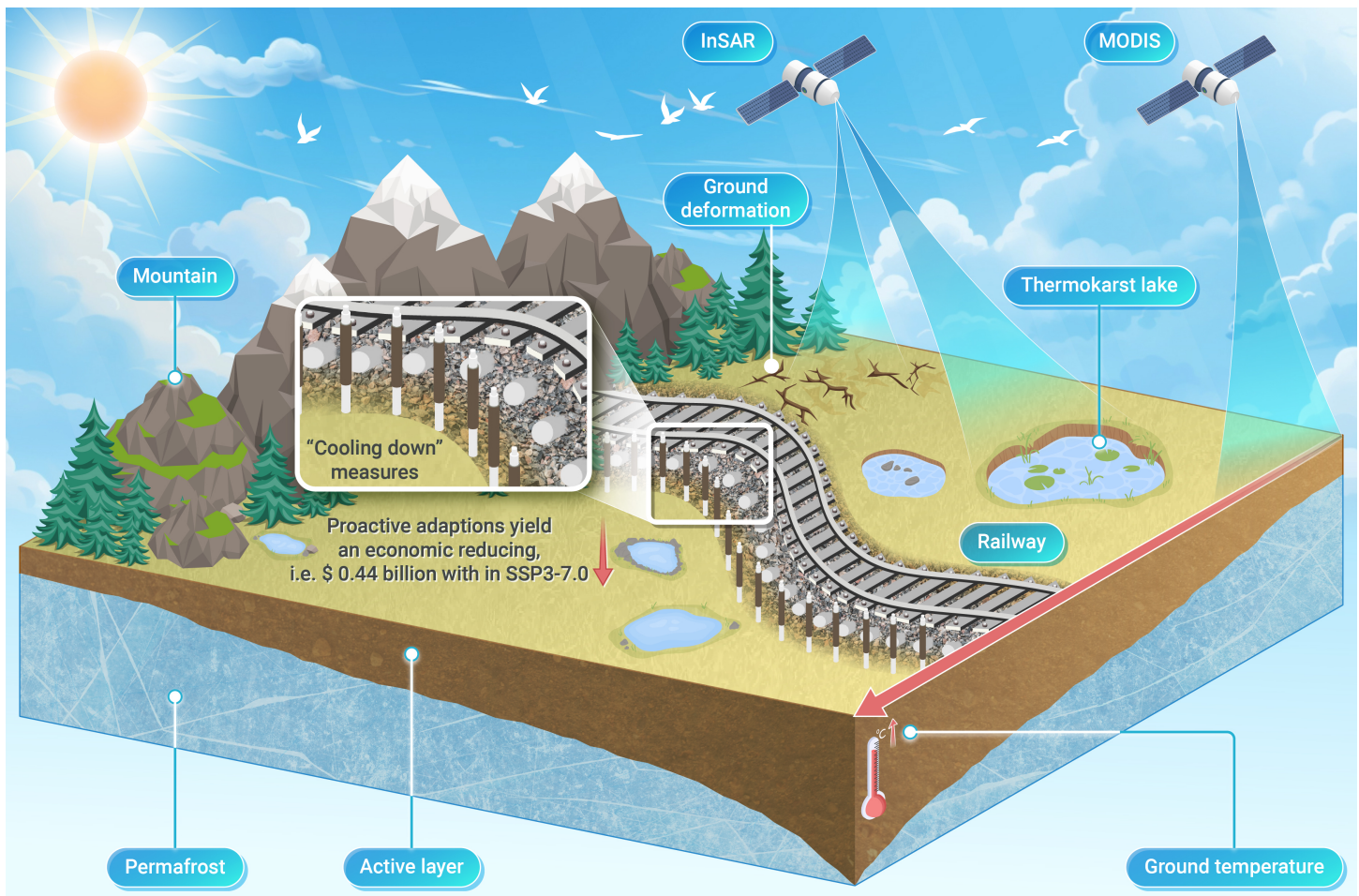
Zhengjia Zhang,¹ Fulong Chen,^{2,3,*} Hui Lin,^{4,5,*} Chao Wang,^{2,3,6} Xiuguo Liu,¹ Mengmeng Wang,¹ and Jin Luo^{4,5}

*Correspondence: chenfl@aircas.ac.cn (F.C.); huilin@cuhk.edu.hk (H.L.)

Received: June 14, 2023; Accepted: February 19, 2025; Published Online: March 6, 2025; <https://doi.org/10.59717/j.xinn-geo.2024.100127>

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GRAPHICAL ABSTRACT



PUBLIC SUMMARY

- Satellite observations and models were used to assess the stability of permafrost.
- Global climate change had resulted in significant effects on the permafrost region.
- Human disturbance intensifies the instability of permafrost within the 500 m zone.
- The economic cost of proactive adaptation for Qinghai–Tibet Railway under global warming has estimated.

Satellite observations characterize the impacts of climate change and human activities on permafrost along Qinghai–Tibet Railway

Zhengjia Zhang,¹ Fulong Chen,^{2,3,*} Hui Lin,^{4,5,*} Chao Wang,^{2,3,6} Xiuguo Liu,¹ Mengmeng Wang,¹ and Jin Luo^{4,5}

¹School of Geography and Information Engineering, China University of Geosciences, 388 Lumo Road, Wuhan 430074, China

²International Research Center of Big Data for Sustainable Development Goals (CBAS), Beijing 100094, China

³Key Laboratory of Digital Earth Science, Aerospace Information Research Institute, Chinese Academy of Sciences, Beijing 100094, China

⁴Key Laboratory of Poyang Lake Wetland and Watershed Research, Jiangxi Normal University, Nanchang 330022, China

⁵Ministry of Education & School of Geography and Environment, Jiangxi Normal University, Nanchang 330022, China

⁶University of Chinese Academy of Sciences, Beijing 100049, China

*Correspondence: chenfl@aircas.ac.cn (F.C.); huilin@cuhk.edu.hk (H.L.)

Received: June 14, 2023; Accepted: February 19, 2025; Published Online: March 6, 2025; <https://doi.org/10.59717/j.xinn-geo.2024.100127>

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Citation: Zhang Z., Chen F., Lin H., et al. (2025). Satellite observations characterize the impacts of climate change and human activities on permafrost along Qinghai–Tibet Railway. *The Innovation Geoscience* 3:100127.

Climate change poses new challenges to the safe operation of large-scale infrastructure in frozen soil regions worldwide. However, climate change feedback of engineering infrastructure in fragile permafrost regions remains unclear. Here, we developed a model combining the temperature at the top of the permafrost (TTOP) and time-series interferometric synthetic aperture radar (InSAR) using multisource remote sensing data to generate the key information (ground temperature, deformation, and frozen soil type) about permafrost along the QTR (Qinghai–Tibet Railway) using two pre-defined buffer zones. We quantitatively characterized the permafrost degradation using spatiotemporal deformations along the 5-km corridor from 2017 to 2018. Over 5% permafrost along QTR (1,142 km) show evident settlement (> 20 mm/year) under global warming. However, the coupled anthropogenic disturbance is also noteworthy as proven by the intensified instability of permafrost within the 500-m buffer zone, although “cooling down” measures are prominent particularly for vulnerable regions. We found that proactive adaptations yield an economic reducing, i.e. \$ 0.44 billion under the climate scenario of SSP3-7.0 in 2020–2069. New findings presented here are insightful for the infrastructure engineering in other permafrost regions.

INTRODUCTION

With ongoing societal development, the demand for land is rapidly increasing, and vulnerable areas will inevitably be exploited. The development of fragile environmental regions is linked to the United Nations 2030 Sustainable Development Goals (SDGs)¹ and the Paris Agreement.² SDG 13 (climate action) aims to “take urgent action to combat climate change and its impacts”.³ Permafrost is a key component of the earth system, underlying approximately one-quarter of the land area in the Northern Hemisphere,^{4–6} and interacting with climate change,⁷ local environment,⁸ hydrological systems,⁹ and human systems.¹⁰ As the world’s highest permafrost region, approximately 28% of the Qinghai–Tibet Plateau (QTP) area is underlain by permafrost.¹⁰ However, in recent years, the QTP become warmer, with the air temperature increasing by up to 0.6°C per decade, which is twice as fast as the global average due to elevation-dependent warming in mountain regions.^{11,12} With societal development and rising demand for transportation systems, fragile environmental areas, including permafrost regions, also have urgent needs for large-scale infrastructure projects. Generally, the construction of permafrost infrastructure projects damages the thermal balance of permafrost environment, thereby contributing to permafrost degradation.^{13,14} Few studies have been conducted on impacts of constructing infrastructure on QTP permafrost environment using remote sensing. Moreover, with the warming global climate, permafrost infrastructures worldwide, such as the Eastern Siberia–Pacific Ocean Pipeline,¹⁵ the Alaska Pipeline,¹⁶ and the Qinghai–Tibet Railway (QTR),^{17,18} are experiencing numerous stability problems. Therefore, understanding the influence of climate change coupled with human disturbance on permafrost infrastructure is significant.

Existing studies on permafrost engineering stability have been typically focused on small-scale analysis using field measurement data, often yielding low-resolution results.^{5,14} Spaceborne remote sensing technology enables

large-scale Earth observation with high spatial resolution (from meters to submeters),^{19–21} providing an opportunity to monitor the global permafrost environment and infrastructure.^{22–24} The QTP is an ideal research area for investigating the influence of climate change on permafrost engineering. As a key engineering structure in permafrost region under China’s large-scale western development strategy, the QTR is the world’s highest and longest railway traversing permafrost. Stretching over 1,100 km from Golmud to Lhasa, approximately 550 km of its route crosses permafrost regions (from Xidatan to Anduo), and 900 km lies at elevation exceeding 4,000 meters.²⁵ During the design and construction of the QTR, engineers considered various factors to avoid unstable areas. However, due to the railway’s extensive length, it inevitably crosses vulnerable permafrost regions. It was reported based on monitored data that the annual mean air temperature along QTR showed increasing trends, with rates of over 0.40°C every 10 years.²⁶ Cooling measures, demonstrated to be effective, have been partially implemented along the QTR, particularly in ice-rich permafrost regions.²² However, these measures cannot cover the entire length of QTR due to economic cost. Numerous case studies have utilized remote sensing technology to access the stability of the QTR,^{25,27,28,29} and evaluate the economic impacts of permafrost degradation on QTP,³⁰ and the entire Northern Hemisphere,³¹ providing a preliminary understanding of the relationship between permafrost infrastructure and climate change.

