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Thermal impacts of engineering activities on permafrost in different alpine ecosystems in Qinghai-Tibet Plateau, China

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Abstract: Climate warming and engineering activities have various impacts on the thermal regime of permafrost in alpine ecosystems of the Qinghai–Tibet Plateau. Using recent observations of permafrost thermal regimes along the Qinghai–Tibet Highway and Railway, the change of such regimes beneath embankments constructed in alpine meadows and steppes are studied. The results show that alpine meadows on the Qinghai–Tibet Plateau can have a controlling role within engineering construction effects on permafrost beneath embankments. The artificial permafrost table (APT) beneath embankments is predominantly controlled by alpine ecosystems, but the change rate of APT is not closely related with those ecosystems; it is mainly related with cooling effects of railway ballast and heat absorption effects of asphalt pavement. Variation of soil temperature beneath embankments is independent of alpine ecosystems, but variation of mean annual soil temperature with depth is closely related to those ecosystems. The vegetation layer in alpine meadows can have an insulation role within engineering activity effects on permafrost beneath embankments. This insulation role is an advantage for alleviating permafrost temperature rise in the short term, but a disadvantage in the long term because of climate warming, suggesting that vegetation layer in alpine meadow should be removed upon initiating engineering construction.

Keywords: Alpine ecosystem, Qinghai–Tibet Highway and Railway, Permafrost, Engineering activities

1. Introduction

Climate warming and engineering activities significantly impact permafrost thermal regimes on the Qinghai–Tibet Plateau

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(Cheng and Wu, 2007; Jin et al., 2008; Wu and Zhang, 2008; Zhang et al., 2008; Yang et al., 2010). However, the response of permafrost to climate warming differs greatly from that of engineering construction (Wu et al., 2007). This difference is mainly caused by permafrost thermal stability (Wu et al., 2007).

Because permafrost is the product of exchange between the ground surface and atmosphere, its response to climate warming and engineering activities is modulated by ground surface conditions, for example, vegetation, soil, and geological conditions (Brown et al., 2000; Hinkel and Nelson, 2003; Frauenfeld et al., 2004). Permafrost has a close relationship with alpine ecosystems, and changes of permafrost can significantly affect those alpine ecosystems (Callaghan and Jonasson, 1995; Jorgenson et al., 2001; Hinzman et al., 2005; Wang et al., 2006; Shur and Jonasson, 2007; Gregory et al., 2012; Wang et al., 2012). Climate warming has varying thermal impacts on permafrost in different alpine ecosystems (Wu et al., 2015). Change in permafrost temperature and active layer thickness (ALT) of alpine meadows is greater than that of alpine steppe (Wu et al., 2015). Therefore, whether engineering activities have thermal impacts on permafrost that vary with ecosystem is a concerning issue. Further, removing vegetation or retaining vegetation in highway or railway construction may cause differences in permafrost change and engineering stability. However, there has been little research in this area.

Engineering activities on the Qinghai–Tibet Plateau, for example, the Qinghai–Tibet Highway (QTH) and Railway (QTR), resulted in the significant rising of permafrost temperatures, increasing of permafrost table and thawing of ground ice near the permafrost table beneath embankments (Wu et al., 2002; Sheng et al., 2002; Ma et al., 2009; Wu et al., 2010b; Mu et al., 2012). However, these research works focus only on impacts of thermal disturbance of highway or railway on permafrost beneath embankments. There has been little attention to interaction among engineering activities, vegetation or soils near the ground surface and permafrost beneath embankments. McHattie and Esch (1983) studied the benefits to permafrost of a peat underlay in roadway construction.

The main objective of this study was to investigate the thermal impacts of engineering activities on permafrost beneath embankments in various ecosystems, using data and information from a continuous record of permafrost temperature monitoring along the QTH and QTR corridor. We first focus on studies of annual means and variability of the artificial permafrost table (APT) beneath embankments in alpine meadows and steppes over the period from 1996/2005 through 2014. We then investigate trends of soil temperature and different impacts of ecosystems in driving changes in soil temperature.

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Finally, we assess advantages or disadvantages of removing vegetation during engineering construction.

2. Data and method

The soil temperature data used were obtained from nine monitoring sites along the QTH and QTR (Figure 1). Because vegetation was removed when the QTH was constructed but was present when the QTR was constructed, these data were obtained from five centerline boreholes beneath the highway embankment (three in alpine steppe and two in alpine meadow) and four beneath the railway embankment (two centerline boreholes in alpine meadow and two shoulder boreholes in alpine steppe). For comparison, soil temperature from a borehole beneath a natural surface was obtained from the same location as the centerline borehole beneath the embankment.

2.1 Site description

Soil temperature was measured at nine sites from the Chumaer high plain in the north to the Tanggula Mountains in the south along the QTH and QTR (Figure 1). Five boreholes were made in the Chumaer high plain (two boreholes along the railway and three along the highway), two in the Beiluhe basin (railway), and another two in the Fenghuo and Tanggula Mountains (highway). Geographic information and ecosystems of these sites are listed Tables 1 and 2.

