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Changes in frozen ground in the Source Area of the Yellow River on the Qinghai–Tibet Plateau, China, and their eco-environmental impacts

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Abstract
The Source Area of the Yellow River is located in the mosaic transition zones of seasonally frozen ground, and discontinuous and continuous permafrost on the northeastern Qinghai–Tibet Plateau. Vertically, permafrost is attached or detached from frost action. The latter can be further divided into shallow (depth to the permafrost table $\leqslant$8 m), deep ($>$8 m) and two-layer permafrost. Since the 1980s, air temperatures have been rising at an average rate of 0.02 °C yr^{-1}. Human activities have also increased remarkably, resulting in a regional degradation of permafrost. The lower limit of permafrost has risen by 50–80 m. The average maximum depth of frost penetration has decreased by 0.1–0.2 m. The temperatures of the suprapermafrost water have increased by 0.5–0.7 °C. General trends of permafrost degradation include reduction in areal extent from continuous and discontinuous to sporadic and patchy permafrost, thinning of permafrost, and expansion of taliks. Isolated patches of permafrost have either been significantly reduced in areal extent, or changed into seasonally frozen ground. Degradation of permafrost has led to a lowering of ground water levels, shrinking lakes and wetlands, and noticeable change of grassland ecosystems alpine meadows to steppes. The degradation of alpine grasslands will cause further degradation of permafrost and result in the deterioration of ecological environments as manifested by expanding desertification and enhancing soil erosion.

Keywords: Source Area of the Yellow River (SAYR), frozen ground, cold regions ecology, degradation, environmental impacts

1. Introduction

Frozen ground plays a critical role in global thermal, water and carbon budgets. Under a changing climate, permafrost dynamics and ecological environments are undergoing rapid and remarkable changes. It is increasingly evident that frozen ground is affected by climate warming. This is manifested in rising ground temperatures and declining areal extents and thickness of permafrost [1–4]. They directly and indirectly impact ecological environments [5, 6]. Many projects have been dedicated to mapping, monitoring, modeling and evaluating permafrost changes and their ecological environmental impacts, with encouraging and promising results [7, 8]. Permafrost and cold regions environments in High Asia, and on the Qinghai–Tibet Plateau (QTP) in particular, have received increasing attention due to their importance in regional socioeconomic development.

The Yellow, Yangtze and Lancang/Mekong Rivers, the so called 'Three Rivers', originate on the northeastern QTP. It is seasonally affected by southeast and south monsoons, and by the dry winds from Central Asia. The vegetation varies from subtropical forests in the southeast to alpine deserts in the west, but generally much of the Plateau is a pastoral landscape.

Permafrost on the QTP has been of much interest to geocryologists, engineers and environmental scientists for 50 years. The total area of permafrost is estimated to be 1.3–1.6 million km^2. The existing permafrost was formed during the last two major glaciations [9]. During the Holocene, several periods of permafrost development and partial decay occurred. Permafrost along the QTP peripheries, including the Source Area of the Yellow River (SAYR), has been more sensitive to climate changes due to its delicate thermal balance and the strong monsoon influence in comparison with those in the interior.

Since the 1970s, the climate warming and a sharp increase in human activities, such as overgrazing of increasing cattle herds, and imprudent utilization of wetlands, pasturelands and water resources, have resulted in a general degradation of frozen ground as evidenced by rising ground temperatures, increased thaw depths, thinning permafrost, reduction of areal extent and increasing fragmentation of permafrost distribution [5, 9, 10]. These have resulted in adverse changes in cold regions environments [11]. On the other hand, degraded grasslands accelerate the rates of change in soil temperatures and moisture contents in the active layer because of declining vegetative coverage [12]. In turn, this increases soil temperatures and reduces soil moisture contents, and further degrades the permafrost.

Driving forces of regional environmental changes include natural causes, such as climate warming, permafrost degradation, increased rodent and insect activities, and anthropogenic causes, such as imprudent exploitation of water, soils, fauna and flora resources for short-term economic benefits. Permafrost degradation, however, is one of the most important factors in accelerating ecological changes [10, 13, 14].

In the SAYR, continuous, discontinuous, sporadic, and isolated patches of permafrost, as well as seasonally frozen ground, are mosaic with frequent transitions. During the past few decades, degradation of grassland ecosystems was persistent, and land desertification accelerated [10, 15]. For example, the rate of degradation of grasslands in Madoi county doubled during the 1980s compared with the 1970s when the degradation was first observed. Since 1973, the grassland degradation has increased by 2.6% yr^{-1}, and the land desertification at an annual average rate of 1.83%. By 1998, about 2.414×10^5 km^2 of grasslands were degraded [14]. Grass productivity declined by 30–80%, and the quality of the grasslands also deteriorated.