Here, we conducted a comprehensive overview of fresh insights into interaction between QTR and climate change, drawn from ten years of remote sensing data (2010 to 2018). We obtained the permafrost distribution of QTP using the temperature at the top of the permafrost (TTOP) model.⁴ Additionally, we monitored ground deformation along the QTR using interferometric synthetic aperture radar (InSAR).³² On this basis, we quantitatively analyzed the permafrost activity intensity of the QTR corridor and its internal relationship with climate change and human activities. Our results indicate that, on a corridor scale (5 km), climate change serves as the main factor affecting permafrost environment. On a local buffer scale (500 m), human activities (construction and operation of the QTR) amplified permafrost instability and degradation. Furthermore, we employed an infrastructure life span model to project the economic cost of permafrost degradation with and without adaptive measurements under two climate scenarios (SSP2-4.5 and SSP3-7.0). The results again verified that proactive adaptation measurements are cost-effective for maintaining linear infrastructure operations under global warming. This study could be used as a representative demonstration for similar engineering construction projects in the later stages, such as the Russia–China natural gas pipeline,³³ the Eurasian high-speed railway,³⁴ and projects in the permafrost region of the United States.

MATERIALS AND METHODS

We analyzed impacts of climate change and human activities on permafrost by compiling and interpreting permafrost ground deformation, permafrost distribution, measured temperature data, and monitored thermokarst lakes. Multi-source remote sensing images, such as synthetic aperture radar (SAR) and optical images, were used to generate the key information of permafrost. First, we used time-series InSAR method to derive

permafrost thaw-induced settlement. Then, we generated the frozen soil distribution map along Qinghai–Tibet Engineering Corridor (QTEC) via TTOP model with optical remote sensing images. Thermokarst lakes were identified using submeter-resolution SAR images to analyze the effects of permafrost infrastructure construction on permafrost. Finally, we utilized the ICICLE (ISER Comprehensive Infrastructure Climate Life-Cycle Estimator) model to estimate the economic loss of the permafrost infrastructure due to climate change under two climate scenarios (SSP2-4.5 and SSP3-7.0). The flowchart of the method is shown in Figure S1. Detailed descriptions of the method were given in this section.

Datasets

In this study, we used multi-source remote sensing images, such as SAR and optical, to generate the key information of permafrost. The remote sensing datasets contain 26 environmental satellite (Envisat) SAR images acquired from 2007 to 2010, 216 Sentinel-1A SAR images acquired from 2017 to 2018, eighteen TerraSAR-X SAR images acquired in October 2014 and October 2019, and 5, 244 Moderate-resolution Imaging Spectroradiometer (MODIS) land surface temperature products from 2001 to 2018. We utilized time-series InSAR to determine ground deformation and detect thermokarst lakes. We used MODIS products to identify permafrost zones on the basis of the TTOP model.⁴

InSAR Processing

Time-series InSAR could monitor ground deformation in the radar line of sight (LOS) with millimeter accuracy by analyzing the phase information from different SAR images over the same area. The main limitations for time-series InSAR in permafrost regions are the temporal decorrelations and nonlinear deformation trend caused by the dynamics of the active layer.²² In permafrost regions, the backscattering of the surface changes significantly in a 1-year cycle. To decrease the effect of temporal decorrelation and generate accurate results, the small baseline subset algorithm was introduced to retrieve the ground motion of permafrost in the QTP.

After co-registering all SAR images of each track, we identified the interferometric pairs using the small-baseline strategy (using a spatial baseline smaller than 100 meters and a temporal baseline smaller than 100 days). We then obtained differential interferograms by removing topographic phase components. To decrease the phase noise and facilitate phase unwrapping, we implemented the spatially adaptive coherence-dependent Goldstein filtering method.³⁵ We excluded the interferometric phase with significant phase-unwrapping error for subsequent deformation estimation steps. We masked pixels with low coherence due to water, dense vegetation, or snow by applying a coherence threshold of 0.7. We employed the minimum cost flow phase-unwrapping algorithm to unwrap the interferometric phase.³⁶ For interferograms with phase ramps that were probably caused by residual orbit error and topographic-related atmospheric phases, we used a polynomial mode to remove the phase ramps. We converted the time-series unwrapped interferometric phase into deformation information using a linear deformation model. By analyzing spatial and temporal filtering, we discriminated between atmospheric phases, nonlinear deformation, and residual phase errors. Finally, we derived time-series displacement and a mean velocity map in the LOS for selected point. Assuming most of the permafrost ground deformation occurs vertically, we converted LOS displacement to vertical displacement using the SAR incidence angle (θ).

TTOP model

We used the TTOP model to map the permafrost distribution of QTP based on nearly 10 years of MODIS temperature products. In accordance with the relationship between climate and permafrost, TTOP is established in consideration of the local topography and soil properties,^{4,37} which is defined as:⁴

$$TTOP = \frac{\left(\frac{k_t}{k_f}\right) \cdot DDT - DDF}{P} = \frac{(r_k \cdot n_t \cdot I_t - n_f \cdot I_f)}{P}, \quad (1)$$

where DDT ($n_t \cdot I_t$) is the surface thawing degree days (seasonal thawing index); DDF ($n_f \cdot I_f$) is the surface freezing degree days (seasonal freezing index); P is the annual period (365 days); n_t and n_f are n factors of the thaw-

ing and freezing seasons, I_t and I_f are the air temperature thawing and freezing index; $r_k = \frac{k_t}{k_f}$ represents the semi-empirical adjustment factors (ratio of the thermal conductivity of the ground in thawed and frozen states), which is related to snow cover, vegetation, and soil properties. DDT and DDF can be computed using MODIS land surface temperature products. Parameter r_k is the coefficient reflecting the soil thermal conductivity between the active layer roof and the ground surface. An evident relationship exists between soil thermal conductivity and land cover and soil moisture. In this study, we derived r_k value based on the landcover and soil moisture classed from Landsat images. Table S3 summarizes the relationship between r_k and landcover.⁴

This application was based on 9-year MODIS temperature product data from 2010 to 2018. To reduce the influence of abnormal years on TTOP calculations, we filtered the data temporally. We then divided the dataset into two periods and averaged TTOP inversion within each interval. According to the permafrost classification basis, permafrost distribution map was generated according to modeled TTOP ground temperatures.

Thermokarst lake extraction

Thermokarst lakes are dynamic landscape features formed by the thawing of ice-rich permafrost thaws.³⁸ In the QTP, numerous thermokarst lakes formed recently along the QTR in association with human activities and climate change. The diameters of thermokarst lakes range from meters to hundreds of meters. To accurately monitor newly formed small thermokarst lakes, we utilized submeter-resolution SAR images acquired from 2014 and 2019 and generated thermokarst lakes density maps using ArcMap software.

Damage economic cost estimation

We derived data for permafrost thawing-related damage cost estimation from the economic record of the QTR phase II project (Golmud to Lhasa), which incurred a total construction cost \$4.738 billion. Based on the assumption that the construction cost per kilometer is the same through the full line, we estimated the cost of the QTR section traversing permafrost regions (Xidatan to Anduo) at \$2.322 billion. The design life of the QTR is 40 years. Using the ICICLE model,³⁹ which calculates the net present value of infrastructure at risk due to climate change (driven by temperature and precipitation shifts), we projected climate-related damage costs over the next 50 years under scenarios with and without adaptation measures. The ICICLE model has been applied in Alaska permafrost region.³⁹

The ISO (International Organization for Standardization) published a factor method to estimate the building service life by accounting for materials properties and environment conditions.⁴⁰ This factor method evaluates service life as a function of infrastructure's component and environment, with the following formula:

$$ESL = RSL \times FactorA \times FactorB \times FactorC \times FactorD \times FactorE \times FactorF \times FactorG, \quad (2)$$

where, ESL is estimated service life. RSL is reference service life. *Factors A to G* are quality of component, design level, work execution level, indoor environment, outdoor environment, in-use conditions, and maintenance level, respectively. Except for the outdoor environment factor, other factors value can be referenced to the guideline provided by,⁴¹ shown as Table S4.