Table 1 Information on nine monitoring sites along the QTH and QTR

Site*	Areas	Latitude (°)	Longitude (°)	Altitude(m)	Observation Period
CMH1	Chumaer High Plain	35.52	93.76	4577	2002–2014
CMH2		35.52	93.76	4572	2002–2014
CMH3		35.52	93.76	4568	2002–2014
CMR1		35.41	93.57	4477	2005–2014
CMR2		35.28	93.22	45.83	2005–2014
BLR1	Beiluhe Basin	34.86	92.92	4633	2002–2014
BLR2		34.85	92.94	4632	2002–2014
FHH1	Fenghuo Mts	34.68	92.92	4950	1996–2014
TGH1	Tanggula Mts.	33.10	91.90	4948	2002–2014

*XXR indicates sites from QTR and XXH sites from QTH

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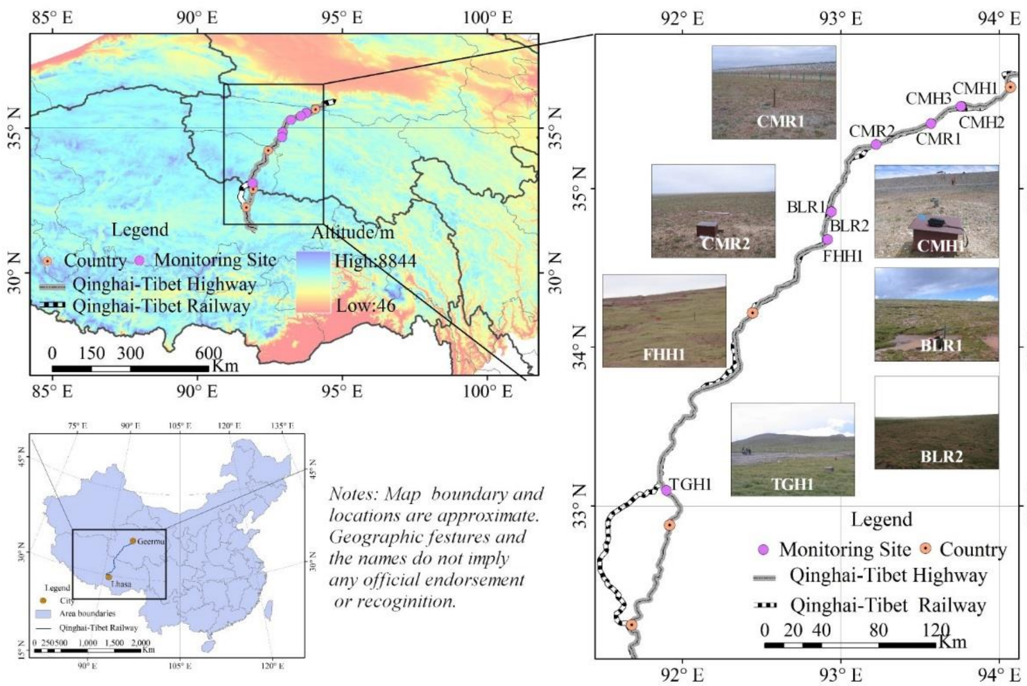

Figure 1 Geographic location of nine monitoring sites

Table 2 Climate and environmental parameters at nine monitoring sites along the QTH and QTR

Site	Climate Conditions		Ecosystem	VC (%)	Permafrost Conditions		
	MAAT (℃)	Precipitation (mm)			MAGT (℃)	ALT (m)	FST
CMH1				5–10			B,H
CMH2				5–10	−1.45	1.79	B,H
CMH3	−5.0 to −5.5	230–250	Alpine Steppe	5–10			B,H
CMR1				20–30	−0.91		B,H
CMR2				20–30	−0.22	4.88	D,F
BLR1	−3.4 to −4.0	230–510	Alpine Meadow	60–70		1.76	H
BLR2				35–40	−0.57	2.23	H
FHH1	−6.0 to −6.5	250–300	Alpine Meadow	85–90	−2.13	2.02	F, B
TGH1	−6.0 to −6.5	250–300		93–97	−1.14	2.02	F, B

MAAT: mean annual air temperature; ALT: active layer thickness; MAGT: mean annual ground temperature at depth of zero annual amplitude, usually 10–15 m depth below ground surface on the Plateau; FST: frozen soil types, where H stands for frozen soils with ice, B for saturated frozen soils, and F for saturated frozen soils with excess ground ice; VC: vegetation cover.