During the early 1950s, the SAYR was surveyed for economic planning and the project of water diversion from the Yangtze River to the Yellow River. A comprehensive expedition organized by Qinghai Provincial Government in 1978 resulted in a large amount of relevant data. Specialized investigations were carried out from the 1970s to the 2000s. They resulted in a 1:500 000 permafrost distribution map for the areas to be affected by the water diversion project [13]. During 2001–2004, 1:250 000 surveys of the ecological environmental geology in the SAYR were completed [14]. In this paper, distributive features of frozen ground and development trends, and their resultant and potential ecological and environmental impacts, are analyzed and discussed on the basis of these data.

2. Study region

2.1. Topography and geomorphology

The SAYR (33°56′–35°31′N, 95°55′–98°41′E, elevation 4100–5442 m asl) encompasses the catchment area above Duoshixia (34°46′25.15″N, 98°20′59.03″E; 4222 m asl) along the Yellow River, with a total catchment area of 2.5×10^4 km^2 (figure 1). It is bordered by the Bayan Har Mountains in the south, by the Buqing Mountains in the north, and by the Geshigeya Mountains in the west. The SAYR slopes SE, and is interspaced with numerous rugged mountains and hills, valleys and intermontane basins, lakes, rivers and high plains. The elevations increase rapidly northwards and southwards at the edges of the SAYR, and it rises gently westwards until the water divide at the Geshigeya Mountains is reached.

Tectonic structures, active faults in particular, which run generally in a NW–SE direction, determine the regional topography. Surrounded by NW–SE trending mountains, the SAYR includes the Gyaring and Ngöring (Sisters) Lakes and the Yellow River floodplains with flat topography and meandering river channels. Aeolian sand lands, dunes, and depressions are generally distributed in the areas between the south of Gyaring Lake and Mount Mianshanling. The circum-lake hills are gentle, and river valleys are wide and shallow.

2.2. Hydrology

The SAYR includes numerous meandering rivers and braided streams of the Yellow River. The majority of them are on the southern banks of the Yellow River, and the catchment areas and water supplies are asymmetrical. According to data from Huang'he'yan (Yellow Riverside) Hydrological Station (34°53′07.09″N, 98°10′18.84″E; 4215 m asl, with a catchment area of 20 930 km^2) near Madoi, the 1955–2005 average flow is 22.61 m^3 s^{-1}, and the average annual discharge is 7.13×10^8 m^3 [16].

There are many lakes, such as the Sisters Lakes, Galala Co, Xingxinghai and Xingxiuhai lake clusters. Most of the lakes discharge freshwater to rivers. The Ngöring Lake (34°46′–35°05′N, 97°32′–98°54′E, 4266–4267 m asl) is the largest. In 2000, the water surface area was 610.7 km^2, and the average water depth was 17.6 m, with the greatest depth of 34.7 m and an estimated water storage of 10.76×10^9 m^3. The Gyaring Lake (34°49′–35°01′N, 97°03′–97°27′E, 4289–4290 m asl) is the next largest. The water surface area was 526.1 km^2, with the greatest depth of 13.1 m and a water storage of 4.67×10^9 m^3. These lakes were fed by precipitation, snow-melt and ice-melt water, rivers, and ground water. They modulate river runoffs and the