For the outdoor environment factor value, we projected the permafrost thawing settlement index (PTSI) and then converted it to factor E . PTSI can be estimated from the active layer thickness (ALT) and the soil ice content.⁴²

$$PTSI = \Delta Z \cdot V_{ice} \quad (3)$$

where ΔZ is the relative change of ALT. V_{ice} is subsurface soil ice content. To estimate the future PTSI, it is assessing that the V_{ice} is not change. We estimated the change of ALT under two climate scenarios (SSP2-4.5 and SSP3-7.0) through the following equation:⁴³

$$Z = \sqrt{2\lambda \times \frac{DDT}{L \times \gamma(W - Wu)}} \quad (4)$$

where λ is soil conduct rate. DDT is accumulate thawing index, which can be calculated from the soil temperature. L is latent heat of ice melting (3.3×10^5

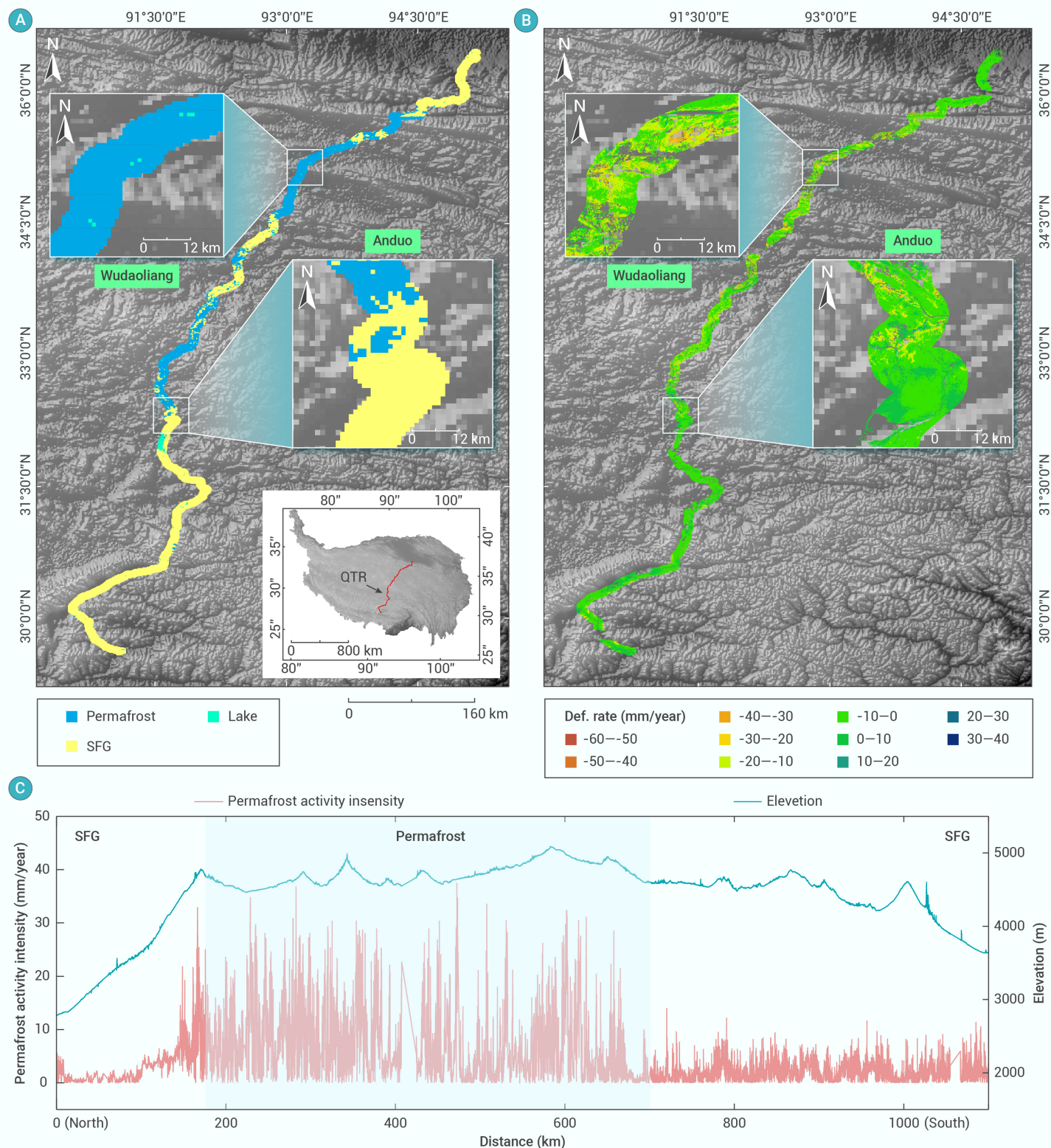


Figure 1. Relationship between the frozen ground deformation and frozen ground types along QTEC (A) ground deformation rate along QTEC. Serious ground deformation have been detected in ice-rich permafrost region, such as Wudaoliang and Anduo permafrost region. (B) permafrost distribution along QTEC. (C) permafrost activity intensity profile along QTEC from Golmud to Lahsa. SFG is for seasonally frozen ground.

J/kg; γ is the dry bulk density of soil (kg/m^3); W is the total water content of the soil during melting (%); W_u is the unfrozen water content in frozen soil (%).

During the projection of ALT, soil moisture will change under future conditions. For example, rainfall will alter soil moisture, and evapotranspiration will also affect it. This involves complex interactions and balances between rainfall and soil moisture. Simulating the impact of future rainfall on soil moisture

is very complex and not the focus of this paper. Therefore, to simplify the projection of ALT, it is assumed that soil moisture and other factors remain unchanged. The temperature is the only variable in the model for monitoring ALT, and the temperature of the model were projected based on climate scenarios (SSP2-4.5 and SSP3-7.0). After PTSI were calculated, we used the nested-means classification method to classify the PTSI into four classes

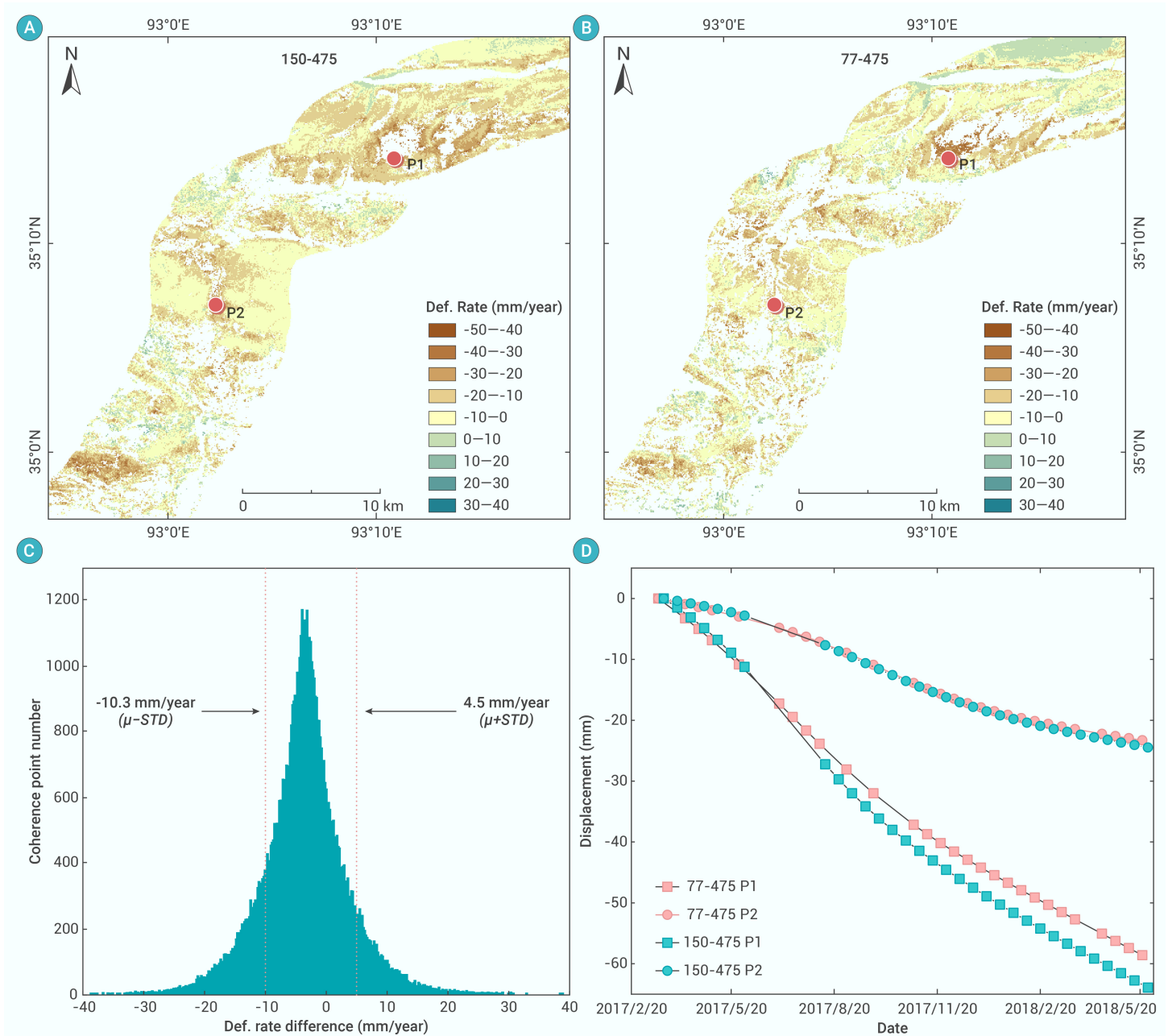


Figure 2. Comparison of the deformation rate within the same overlap from different SAR imaging tracks (A) deformation rate at Beiluhe region from track 150-475; (B) deformation rate at Beiluhe region from track 77-475; (C) histograms of the deformation rate difference between track 150-475 and track 77-475, with the mean value of -2.9 mm/year and STD of 7.4 mm/year; (D) time-series displacement of points p1 and p2 in track 150-475 and track 77-475, respectively.

and calculated the corresponding factor E values based on the corresponding relationship,³⁸ shown as Table S5. Finally, we estimated the factor E for the SSP2-4.5 and SSP3-7.0, with the value of 0.7 and 0.75 for SSP2-4.5 and SSP3-7.0, respectively. The estimated service life of QTR were 24.7 and 26.7 for SSP2-4.5 and SSP3-7.0, respectively. More information can be found in.⁴⁴

After estimating the service life, we calculated economic cost (with and without adaptation) related to climate change based on the ICICLE model.³⁹ To adaptive climate change and extend the service life of railway engineering, new structure and cooling measurement should be built. We also considered the extra cost for the adaptation for climate change. It was difficult to calculate the specific costs for each measure. Inspired by the recommendation by previous study,³⁹ additional 5% adaptation cost was incurred for the SSP2-4.5 climate scenarios and 8.7% for SSP3-7.0 climate scenarios in this study. Once the adaptation measurement has been utilized for permafrost infrastructure, it is assumed that no climate-change related damages were caused during the design lifespan.¹³ Considering inflation rate, 2.47% real discount rate was achieved for the economic cost.

More information about data processing and analyses are in supplementary Test S1 and Figure S1.