Mean annual air temperature ranges from about −5.0 to −5.5 °C in the Chumaer high plain to about −6.0 to −6.5 °C in the Tanggula Mountains (Table 2). The climate over the Qinghai–Tibet Plateau is extremely continental with annual total precipitation generally < 300 mm, but this precipitation ranges from 230 to 510 mm in the Beilu Basin (Wu et al., 2015). There was no steady or winter-long snow cover on the ground at any site during the study period.

Alpine grassland along the QTH and QTR mainly includes alpine meadow and alpine steppe (Wang et al., 2006). Five monitoring sites in the Chumaer high plain are in alpine steppe, with vegetation cover ranging from 5–10% at CMH1, CMH2 and CHM3, and 20–30% at CMR1 and CMR2 (Figure 1). Two sites in the Beiluhe basin are in alpine meadow, with vegetation cover 30–40% at BLR2 and 60–70% at BLR1. Another two monitoring sites, in the Fenghuo and Tanggula Mountains, respectively, are also in alpine meadow, with vegetation cover ~85–90% at FHH1 and ~93–97% at TGH1. Near-surface sediments are dominated by gravel and sandy soil in alpine steppe and clayey and silt soil with little gravel in alpine meadow. Soil organic content is relatively low where there is no peat layer in alpine steppe, and high where there is such a layer (< 10 cm).

2.2 Soil temperature measurements

All monitoring sites were established in 2002 except for FHH1 in 1996 and CMR1 and CMR2 in 2005. There were five sites along the QTH and four along the QTR. Soil temperature measurements from all sites are continuous until the present. Soil temperature was measured at depths 0.5–18 m beneath the surface of the embankment centerline at all sites, except for that beneath the sunny-side shoulder at CMR1 and CMR2. All measurements were made by a string of thermistors at depth increments of 0.5 m. These thermistors were made by the State Key Laboratory of Frozen Soil Engineering. Laboratory temperature accuracy of these sensors is ±0.05 ℃. For all sites along the QTH, in situ measurements were conducted by well-trained technicians using a data logger (CR3000, Campbell Scientific Inc., USA), with automatic measurements on the 5th and 20th days of each month. For all sites along the QTR, in situ measurements were automatically collected each day by this data logger, at 10:00 a.m. Beijing Standard Time.

2.3 Method

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We analyzed long-term trends and variability of APT, ALT, and permafrost temperature beneath embankments in alpine meadow and steppe from 2002 through 2014. APT (ALT) was estimated as the maximum thaw depth in late autumn, through linear interpolation of soil temperature profiles between two neighboring points about and below 0 ℃ isotherm beneath embankments at all sites. Long-term trends of APT were estimated by linear regression, using 13 years of APT data at each site, with $p < 0.01$. Long-term trends of annual mean permafrost temperature were estimated by half-monthly measurements for QTH and daily measurements for QTR. Long-term variability of permafrost temperature was estimated via linear regression, using 13 years of annual mean permafrost data at each site, with $p < 0.01$.

3. Results

3.1 Change in APT beneath embankments

Based on soil temperature beneath embankments in alpine meadow and steppe, mean APT beneath those embankments in alpine steppe from 2002 through 2014 ranged from 6.5 m at CMR1 and CMH2 to 7.83 m at CMH3, with average 7.03 m. That in alpine meadow from 2002 (1995 at FHH1) through 2014 ranged from 3.56 m at FHH1 to 7.43 m at TGH1, with average 4.68 m (3.76 m if excluding TGH1, whose value (7.43 m) appeared anomalous) (Table 3). The difference of APT between alpine meadow and steppe is 2.35 m (3.27 m excluding TGH1). This difference is similar to that beneath natural surfaces in alpine meadow and alpine steppe (Wu et al., 2010c; Zhao et al., 2010; Li et al., 2012). These results indicate that APT beneath both highway and railway embankments in alpine meadow is much smaller than that in alpine steppe, meaning that permafrost beneath embankments in alpine meadow has more “cool energy” in winter to decrease temperature than that in alpine steppe.

ALT beneath natural surfaces increased continuously because of climate warming along the QTH and QTR (Figure 2). The annual ALT increase rate ranged from 1.79 cm/a at CMR2 to 5.45 cm/a at FHH1, with average 3.54 cm/a (Table 3). As with the annual ALT increase rate in the Beiluhe Basin (Wu et al., 2015), the rate in alpine meadow, which ranged from 3.53 cm/a at TGH1 to 5.45 cm/a at FHH1 with average 4.28 cm/a, was higher than that in alpine steppe. The latter ranged from 1.79 cm/a at CMR2 to 2.31 cm/a at CMH2 with average 2.05 cm/a (Table 3).