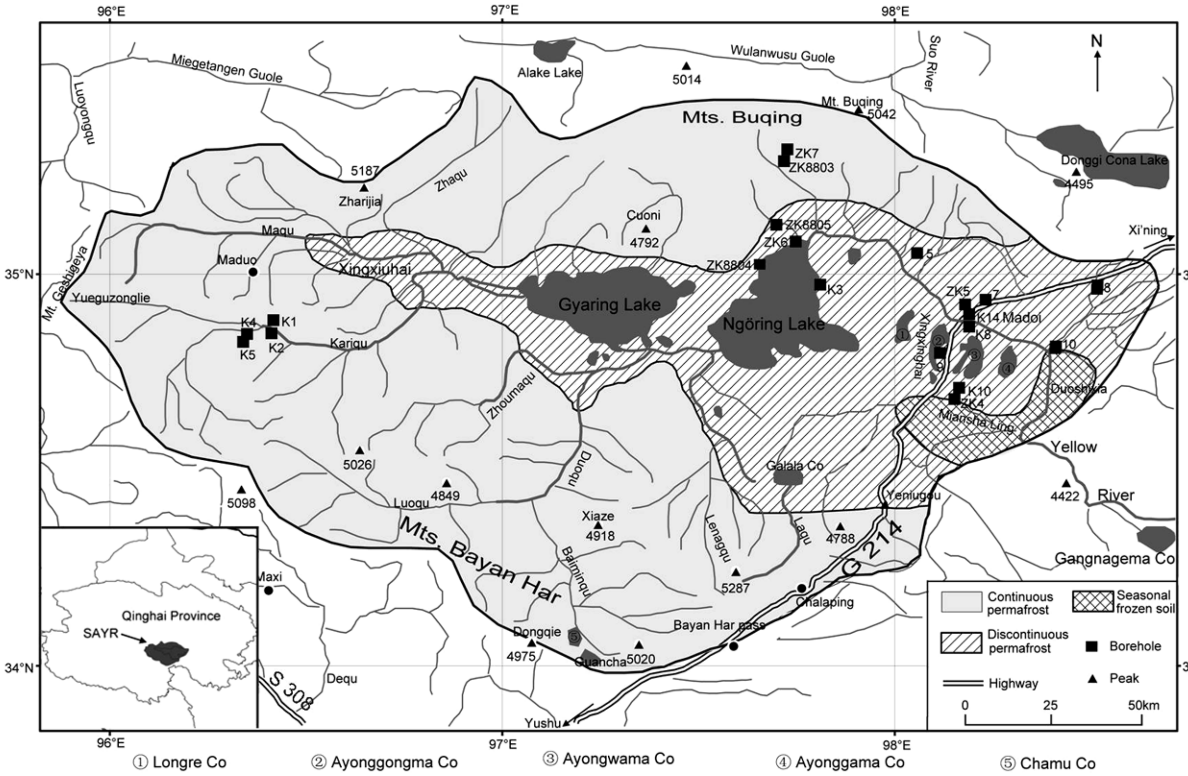

Figure 1. Topography, permafrost and boreholes in the SAYR.

Table 1. Meteorological features in the sources area of the Yellow River [17].

				Average air temp. (°C)				Annual average					
Station	Long. (E)	Lat. (N)	Elev. (m)	Ann.	Jan.	Jul.	Ann. range	Frost-free days (d)	Precip. (mm)	Evap. (mm)	Sunshine (h)	Insol. (MJ m^{-2})	Notes
Madoi	98°13′	34°55′	4272	−4.0	−16.0	7.5	23.5	18	313	1351	2717	6474	Modoi 1995–2005
Ngöring L. hydrol. st.	97°45′	35°05′	4273	−4.5	−17.1	7.6	24.7	19	340	1065	2685	6534	N bank of Nyoring L. 1985–1989
Duoqu	97°21′	34°48′	4285	−4.0	−16.5	7.1	23.6	17	363	1045	2650	6500	S outlet of Gyaring L. 2000–2001
Yeniugou	97°58′	34°29′	4370	−4.2	−16.9	7.8	24.7		335		2799	6787	2000–2001
Maduo village	96°22′	35°02′	4450	−4.3	−17.5	7.6	25.1	16	376	1528	2702	6568	2000–2001

local microclimate. However, the lake water levels have been sinking.

2.3. Climate

The climate is semi-arid alpine (table 1). The mean annual air temperatures (MAATs) are lower than −4 °C, with 15–20 frost-free days in a year. The lakes and rivers freeze up for more than seven months in a year. There is no clear division of seasons, but diurnal variations of temperatures are large. Solar radiation is strong throughout the year, with annual total sunshine hours varying between 2500 and 2800 h and insolation from 6400 to 6800 MJ m^{-2} [17].

The annual precipitation varies between 300 and 400 mm, and is mainly in the form of rain storms or snow/hailstones. There are clear differences between the dry and wet seasons; much of the precipitation (70–80%) falls in the warm seasons. The cold seasons are dry, with prevailing westerly winds. The annual average evaporation is about 1000–1500 mm. The average rate of decrease in precipitation was 25 mm yr^{-1} during 1980–2000 [16], often occurring in the warm seasons.