RESULTS

Activity intensity of the Qinghai-Tibet Engineering Corridor (QTEC)

We monitored the ground deformation of QTEC from March 2017 to May 2018 using time-series InSAR technology (Figure S1) with over 200 Sentinel-1A images (Table S1), as shown in Figure 1A. Areas with evident deformation were found in the section of the QTR from Xidatan to Anduo, with a maximum deformation rate greater than -40 mm/year. We utilized the TTOP model to map the permafrost distribution by using nearly 10 years MODIS temperature products (Table S2). Based on the calculated TTOP, and permafrost was mapped with the TTOP < 0, as shown in Figure 1B. We compared the generated permafrost distribution with the results of Obu et al.⁴ and Zou et al.,⁴⁵ with the similarity of 87.62% and 83.07%, respectively (Figures S2-S3), demonstrating the accuracy of our results. It can be seen that permafrost zone mainly extends from Xidatan to Anduo, with sporadic

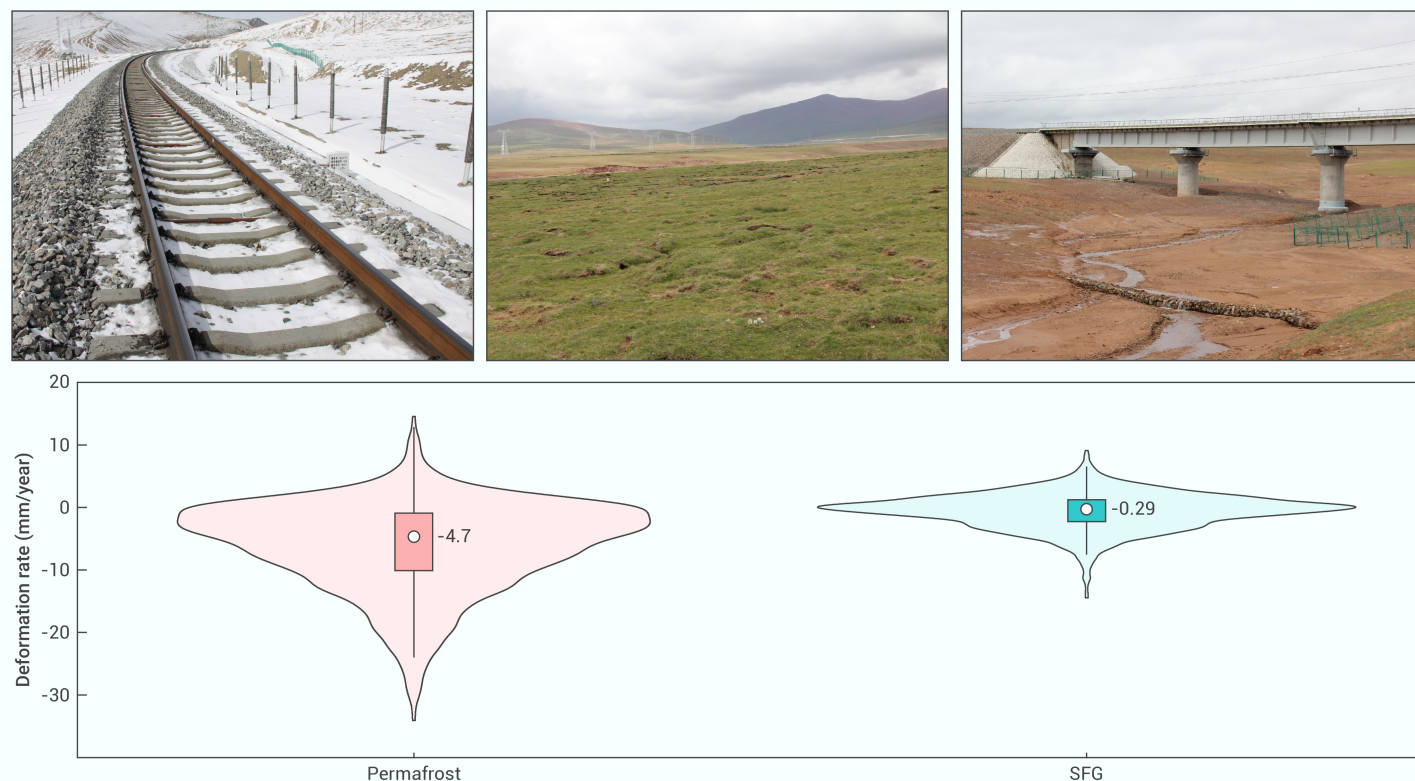


Figure 3. Ground deformation statistics and error analysis of permafrost and seasonally frozen ground (SFG) (A) Deformation rate distribution of permafrost and SFG. Median values are marked. (B), (C) are the field photos in permafrost area. (D) is the field photo in SFG area.

seasonal frozen ground (SFG) distribution in between. We compared the deformation velocity and permafrost mapping results (Figures 1A-B), and found that areas with evident deformation were mainly concentrated in permafrost regions. The maximum subsidence rate reached 40 mm/year for the ice-rich permafrost regions, such as Wudaoliang and Anduo permafrost regions (Figure 1B).

Owing to the influences of topography and radar imaging geometry, permafrost ground surface deformation contains both settlement and heaving. To depict the permafrost activity along QTEC accurately, we regarded the absolute value of estimated deformation rate derived from InSAR as permafrost activity intensity (Figure 1C). For the SFG regions at both ends of the QTEC (Figure 1B), permafrost intensity varied in the range of 0–10 mm/year. For permafrost region in the hinterland of QTP, permafrost intensity was in the range of 0–40 mm/year (Figure 1C). Within the areas with a large deformation rate (over 20 mm/year), 92% were mainly distributed in permafrost region. The similarity result implies that permafrost thaw poses great potential risk to the QTR.¹⁴

To verify the accuracy of estimated deformation results with Sentinel-1A images, we conducted a comparative analysis of the overlapping part deformation of two track results (150–475 and 77–475). We selected the measurement points in overlap areas of the two tracks. The statistical distribution of deformation differences was shown in Figure 2, with a mean value of -2.9 mm/year and STD (Standard Deviation) of 7.4 mm/year. Moreover, we selected the deformation time series of the same point in the two orbits for comparative analysis. It was evident that time-series displacements at the two points from two tracks were highly consistent, which indicated the correctness of our deformation results (Figure 2). In addition, we have compared InSAR results with levelling results collected from other researches.⁴⁶ Three leveling points (A, B, and C, location in Figure S4) with the observation period from 4 January 2018 to 9 February 2018 were used for validation. The error between leveling results and InSAR results at three leveling points were 1.7 mm, 4.9 mm, and 5.4 mm, confirming the validity of our InSAR results.

Permafrost and seasonally frozen ground thawing-related deformation

Generally, permafrost with lower MAGT values exhibits more stable thermal state and less ground deformation.^{47,48} The QTEC section from Xidatan to Anduo is permafrost region, which also show significant activity intensity (Figure 1). In particular, in ice-rich permafrost regions with larger MAGT value, such as Beiluhe and Anduo, the deformation rate ranged from -40 mm/year to 20 mm/year (Figure S5).

In our results, we compared deformation feature of permafrost and SFG. Previous studies reported that slope control the distribution and evolution of excess water, and then is related to permafrost deformation.²³ To minimize the influence of topographic slope on deformation, we excluded displacement points with a slope larger than 20° from the analysis. The mean displacement rates for permafrost and SFG were -4.7 mm/year, -0.29 mm/year, respectively (Figure 3A). Regardless of other factors, areas with thicker permafrost layers exhibit greater subsidence due to thawing of underlying permafrost under climate warming. Conversely, seasonal thawing-freezing dynamic process dominate in SFG regions, where no permafrost layer exists underlying the subsurface.

The deformation deviations of permafrost and SFG are diverse (Figure 3A). These deformation uncertainties likely related to the complex permafrost traversed by the QTR. First, the geological environment of permafrost regions is complex. Soil moisture within the active layer undergoes periodic freezing and thawing in response to temperature fluctuations, which affects the surface environment of permafrost region. Second, the QTR crosses diverse landscapes, including mountainous areas, meadows, snow-covered regions, and river systems (Figures 3B-D). While the theoretical accuracy of ground deformation with time-series InSAR can reach 5 mm,^{49,50} practical accuracy diminishes in the QTR's complex permafrost environment. The deformation overlap of the two tracks was compared (Figure 2), and the two deformation results were consistent with an accuracy of 7.4 mm/year. In certain permafrost regions, deformation dispersion increased significantly, reflecting complexity of permafrost environment. Such deformation dispersion is probably caused by the following factors: (1) The permafrost thawing and freezing process is complex, indicating nonlinear deformations affected by several factors, such as temperature, landcover, snow cover, and soil moisture.^{18,23} (2) Several sections of the QTEC are covered with snow. The signal of the