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Table 3 Change rate of artificial permafrost table (APT)

Site Name	APT change beneath Embankment				ALT change beneath nature surface			
	Max (m)	Min (m)	Mean (m)	Rate (cm/a)	Max (m)	Min (m)	Mean (m)	Rate (cm/a)
Ecosystem	Alpine steppe							
CMH1	8.06	6.40	7.33	11.17				
CMH2	7.06	5.52	6.50	8.14	1.94	1.62	1.79	2.31
CMH3	8.39	6.16	7.83	14.26				
CMR1	7.53	4.90	6.50	−31.78				
CMR2	7.70	6.58	6.98	−7.45	4.98	4.75	4.88	1.79
Ecosystem	Alpine meadow							
FHH1	3.84	3.19	3.56	−2.06	2.35	1.2	1.75	5.45
TGH1	8.40	6.08	7.43	19.20	2.26	1.82	2.02	3.53
BLR1	4.96	3.53	4.09	−9.95	2.1	1.44	1.76	3.68
BLR2	4.41	3.36	3.62	−7.12	2.49	1.95	2.23	4.46

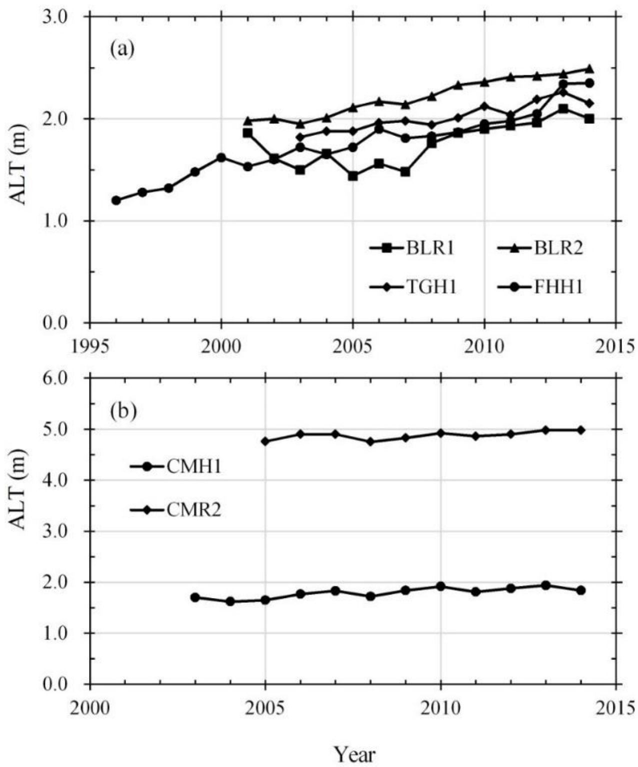

Figure 2 Active layer thickness (ALT) beneath natural surface in alpine meadow (a) and alpine steppe (b)

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Notably, there was a substantial difference between the QTH and QTR in annual APT change rate, and this difference was independent of alpine meadow or alpine steppe. For the QTH, APT beneath embankments continuously increased except at FHH1 (where it decreased at annual rate −2.26 cm/a) (Figure 3a). This rate of increase ranged from 8.14 cm/a at CMH2 to 19.20 cm/a at TGH1, with average 13.2 cm/a. For the QTR, APT beneath embankments continuously decreased (Figure 3). The annual rate of decrease ranged from −31.78 cm/a at CMR1 to −7.45 cm/a at CMR2, with average −14.1 cm/a. This great difference in annual APT change rate between the QTH and QTR contributed to strong heat absorption by asphalt pavement (Sheng et al., 2002; Wu et al., 2010a), cooling of railway ballast pavement (Lai et al., 2003; Cheng et al., 2007; Ma et al., 2008), and strengthening measures of the QTR after 2007 (Hou et al., 2015). Another contribution was engineering activity increase of interannual APT variation beneath embankments (Wu et al., 2007; Gao et al., 2015). As a consequence, there was no clear effect of alpine ecosystems on interannual APT change.

3.2 Changes in permafrost temperature

Because vegetation was removed during QTH construction but present during QTR construction, it is important to analyze the effect of the vegetation layer on soil thermal regime in alpine meadow and steppe for both constructions. Therefore, we examined long-term variability of soil temperature at 0.5 m beneath the embankment base, near-permafrost table temperature, and permafrost temperature at depth 10 m (Figure 4).

Figure 5 shows change of mean annual soil temperature at depth 0.5 m beneath the embankment base along the QTH and QTR in alpine meadow and steppe. Mean annual soil temperature at that depth along the QTR had a decreasing trend, but that along the QTH had an increasing trend except for decrease at FHH1. At QTR sites, the rate of mean annual soil temperature decrease at the 0.5 m depth beneath embankment base ranged from −0.16 °C/10a at BLR2 to −1.5 °C/10a at CMR1 with average −0.60 °C/10a (Table 4). At QTH sites except FHH1, the rate of mean annual soil temperature increase at 0.5 m depth beneath embankment base ranged from 0.76 ℃/10a at CMH3 to 1.24 ℃/10a at TGH1, with average 0.84 ℃/10a (Table 4).

Figure 6 shows change of near-permafrost table temperature beneath embankments along the QTH and QTR in alpine meadow and steppe. Over the observation period, that temperature beneath embankments along the QTR showed a decreasing trend, but that along the QTH had an increasing trend except for decrease at FHH1. At QTR sites, the rate of near-permafrost

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table temperature decrease ranged from −0.01 °C/10a at CMR2 to −0.39 °C/10a at BLR1, with average −0.18 °C/10a (Table 4). At QTH sites except FHH1, the rate of increase ranged from 0.13 ℃/10a at CMH3 to 0.38 ℃/10a at TGH1, with average 0.26 ℃/10a.

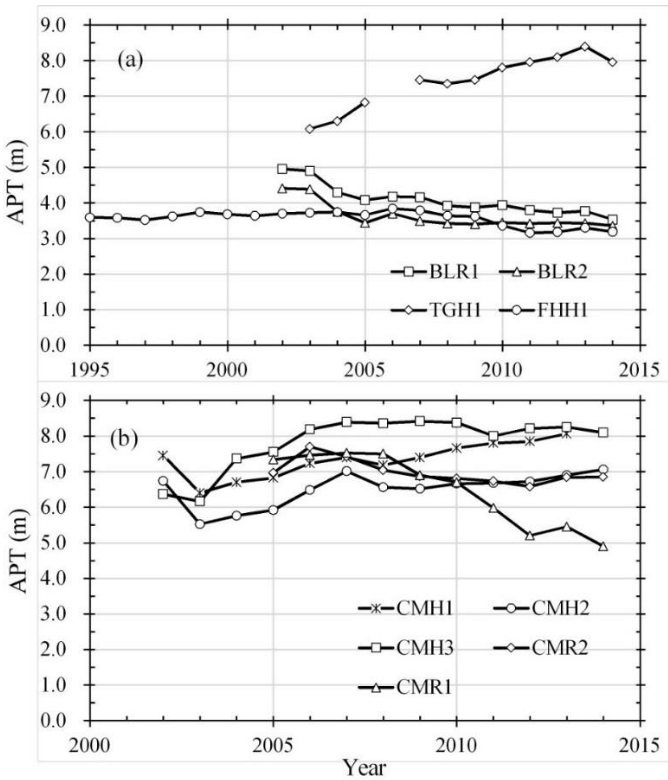

Figure 3 Artificial permafrost table (APT) beneath embankment in alpine meadow (a) and alpine steppe (b)

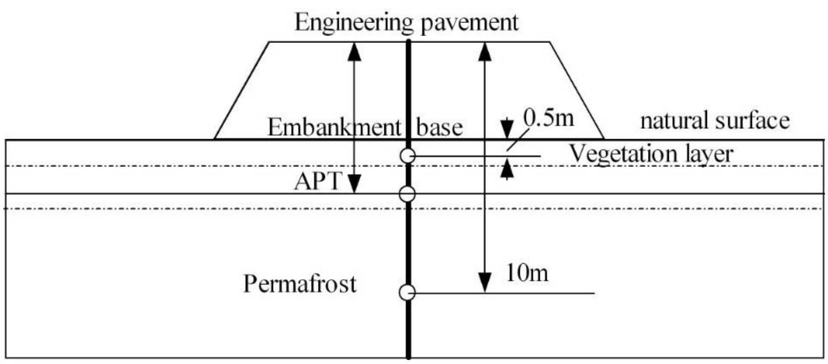

Figure 4 Temperature at key depths

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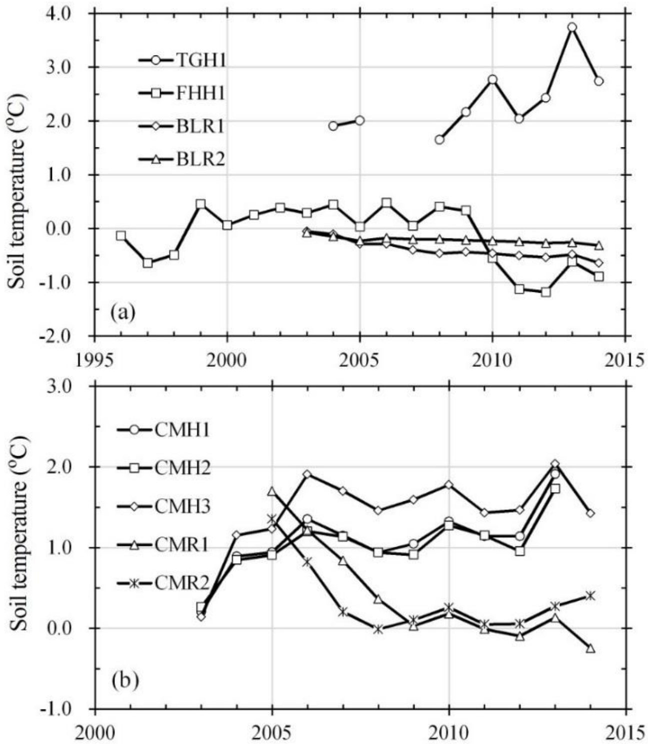