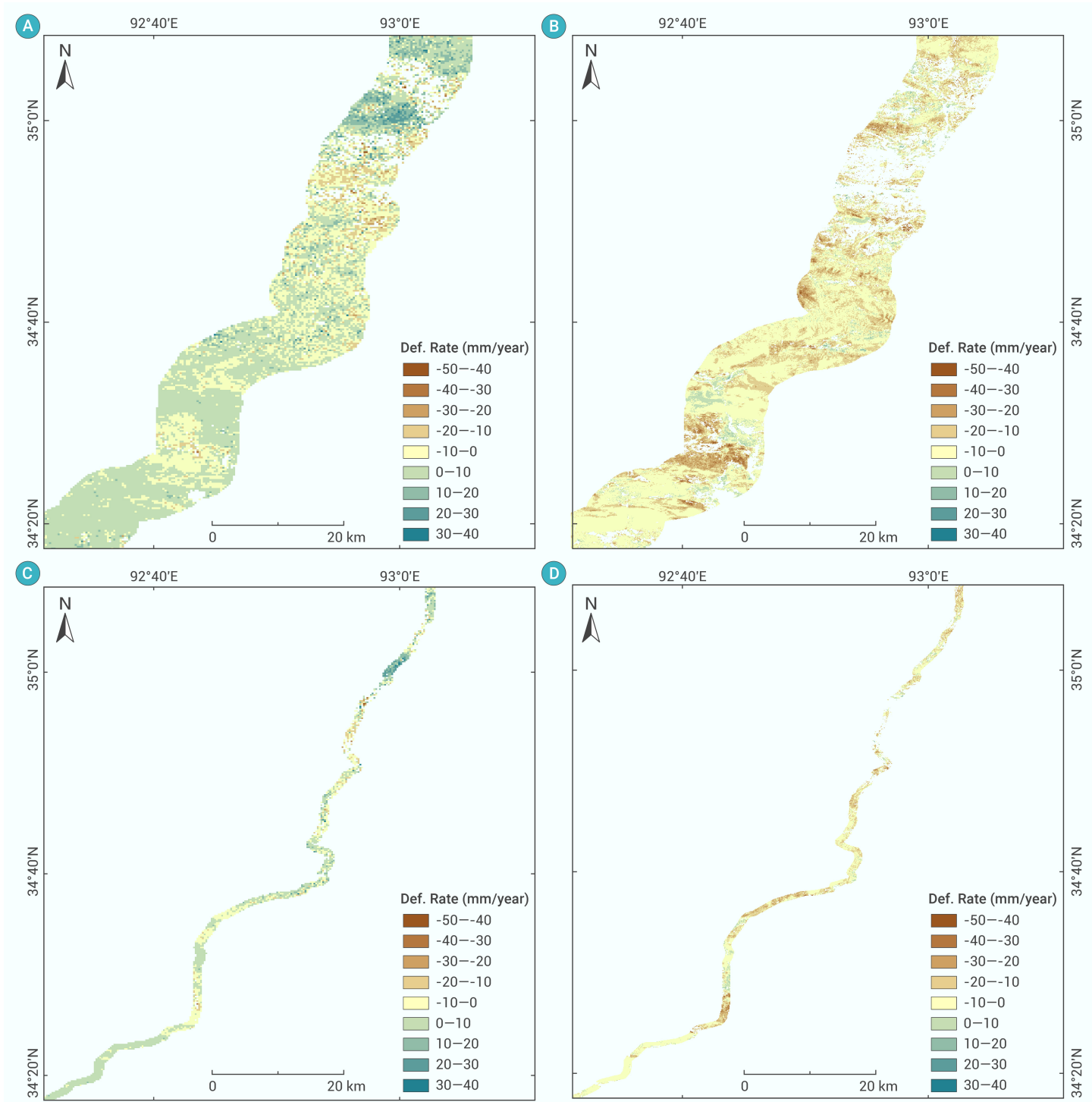


Figure 4. Permafrost thawing-related deformation along QTR before and after its operation (A) 2007–2010 observed by Envisat images, and (B) 2017–2018 observed by Sentinel-1A images. QTEC is for Qinghai-Tibet engineering Corridor. Deformation within 500m buffer zone along QTR in the period of 2007–2010 (C) and 2017–2018 (D).

synthetic aperture radar (SAR) can penetrate the snow, introducing uncertainty in InSAR results.⁵¹ (3) Alpine meadows are widely distributed in the ice-rich permafrost region. The seasonal changes in alpine meadows cause significant temporal decorrelation, reducing InSAR reliability.⁵²

Long-term QTR deformation

To analyze the effects of QTR construction on permafrost stability, we assessed ground stability during the early operational phase of QTR project. The QTR began operation in July 2006. While impacts on permafrost were initially negligible in the first few years, cumulative effects of human activities became apparent after a decade of operation. We monitored surface defor-

mation along the QTEC during the initial operation years of the QTR operation using time-series InSAR with 27 Envisat SAR images from 2007 to 2010, and compared these results with data from 2017 to 2018 (Figures 4A–B). Our results showed that within a 5 km wide corridor in the Beiluhe region, the average deformation rate from 2007 to 2010 ranged between -40 mm/year and 30 mm/year. The spatial distribution of deformation rate aligned with the annual settlement rate from 2017 to 2018, suggesting the corridor-scale deformation is mainly driven by climatic and environmental changes.

We also generated deformation distribution within a 500 m buffer zone along the QTR to analyze the effect of human disturbance (i.e., infrastructure construction) on permafrost (Figures 4C–D). In the observation period of

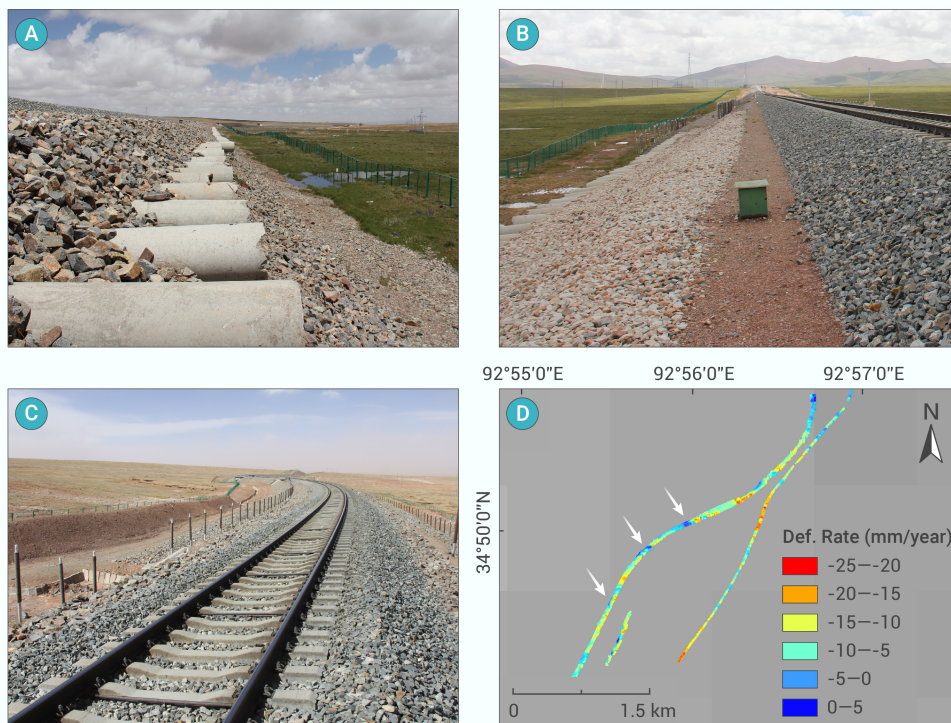


Figure 5. Typical "cooling down" measures along the Qinghai-Tibet Railway (QTR) embankment
Three "cooling down" measures field photos (A) ventiducts, (B) crushed rock cover and rock base, (C) thermal pile. (D) Estimated deformation rate of QTR and Qinghai-Tibet Highway using time-series InSAR with TerraSAR-X images from 20 June 2014 to 9 August 2016. The mild uplift areas due to cooling measures are marked by black arrows.

DISCUSSION

Permafrost and seasonally frozen soil freeze-thaw mechanisms

In over 5% of permafrost regions, subsidence rate exceeded 20 mm/year, indicating large areas permafrost degradation in QTEC. Areas with serious deformation are usually related to permafrost drainage environments.^{56,57,58} Lu et al. found that continuous trend of the permafrost ground deformation around Salt Lake due to increased water erosion and ground ice resulting.⁵⁸ Ground water or ice content in permafrost layer plays a significant role in deformation intensity in permafrost regions.²³ Soil properties and moisture levels in loose sediment layers directly control ground deformations.²³

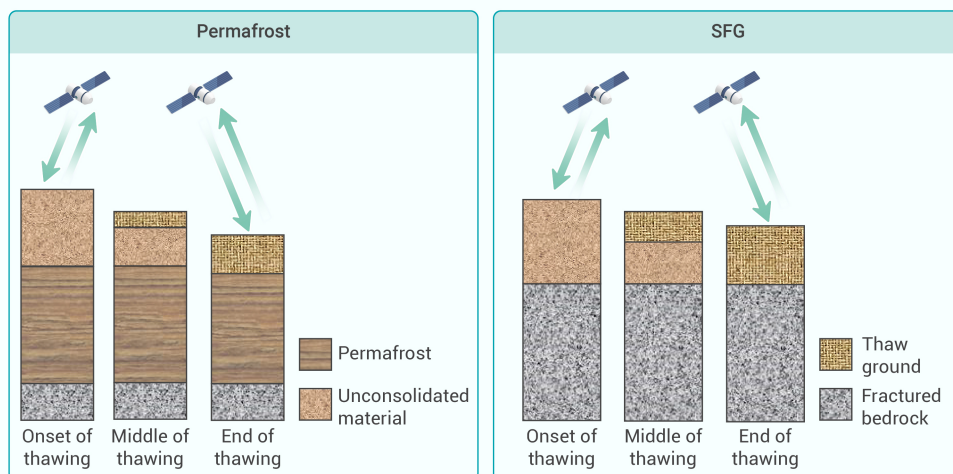


Figure 6. Deformation mechanism analysis of permafrost and seasonally frozen ground (SFG).

SFG generally exhibited stability with small deformation signal. Only some mountain valleys, such as Xidatan and Dangxiong, presented evident deformation (Figure S6). In mountainous SFG regions of the QTP, seasonal rainfall and wind-driven erosion processes deposit loose sediments in valleys. These deposits retain higher soil moisture than other regions, driving pronounced gully deformation. Our analysis revealed a correlation between deformation signals and slope orientation, though spatial lag occurs (Figure S6). This is primarily due to the accumulation of a large

2007–2010 along the 500 m buffer zone, permafrost exhibited relatively stable deformation rate ranged between 0 and -10 mm/year. By contrast, we observed significant subsidence (> 30 mm/year) at multiple locations within the 500 m buffer during 2017–2018 (Figure 4D). This difference could be linked to the balance of permafrost thermal state caused by QTR construction and operation, accelerating permafrost degradation in vulnerable sections.^{17,26,53,54}

For the ice-rich permafrost regions like Beiluhe, engineers have implemented "cooling down" measures beneath embankments, such as crushed rock cover, rock base, shadowed broad, ventilation ducts, and thermal pile (Figure 5). These "cooling down" measures can reduce summer solar heat absorption in roadbed, thereby cooling it and ensuring its stability.⁵⁵ In our study, our high-resolution InSAR-derived deformation results demonstrated that QTR sections with cooling measures exhibited lower deformation rates compared to untreated areas (Figure 5D), confirming the effectiveness of cooling measures. These "cooling down" effects have been validated by previous results using high-resolution TerraSAR-X staring spotlight (ST) mode images (Figure 5), which is consistent with our previous studies.^{22,27} By reducing the external heat absorption and increasing or maintaining internal heat dissipation,²⁵ such measures effectively mitigated permafrost thawing.

amount of alluvial matter in mountain gullies and flow passing through them, causing evident subsidence.⁵⁹ SFG deformation responds to seasonal factors including rainfall, wind, temperature fluctuations, and freeze-thaw cycles.⁶⁰ Generally, surface deformation of SFG is predominantly seasonal with negligible long-term trends. In the process of metamorphosis, significant long-term deformations occur due to changes in the ice content or soil structure, resulting from alterations in SFG sub-layer.