Figure 5 Mean annual soil temperature at depth 0.5 m beneath embankment base in alpine meadow (a) and alpine steppe (b)

Table 4 Variation rate of mean annual soil temperature at depth 0.5 m beneath embankment base (EBT0.5), near-permafrost table temperature (NPT), and permafrost temperature at depth 10 m (PT10) beneath embankment

Site Name	change rate of soil temperature beneath Embankment, ℃/10a			Observed Period
	EBT0.5	NPT	PT10	
Ecosystem			Alpine Steppe	
CMH1	0.91	0.31	0.41	2002–2014
CMH2	0.77	0.23	0.17	2002–2014
CMH3	0.76	0.13	0.09	2002–2014
CMR1	−1.50	−0.19	-	2005–2014
CMR2	−0.23	−0.01	0.07	2005–2014
Ecosystem			Alpine Meadow	
FHH1	−0.42	−0.22	0.19	2002–2014
TGH1	1.24	0.38	0.19	2002–2014
BLR1	−0.45	−0.39	0.44	1996–2014
BLR2	−0.16	−0.11	0.17	2002–2014

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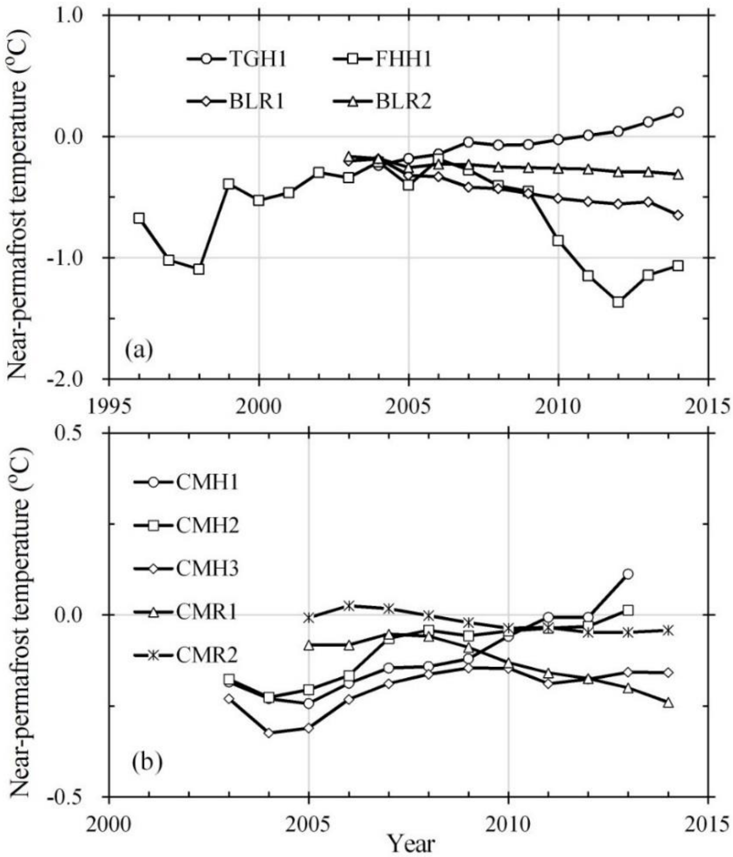

Figure 6 Near-permafrost table temperature beneath embankment in alpine meadow (a) and alpine steppe (b)

Figure 7 shows change of permafrost temperature at depth 10 m beneath the embankment surface of the QTH and QTR in alpine meadow and steppe. That temperature had an increasing trend. At the QTR sites, the rate of permafrost temperature increase at 10 m depth ranged from 0.07 ℃/10a at CMR2 to 0.44 ℃/10a at BLR1, with average 0.23 ℃/10a; however, there was no obvious increasing trend at CMR1 (Table 4). At the QTH sites, the rate of temperature increase ranged from 0.08 ℃/10a at CMH3 to 0.41 ℃/10a at CMH1, with average 0.21 ℃/10a.

Change of soil temperature at depth 0.5 m beneath the embankment base and near-permafrost table temperature beneath the embankment appeared independent of alpine ecosystem (alpine meadow or alpine steppe), and was only related to the cooling of QTR ballast pavement and heat absorption of QTH asphalt pavement. Change of permafrost temperature at depth 10 m was independent of engineering type (QTH or QTR), and the increase rate of this temperature approached 0.23 ℃/10a for QTR and 0.21 ℃/10a for QTH. Notably, the average rate of this temperature increase in alpine meadow (0.25 ℃/10a) was higher than that in alpine steppe (0.18 ℃/10a). This change of permafrost temperature at depth 10 m beneath the embankment had a similar pattern as that temperature beneath a natural surface (Wu et al., 2015). This indicates that the effect of climate change on permafrost at that depth beneath the embankment is stronger than that of engineering activities on this permafrost.

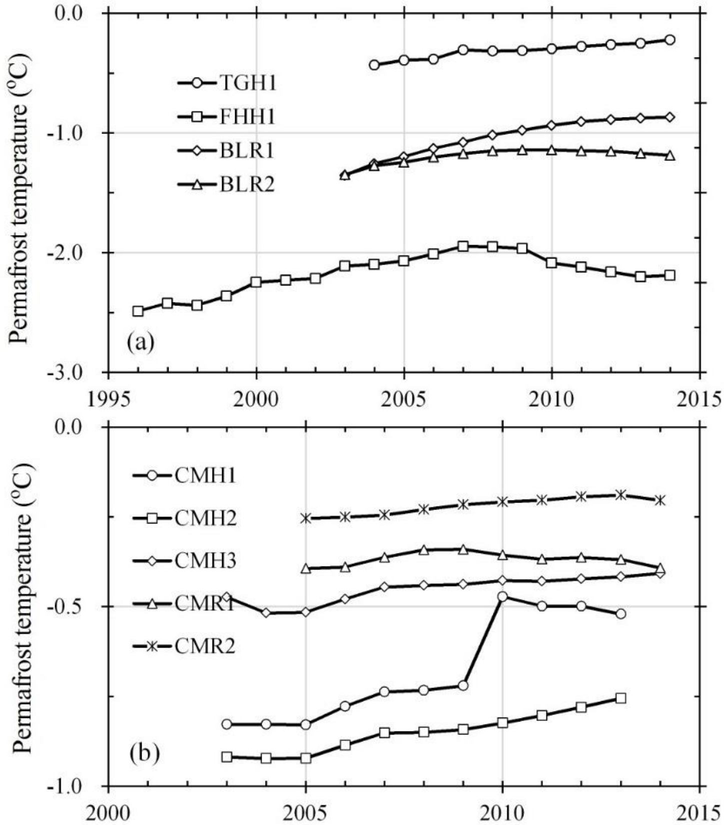

Figure 7 Permafrost temperature at depth of 10 m beneath embankment surface in alpine meadow (a) and alpine steppe (b)

4. Discussion

Vegetation in alpine ecosystems is important in the freezing-thawing process and permafrost thermal regime (Zhang et al., 2005; Shur and Jorgenson, 2007; Hinzman et al., 2005; Wang et al., 2012). The response of permafrost in different alpine ecosystems to climate change varies greatly (Wu et al., 2015). Because the vegetation layer beneath embankments can play a controlling role in the change of APT and the permafrost thermal regime, the effect of engineering activities on permafrost likely varies with alpine ecosystem. However, we cannot infer that change of APT, soil temperature and permafrost temperature are closely related with the influence of the vegetation layer in alpine meadow and steppe. Therefore, we analyzed variation of soil temperature with depth beneath embankments in alpine meadow. Figure 8 shows variation of mean annual soil temperature with depth beneath the embankment at BLR1 (a) and BLR2 (b) for the QTR, where there was a vegetation layer in the alpine meadow, and at TGH1 (c) and FHH1 (d) for the QTH, where that vegetation layer was removed. From this figure, mean annual soil temperature gradually approached a certain value (about −0.77 °C at BLR1 in panel a and −0.36 °C at BLR2 in panel b) for the vegetation layer case. However, there was no such finding (panels c and d) for the QTH without a vegetation layer. These variations indicate that the vegetation layer in an alpine meadow may have an insulating role within the effect of engineering activities on permafrost beneath embankments. We also analyzed changes of permafrost thermal regime beneath embankments in alpine steppe, for both QTR with a vegetation layer and QTH without that layer. As a result, there was no pattern similar to the pattern in Figure 8a and b, demonstrating that the vegetation layer of alpine steppe has no insulation effect. Therefore, the vegetation layer of an alpine meadow can effectively prevent heat disturbance from engineering construction from propagating rapidly downward and raising permafrost temperature over the short term.

Generally, an insulation layer within an embankment can reduce heat disturbance from short-term engineering activities (Esch, 1987; Cheng et al., 2004; Wen et al., 2005). However, such a layer is a disadvantage during long-term effects of climate warming over the period of engineering operation (Liu et al., 2002; Sheng et al., 2006), especially for warm permafrost. Further, the cooling impact of a crushed rock embankment on permafrost beneath the embankment is weakened by the insulation effect of a vegetation layer in alpine meadow. Therefore, we suggest that the vegetation layer be removed during engineering construction in alpine meadows.