The deformation difference between permafrost and SFG originates from the difference of physical structure. The vertical structure of permafrost generally consists of three layers. From top to bottom, these layers include shallow surface layer (active layer), permafrost layer, and broken bedrock layer (Figure 6). SFG has only two layers in the vertical direction: surface shallow layer (active layer) and fractured bedrock layer (Figure 6).^{61,62} From Figure 6, it can be seen that deeper permafrost layer contain a significant amount of ground ice. When temperature rises, ground ice in the deeper permafrost layer thaws, and the surface subsides. Therefore, the surface subsidence rate in the permafrost region is relatively high. In SFG region, the ice content is low and the extent of thawing is shallow. As a result, ground deformation of the SFG is rela-

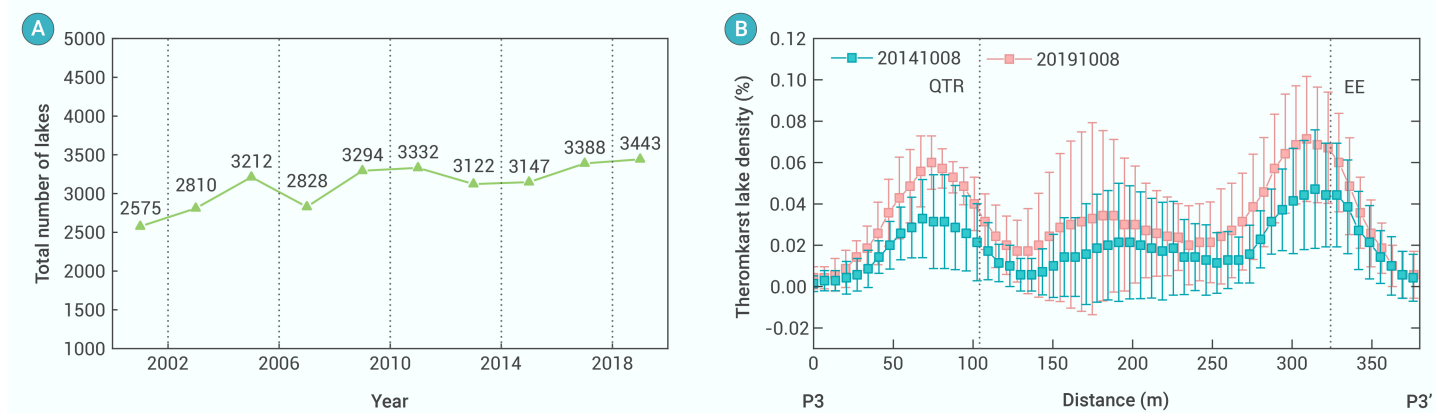


Figure 7. Thermokarst lakes along QTR (A) Temporal variation of the thermokarst lake areas account in the observation period of 2001–2019 within the 5 km corridor along QTR from 2001 to 2019. The increasing trend of the thermokarst lake is not evident. (B) The thermokarst lake density along profile P3–P3' (Figure S7) in Beiluhe permafrost region on 2014 and 2019 with TerraSAR-X ST mode images. Obvious increasing trend of the thermokarst lake is observed, in particular along subzones immediately in the vicinity of infrastructures (i.e., QTR and experimental embankment) within a distance of 100–150 m.

tively subtle.

Effects of climate change and human activity on permafrost

Permafrost degradation often triggers the formation of thermokarst lakes on both sides (i.e. in the vicinity of 500 m) of infrastructure. To distinguish the impacts of climate change and human activities, we monitored thermokarst lakes changes within 5 km and 500 m buffer zones along QTR. Using Google Earth Engine, we mapped thermokarst lakes within the 5 km corridor along QTR from 2001 to 2019 (Figure 7A). The thermokarst lake areas within this corridor shown no significant expansion within the past 20 years. However, within the local buffer zone (500 m wide), numerous thermokarst lakes developed between the two sides of QTR, especially in the ice-rich permafrost region, implying permafrost degradation.⁶³ We extracted thermokarst lakes along the QTR in Beiluhe permafrost region using two TerraSAR-X ST mode images acquired in 2014 and 2019 (Figure S7). We identified a total of 316 and 448 thermokarst lakes were detected for 2014 and 2019, respectively, and then generated density map. The results indicated that the number and density of thermokarst lakes around the original drainage systems increased minimally, while thermokarst lakes on both sides of the frozen soil project increased significantly. Lake density profiles across the QTR and experimental embankment (Figure 7B) showed a 20%–40% rise between 2014 and 2019, especially near the infrastructure (the QTR and the experimental embankment). This trends reflected the effects of human activities on permafrost thawing. It can be inferred that human activities contribution on permafrost degradation exceeds 20% in Beiluhe region based on the disproportionate growth of thermokarst.

Permafrost infrastructure economic loss under climate change

Permafrost-thawing induced ground subsidence undermines the structural integrity of infrastructures and increases maintenance or redundant construction cost.¹⁰ Studies have shown that thermokarst subsidence is one of the most significant hazards along the QTR.¹⁷ Proactive adaptation measurements, such as air convection embankment and heat drains, effectively mitigate climate change impacts on permafrost infrastructure.⁵⁵ However, these active foundation protection and cooling measures would incur additional construction costs. To better serve the QTR, we estimated the economic losses of the QTR due to climate change under scenarios with and without proactive adaptation measurements. Using the BCC-CSM2-MR model from Phase 6 of the Coupled Model Intercomparing Project (CMIP6), we projected economic costs related to permafrost settlement in QTEC from 2020–2069. Considering two versatile climate scenarios of SSP2-4.5 and SSP3-7.0, we calculated the climate change-induced costs to maintain the infrastructure using the ICICLE model from 2020 to 2069.³⁹

We generated permafrost thawing settlement index (PTSI) maps for both climate scenarios of SSP2-4.5 and SSP3-7.0, as shown in Figure S8. It is assumed that when the life span reaches critical thresholds, it becomes more feasible to rebuild the QTR than repair. The threshold is set 80% of designing

life span according to previous studies.⁶³ Results showed that accumulate economic damages to QTR (without adaptation) from climate change in the following fifty years were about \$3.63 billion for SSP2-4.5 and \$3.73 billion for SSP3-7.0. With the applied adaptation, accumulate damages to QTR decreased to about \$3.19 billion for SSP2-4.5 and \$3.29 billion for SSP3-7.0, revealing a \$0.44 billion cost reduction per scenario. Moreover, implementing proactive “cooling down” measures (Figure 5) enhanced QTR embankment stability, significantly mitigating permafrost disasters risk under climate change.

The uncertainty of the method

Permafrost degradation due to climate warming can lead to thaw-related hazards, such as ground subsidence, thermokarst in low-lying areas, mass wasting on slopes, posing great risks to infrastructure and buildings in permafrost regions worldwide.^{54,64} In ice-rich permafrost regions, permafrost thawing-induced subsidence is particularly pronounced. Except for the nature influences, anthropogenic activities would exacerbate infrastructure damage.^{14,17,25} Adaptive measurement for infrastructure embankment effectively stabilize permafrost, decrease ground deformation related to permafrost thawing, and enhance infrastructure structural resilience (Figure 5).

Previous studies mainly focused on permafrost thawing and their impacts on infrastructure in high-latitude permafrost regions.^{13, 14, 39, 65} However, the QTP hosts the high-altitude permafrost, where temperature increasing rates were higher than other permafrost regions.¹² Seasonal climate change causes dramatic land cover changes in permafrost regions, resulting in serious InSAR decorrelations and biased deformation estimations.^{22,23,66} To minimize the impact from the decorrelation, we used multi-temporal InSAR (See Materials and Method section) for deformation estimation. Some areas with severe decorrelation even have less measurement points in our result (Figure 1). For complex scenario, i.e. the permafrost covered with vegetation and snow in the high latitude (Siberia, Arctic), long wavelength (L-band) radar images are recommended.⁶⁷ In addition, we conducted long-term InSAR observations and comparative analyses only in the regions from Tuotuohe to Anduo. The extended monitoring duration along the QTEC implies the need for more SAR images processing and innovative algorithms, which is our future research objective.

To project permafrost distribution with the global warming, we utilized the BCC-CSM2-MR climate model of the CMIP6 to simulate temperature under two climate scenarios. CMIP6 integrates many climate models to assess potential effects under future climate change.^{57,68} BCC-CSM2-MR climate model shows great performance at both the global scale and the regional scale in East Asia.⁶⁹ As time passes, new climate projection model with high temporal and spatial resolution will be available for small scale region, which would help to refine localized service life predictions for infrastructure.

For economic cost estimation related to climate change, additional 5% adaptation cost was incurred for the SSP2-4.5 climate scenarios and 8.7% for

SSP3-7.0 climate scenarios without considering the effects and cost of different adaptation measurements. To improve cost estimation in the future, more information about QTR were needed, such as which kind of "cooling measurement" is suitable for permafrost degradation region. It should be noticed that with future climate warming, the transition of permafrost to SFG may potentially reduce the costs of constructing infrastructures on SFG regions, partially offsetting future expenditures. This unaccounted factor in our study may introduce uncertainty into economic assessment.