5. Conclusions

Based on soil temperature data of nine monitoring sites over the period 2002/2004 through 2014 along the QTH and QTR, we studied the variation of APT and soil temperature beneath embankments. The results show that alpine ecosystems on the Qinghai–Tibet Plateau can modify the effect of engineering construction on permafrost beneath embankments. Average APT beneath embankments was between 4.68 m at alpine meadow sites and 7.03 m at alpine steppe sites. However, the variation rate of APT was not closely related with alpine ecosystem but only with engineering type. APT beneath QTH embankments had an increasing trend, with average 13.2 cm/a. In contrast, APT beneath QTR embankments had a decreasing trend, with at −14.1 cm/a. These findings indicate that alpine ecosystems can control APT magnitude beneath embankments but cannot control the rate of APT change. That rate is related to the cooling of railway ballast and heat absorption of asphalt pavement.

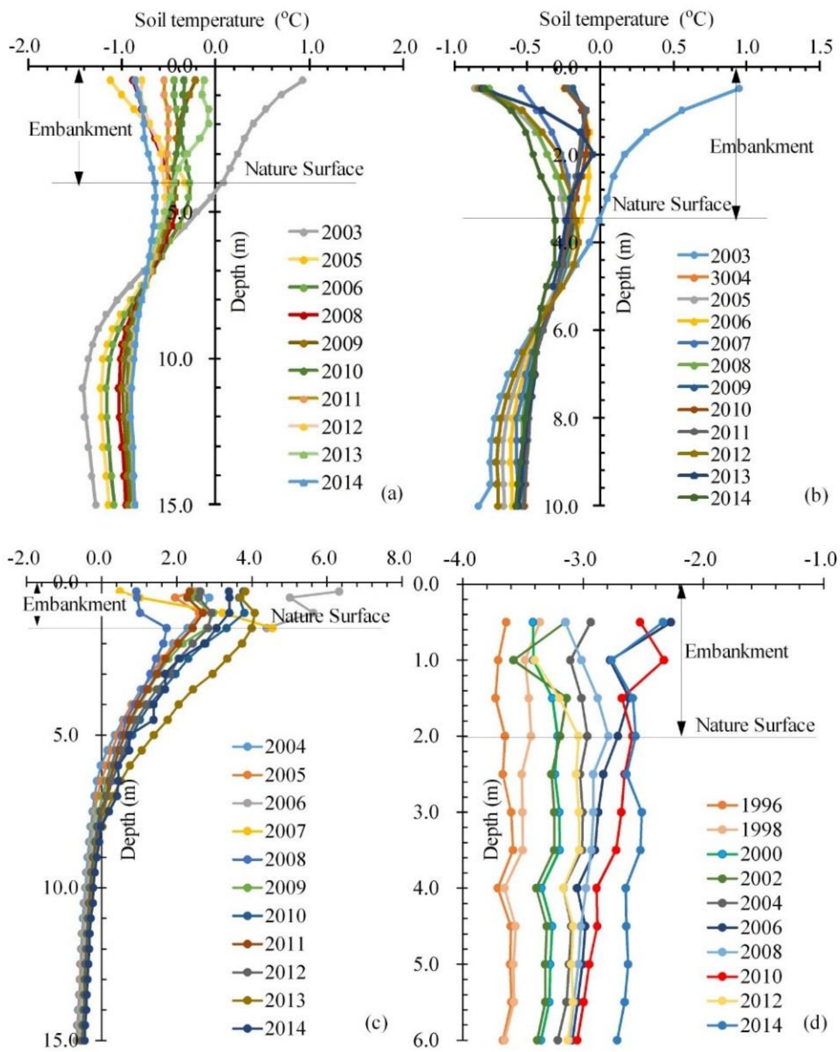

Figure 8 Change of mean annual soil temperature with depth beneath embankment at BLR1 (a) and BLR2 (b) for QTR, and at TGH1 (c) and FHH1 (d) for QTH in alpine meadow

Soil temperature at depth 0.5 m and near-permafrost table temperature beneath embankments in QTH alpine ecosystems had an increasing trend over the period of observation, with averages 0.84 ℃/10a and 0.26 ℃/10a, respectively. However, there was a decreasing trend for QTR, with respective averages −0.60 °C/10a and −0.18 °C/10a. Permafrost temperature at depth 10 m beneath the embankment surface had an increasing trend, with average 0.22 ℃/10a. The changes in soil temperature at depth 0.5 m and near-permafrost table temperature are closely related to the cooling of railway ballast and heat absorption of asphalt pavement, but unrelated to alpine meadow and steppe. The rate of permafrost temperature increase at depth 10 m in alpine meadow (0.25 ℃/10a) was slightly higher than that in alpine steppe (0.18 ℃/10a).

Change in mean annual soil temperature with depth beneath embankment surfaces in alpine meadow with a vegetation layer differed from that without a vegetation layer. This suggests that vegetation layer of alpine meadow has an insulation role within the effects of engineering activities on permafrost beneath embankment. This insulation effect is an advantage for alleviating permafrost temperature increase in the short-term, but a disadvantage in the long term because of climate warming. Therefore, we suggest that the vegetation layer in alpine meadow be removed at the beginning of engineering construction.

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