Therefore, the multi-source remote sensing approach presented in this paper can be applied to other permafrost regions worldwide, providing scientific guidance for sustainable development in permafrost regions.

CONCLUSION

This study analyzed the impacts of global climate change and human activities on permafrost along the QTR from the corridor–local buffer scales combining the TTOP model and time-series InSAR method with nearly 10 years of remote sensing images. Our findings revealed that global climate change had resulted in significant effects on permafrost region. Regions with high permafrost activity were mainly concentrated in permafrost regions along the QTR corridor (5 km), and over 5% of the permafrost region underwent serious ground subsidence (> 20 mm/year) related to thawing. Human disturbance would further exacerbate permafrost thawing immediately in proximity to the QTR. Compared to initial years of the QTR operation, more subregions with serious subsidence were detected in the Beiluhe region after 10 years of operation within the buffer zone of 500 m. We projected economic cost with and without provocative adaptation measurements to maintain the QTR under two climate scenarios from 2020 to 2069. Our results showed that climate-induced damages without adaptation will come to \$3.63 billion for SSP2-4.5 and \$3.73 billion for SSP3-7.0. This study provides new insights on the interaction between permafrost and climate change coupled with human disturbance. These findings may serve as representative guidance for other permafrost engineering projects and contribute to the implementation of SDG 13 of climate action.

REFERENCES

- Griggs D. J., Nilsson M., Stevance A., et al. (2017). A guide to SDG interactions: from science to implementation. *International Council for Science, Paris*
- Bodansky D. (2016). The legal character of the Paris Agreement. *Review of European, Comparative & International Environmental Law*. **25**:142–150. DOI:10.1111/reel.12154
- Fuso Nerini, F., Sovacool B., Hughes, N., et al. (2019). Connecting climate action with other Sustainable Development Goals. *Nat. Sustain.* **2**:674–680. DOI:10.1038/s41893-019-0334-y
- Obu J., Westermann S., Bartsch A., et al. (2019). Northern Hemisphere permafrost map based on TTOP modelling for 2000–2016 at 1 km² scale. *Earth-Sci. Rev.* **193**:299–316. DOI:10.1016/j.earscirev.2019.04.023
- Biskaborn B. K., Smith S. L., Noetzel J., et al. (2019). Permafrost is warming at a global scale. *Nat. Commun.* **10**:1–11. DOI:10.1038/s41467-018-08240-4
- Gruber S. (2012). Derivation and analysis of a high-resolution estimate of global permafrost zonation. *Cryosphere* **6**:221–233. DOI:10.5194/tc-6-221-2012
- Schuur E. A., McGuire A. D., Schädel C., et al. (2015). Climate change and the permafrost carbon feedback. *Nature* **520**: 171–179. DOI:https://doi.org/10.1038/nature14338
- Yang R., Zhu L., Wang J., et al. (2017). Spatiotemporal variations in volume of closed lakes on the Tibetan Plateau and their climatic responses from 1976 to 2013. *Climatic Change* **140**:621–633. DOI:10.1007/s10584-016-1877-9
- Wu Y., Zhong Y., Liu S. et al. (2025). Hydrogeodesy Facilitates the Accurate Assessment of Extreme Drought Events. *J. Earth Sci.* **36**:347–350. DOI:10.1007/s12583-024-0123-z
- Wu Q., Zhang T. and Liu Y. (2011). Thermal state of the active layer and permafrost along the Qinghai-Xizang (Tibet) railway from 2006 to 2010. *Cryosphere* **6**:607–612. DOI:10.5194/tc-6-607-2012
- Shukla P. R., Skeg J., Buendia E. C., et al. (2019). Climate Change and Land: An IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems
- Pepin N., Bradley R. S., Diaz H. F., et al. (2015). Elevation-dependent warming in mountain regions of the world. *Nat. Clim. Change* **5**:424–430. DOI:10.1038/NCLIMATE2563
- Melvin A. M., Larsen P., Boehlert B., et al. (2017). Climate change damages to Alaska public infrastructure and the economics of proactive adaptation. *Proc. Natl. Acad. Sci. USA* **114**:E122–E131. DOI:10.1073/pnas.1611056113
- Hjort J., Karjalainen O., Aalto J., et al. (2018). Degrading permafrost puts Arctic

infrastructure at risk by mid-century. *Nat. Commun.*, **9**. DOI:10.1038/s41467-018-07557-4

- Fondahl G., and Sirina A. (2006). Rights and risks: Evenki concerns regarding the proposed Eastern Siberia-Pacific Ocean pipeline. *Sibirica* **5**:115–138. DOI: https://api.semanticscholar.org/CorpusID:143626002
- Li H., Lai Y., Wang L., et al. (2019). Review of the state of the art: interactions between a buried pipeline and frozen soil. *Cold Reg. Sci. Technol.* **157**:171–186. DOI:10.1016/j.coldregions.2018.10.014
- Niu F., Lin Z., Lu J., et al. (2011). Characteristics of roadbed settlement in embankment–bridge transition section along the Qinghai-Tibet Railway in permafrost regions. *Cold Reg. Sci. Technol.* **65**:437–445. DOI:10.1016/j.coldregions.2010.10.014
- Jin H., Zhao L., Wang S., et al. (2006). Thermal regimes and degradation modes of permafrost along the Qinghai-Tibet Highway. *Sci. China Ser. D*. **49**:1170–1183. DOI:10.1007/s11430-006-2003-z
- Duan W., Maskey S., Chaffe P. L., et al. (2021). Recent advancement in remote sensing technology for hydrology analysis and water resources management. *Remote Sens.* **13**:1097. DOI:10.3390/rs13061097
- Li D., Tong Q., Li R., et al. (2012). Current issues in high-resolution earth observation technology. *Science China earth sciences* **55**:1043–1051. DOI:10.1007/s11430-012-4445-9
- Kuenzer C., Ottinger M., Wegmann M., et al. (2014). Earth observation satellite sensors for biodiversity monitoring: potentials and bottlenecks. *Int. J. Remote Sens.* **35**:6599–6647. DOI:10.1080/01431161.2014.964349
- Chen F., Lin H., Zhou W., et al. (2013). Surface deformation detected by ALOS PALSAR small baseline SAR interferometry over permafrost environment of Beiluhe section, Tibet Plateau, China. *Remote Sens. Environ.* **138**:10–18. DOI:10.1016/j.rse.2013.07.006
- Daout S., Dini B., Haerberli W., et al. (2020). Ice loss in the Northeastern Tibetan Plateau permafrost as seen by 16 yr of ESA SAR missions. *Earth Planet. Sci. Lett.* **545**:116404. DOI:10.1016/j.epsl.2020.116404
- Jorgenson M. T., and Grosse G. (2016). Remote sensing of landscape change in permafrost regions. *Permafr. Periglac. Process.* **27**:324–338. DOI:10.1002/ppp.1914
- Chen F., Lin H., Li Z., et al. (2012). Interaction between permafrost and infrastructure along the Qinghai–Tibet Railway detected via jointly analysis of C-and L-band small baseline SAR interferometry. *Remote Sens. Environ.* **123**:532–540. DOI:10.1016/j.rse.2012.04.020
- Zhao L., Zou D., Hu G., et al. (2021). A synthesis dataset of permafrost thermal state for the Qinghai–Tibet (Xizang) Plateau, China. *Earth System Science Data*, **13**:4207–4218. DOI:10.5194/essd-13-4207-2021
- Zhang Z., Wang M., Liu X., et al. (2019). Deformation feature analysis of Qinghai–Tibet railway using TerraSAR-X and Sentinel-1A time-series interferometry. *IEEE J. Sel. Topics Appl. Earth Observ. Remote Sens.* **12**:5199–5212. DOI:10.1109/JSTARS.2019.2954104
- Chang L. and Hanssen R. F. (2015). Detection of permafrost sensitivity of the Qinghai–Tibet railway using satellite radar interferometry. *Int. J. Remote Sens.* **36**:691–700. DOI:10.1080/01431161.2014.999886
- Luo L., Ma W., Zhao W., et al. (2018). UAV-based spatiotemporal thermal patterns of permafrost slopes along the Qinghai–Tibet Engineering Corridor. *Landslides* **15**:2161–2172. DOI:10.1007/s10346-018-1028-7
- Ran Y., Cheng G., Dong Y., et al. (2022). Permafrost degradation increases risk and large future costs of infrastructure on the Third Pole. *Communications Earth & Environment* **3**:238. DOI:10.1038/s43247-022-00568-6
- Streletskiy D. A., Clemens S., Lanckman J. P., et al. (2023). The costs of Arctic infrastructure damages due to permafrost degradation. *Environ. Res. Lett.* **18**:015006. DOI:10.1088/1748-9326/acab18
- Zhang Z., Lin H., Wang M., et al. (2022). A review of satellite synthetic aperture radar interferometry applications in permafrost regions: Current status, challenges, and trends. *IEEE Geoscience and Remote Sensing Magazine* **10**:93–114. DOI:10.1109/MGRS.2022.3170350
- Liu, D. and Xu, H. (2021). A rational policy decision or political deal. *A multiple streams' examination of the Russia-China natural gas pipeline. Energy Policy* **148**:111973. DOI:10.1016/j.enpol.2020.111973
- Bennett M. M. (2016). The silk road goes north: Russia's role within China's Belt and Road Initiative. *Area Development and Policy* **1**:341–351. DOI: 10.1080/23792949.2016.1239508 DOI:10.1080/23792949.2016.1239508
- Goldstein R. M. and Werner C. L. (1998). Radar interferogram filtering for geophysical applications. *Geophys. Res. Lett.* **25**:4035–4038. DOI:10.1029/1998GL900033
- Costantini M., Malvarosa F., and Minati F. (2012). A general formulation for redundant integration of finite differences and phase unwrapping on a sparse multidimensional domain. *IEEE Trans. Geosci. Remote Sens.* **50**:758–768. DOI:10.1109/TGRS.2011.2162630
- Smith, M.W. and Riseborough, D. W. (1996). Permafrost monitoring and detection of climate change. *Permafr. Periglac. Process.* **7**:301–309. DOI:10.1002/(SICI)1099-1530(199610)7:4<301::AID-PPP231>3.0.CO;2-R
- Kokelj S. V., Lacelle D., Lantz T. C., et al. (2013). Thawing of massive ground ice in mega slumps drives increases in stream sediment and solute flux across a range of watershed scales. *J. Geophys. Res. Earth* **118**:681–692. DOI:10.1002/jgrf.20063

39. Larsen P. H., Goldsmith S., Smith O., et al. (2008). Estimating future costs for Alaska public infrastructure at risk from climate change. *Global Environ. Change* **18**:442–457. DOI:10.1016/j.gloenvcha.2008.03.005
40. ISO 15686-1, Buildings and constructed assets- Service life planning- Part 1: General principles and framework, International Standard Organisation, Geneva (2011)
41. Hoeve T. E., Zhou F., and Zhang A. (2006). Potential cost impacts for adaptation of building foundations in the Northwest Territories. In *2006 IEEE EIC Climate Change Conference* (pp. 1–9). DOI: 10.1109/EICCCC.2006.277258
42. Nelson F. E., Anisimov O. A., and Shiklomanov N. I. (2001). Subsidence risk from thawing permafrost. *Nature* **410**:889–890. DOI:10.1038/35073746
43. Xu, X. and Wu, Q. (2021). Active layer thickness variation on the Qinghai - Tibetan Plateau: Historical and projected trends. *Journal of Geophysical Research: Atmospheres* **126**:e2021JD034841. DOI:10.1029/2021JD034841
44. Hong E. (2012). Permafrost settlement caused by climate warming in Alaska and the estimation of its damage costs for public infrastructure. *University of Alaska Fairbanks*. DOI: <http://hdl.handle.net/11122/9144>
45. Zou D., Zhao L., Sheng Y., et al. (2017). A new map of permafrost distribution on the Tibetan Plateau. *The Cryosphere* **11**:2527–2542. DOI:10.5194/tc-11-2527-2017
46. Hong Z., and Jin S. (2021). Permafrost deformation in Qinghai-Tibet Plateau time-series PS-InSAR. *Bull. Surv. Mapp.* **1**: 35–40. (In Chinese) DOI: 10.13474/j.cnki.11-2246.2021.0007
47. Wagner A. M., Lindsey N. J., Dou S., et al. (2018). Permafrost degradation and subsidence observations during a controlled warming experiment. *Sci. Rep.* **8**:10908. DOI:10.1038/s41598-018-29292-y
48. Wu Q., Zhang T., and Liu Y. (2010). Permafrost temperatures and thickness on the Qinghai-Tibet Plateau. *Global Planet. Change* **72**:32–38. DOI:10.1016/j.gloplacha.2010.03.001
49. Ferretti A., Prati C., and Rocca F. (2000). Nonlinear subsidence rate estimation using permanent scatterers in differential SAR interferometry. *IEEE Trans. Geosci. Remote Sens.* **38**:2202–2212. DOI:10.1109/36.868878
50. Mora O., Mallorqui J. J., and Broquetas A. (2003). Linear and nonlinear terrain deformation maps from a reduced set of interferometric SAR images. *IEEE Trans. Geosci. Remote Sens.* **41**:2243–2253. DOI:10.1109/TGRS.2003.814657
51. Rignot E., Echelmeyer K., and Krabill W. (2001). Penetration depth of interferometric synthetic aperture radar signals in snow and ice. *Geophys. Res. Lett.* **28**:3501–3504. DOI:10.1029/2000GL012484
52. Ahmed R., Siqueira P., Hensley S., et al. (2011). A survey of temporal decorrelation from spaceborne L-Band repeat-pass InSAR. *Remote Sens. Environ.* **115**:2887–2896. DOI:10.1016/j.rse.2010.03.017
53. Ma W., Mu Y., Wu, Q., et al. (2011). Characteristics and mechanisms of embankment deformation along the Qinghai–Tibet Railway in permafrost regions. *Cold Reg. Sci. Technol.* **67**:178–186. DOI:10.1016/j.coldregions.2011.02.010
54. Sun Z., Ma W., Zhang S., et al. (2018). Embankment stability of the Qinghai–Tibet railway in permafrost regions. *J. Cold Reg. Engin.* **32**:04018001. DOI:10.1061/(ASCE)CR.1943-5495.0000153
55. Hjort J., Streletskiy D., Doré G., et al. (2022). Impacts of permafrost degradation on infrastructure. *Nature Rev. Earth Environ.* **3**:24–38. DOI:10.1038/s43017-021-00247-8
56. Lin Z., Gao Z., Fan X., et al. (2020). Factors controlling near surface ground-ice characteristics in a region of warm permafrost, Beiluhe Basin, Qinghai-Tibet Plateau. *Geoderma* **376**:114540. DOI:10.1016/j.geoderma.2020.114540
57. Chen L., Fortier D., McKenzie J. M., et al. (2020). Impact of heat advection on the thermal regime of roads built on permafrost. *Hydrol. Process.* **34**:1647–1664. DOI:10.1002/hyp.13688
58. Lu P., Han J., Li Z., et al. (2020). Lake outburst accelerated permafrost degradation on qinghai-tibet plateau. *Remote Sens. Environ.* **249**:112011. DOI:10.1016/j.rse.2020.112011
59. Chen J., Liu L., Zhang T., et al. (2018). Using persistent scatterer interferometry to map and quantify permafrost thaw subsidence: A case study of Eboling Mountain on the Qinghai - Tibet Plateau. *J. Geophys. Res. Earth* **123**:2663–2676. DOI:10.1029/2018JF004618
60. Zhang Z., Jin Q., Liu L., et al. (2025). Improved ALT retrieval in the Yellow River source region using time-series InSAR and multilayer soil moisture modeling. *J. Hydrol.* **654**:132847. DOI:10.1016/j.jhydrol.2025.132847
61. Evans S. G., and Ge S. (2017). Contrasting hydrogeologic responses to warming in permafrost and seasonally frozen ground hillslopes. *Geophys. Res. Lett.* **44**:1803–1813. DOI:10.1002/2016GL072009
62. Ireson A. M., Van Der Kamp G., Ferguson G., et al. (2013). Hydrogeological processes in seasonally frozen northern latitudes: Understanding, gaps and challenges. *Hydrogeol. J.* **21**:53–66. DOI:10.1007/s10040-012-0916-5
63. Niu, F., Lin, Z., Lu, J., et al. (2015). Assessment of terrain susceptibility to thermokarst lake development along the Qinghai–Tibet engineering corridor, China. *Environmental earth sciences* **73**:5631–5642. DOI:10.1007/s12665-014-3818-0
64. Smith S. L., O'Neill H. B., Isaksen K., et al. (2022). The changing thermal state of permafrost. *Nat. Rev. Earth Env.* **3**:10–23. DOI:10.1038/s43017-021-00240-1
65. Schneider von Deimling T., Lee H., Ingeman-Nielsen T., et al. (2021). Consequences of permafrost degradation for Arctic infrastructure—bridging the model gap between regional and engineering scales. *Cryosphere* **15**:2451–2471. DOI:10.5194/tc-15-2451-2021
66. Rouyet L., Lauknes T. R., Christiansen H. H., et al. (2019). Seasonal dynamics of a permafrost landscape, Adventdalen, Svalbard, investigated by InSAR. *Remote Sens. Environ.* **231**:111236. DOI:10.1016/j.rse.2019.111236
67. Burke E. J., Zhang Y., and Krinner G. (2020). Evaluating permafrost physics in the Coupled Model Intercomparison Project 6 (CMIP6) models and their sensitivity to climate change. *Cryosphere* **14**:3155–3174. DOI:10.5194/tc-14-3155-2020
68. Eyring V., Bony S., Meehl G. A., et al. (2016). Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization. *Geosci. Model Dev.* **9**:1937–1958. DOI:10.5194/gmd-9-1937-2016
69. Wu T., Lu Y., Fang Y., et al. (2019). The Beijing Climate Center climate system model (BCC-CSM): the main progress from CMIP5 to CMIP6. *Geosci. Model Dev.* **12**:1573–1600. DOI:10.5194/gmd-12-1573-2019

FUNDING AND ACKNOWLEDGMENTS

The authors would like to thank European Space Agency (ESA) for providing free and open Sentinel-1A data and historical archive ENVISAT data and also thank DLR for providing TerraSAR-X data. We thank Prof. Michael F. Goodchild for his review and insightful comments in the finalization of this manuscript. This work was supported in part by the funded the National Natural Science Foundation of China under Grant (41801348, 41930110), the Jiangxi Provincial Technology Innovation Guidance Program (National Science and Technology Award Reserve Project Cultivation Program under Grant 20212AEI91006) and the Strategic Priority Research Program of the Chinese Academy of Sciences (No. XDA19030502). The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

AUTHOR CONTRIBUTIONS

Z. Z., F. C., H. L., and C. W. designed research; Z. Z., F. C., X. L., and M. W. performed research; Z. Z., F. C., H. L. and J. L. analyzed data; Z. Z., F. C. wrote the paper. All authors reviewed the manuscript.

DECLARATION OF INTERESTS

The authors declare no competing interests.

DATA AND CODE AVAILABILITY

All data and codes used in this study are available in the public domain as follows. (1) The raw Envisat SAR data are publicly available at <https://earth.esa.int/eogateway/catalog>. (2) The raw Sentinel-1 SAR data are available at the Copernicus Open Access Hub (<https://scihub.copernicus.eu>) and Alaska Satellite Facility (<https://search.asf.alaska.edu/>). (3) The raw TerraSAR-X data are through scientific proposal HYD2420. , human activities(4) The MODIS products are available from the Atmosphere Archive and Distribution System Distributed Active Archive Center of National Aeronautics and Space Administration (LAADS-DAAC, NASA), <https://modis.gsfc.nasa.gov/>.