2.4. Soils and vegetation

In the upper mountains (4800–5100 m asl), the soils are generally gravelly and of alpine tundra or desert type. In the lower mountains and piedmonts at 4400–4800 m, the soils are characterized in general as alpine steppes or typical/paludal alpine meadows in depressions and lowlands. At 4100–4400 m asl, the soils are characteristic of alpine steppes, generally gravelly, sandy and prone to erosion and the organic content to decomposition. However, in the river plains at about 4200 m asl, aeolian erosion is pronounced and exposed ground surfaces are prone to wind action. Aeolian sandy soils are abundant. Paludal soils are developed in lowlands and depressions.

The vegetation is dwarfed and herbaceous, and dominated by paludal and typical alpine meadows and steppes. In some upper mountains, sparse vegetation consists of spotty cushion vegetation, such as *Androsace tapete* and *Arenaria pulvinata*. Pioneering species are generally encountered on the screes or protaluses. The vegetation in the alpine steppes consists mainly of perennial and xerophytic thickets of *Poe alpigena*, *Stipa purpurea*, and *Agropyron cristatum* and is present in wide intermontane valleys, fluvial and alluvial fans, and river or lake terraces at 4300–4600 m asl. Alpine meadows consisting mainly of species of *Kobresia pygmaea*, *K. humilis*, *K. capillifolia*, *K. tibetica*, *K. prattii*, *and K. kansuensis* are present in lowlands, wide valleys and flat mountain tops. Paludal meadows mainly consist of *K. tibetica*, *K. pygmaea*, *K. kansuensis*, and *Carex moorcroftii* in the wetlands and valleys and on river terraces with standing water. Shrub-meadows consist mainly of *Rhododendron thymifolium, Salix oritrepha, Spiraea alpina* and *Dasiphora fruticosa* on the Yellow River banks. At present, xerophilization, halophilization, and adaptation to sandy environments have become the leading trends in vegetation successions. Floristic structures become simple, and the vegetative coverage is declining. Phytocommunity biodiversity biomass and productivity have declined.

2.5. Socioeconomic environments

The SAYR includes the major portion of Madoi county and parts of Chendo and Qümalêb counties, with a population of about 70 000. The majority (70%) of the population are Tibetan, living by raising cattle. Husbandry has developed rapidly since the 1970s, with tripled total herds of 1107 500 heads of sheep or equivalent during the past 30 years. There are only a few salt farms, hydroelectric power plants, and resource-exploitative firms. In 2000, the total GDP of the SAYR reached 2.1×10^8 yuan (about 2.5×10^7 USD), with annual disposable income of 1283 yuan (about 155 USD) *per capita*. Basic energy, transportation and communications infrastructures have improved in recent years.

However, due to persistent increases in cattle herds, overgrazing has become a disturbing fact, and the livestock grazing is largely traditional nomadic in search of water sources and grasslands. In the lowlands, with generally good grasslands close to residential centers, frequent and concentrated grazing has damaged or suppressed the growth and reproduction of vegetation. This exploitative operation has accelerated degradation of grasslands.

3. Frozen ground

3.1. Distribution and types of frozen ground

Distribution of frozen ground and kinds of seasonal freeze–thaw processes are influenced by elevational climate zoning, but they are made more complicated by lakes and rivers. The lower limit of permafrost varies between 4215 and 4400 m asl. Borehole data show the basic features of the frozen ground (table 2) [14, 18].

The SAYR has a mosaic of various types of frozen ground. East of the Ngöring Lake, only isolated patches of and sporadic permafrost and seasonally frozen ground are present at elevations lower than 4400 m in river valleys and basins with high soil moisture. For example, permafrost was present in boreholes ZK5 and ZK6 on river banks or lake shores, but permafrost was absent in borehole ZK7 on dry land. In particular, seasonally frozen ground is only present lower than 4250 m asl from Huang’he’yan to Duoshixia along the Yellow River, and the Requ and Hei’he Rivers, as shown in boreholes ZK4 and K8. Due to the increasing elevation westwards, southwards and northwards from the Sisters Lakes, there is a transition from lake shore taliks to isolated patches of permafrost and discontinuous permafrost, and continuous permafrost at elevations higher than 4400 m asl as shown in boreholes ZK7 and K8003. Taliks due to the thermal influences of lakes, rivers and active faults are as wide as 100–300 m, as revealed in borehole K3. Permafrost is often continuous on all slopes above 4400–4500 m asl, such as in the valleys along the Kariqu and Yueguzongliequ Rivers, with extensive presence of wetlands.

On the basis of borehole data (table 2), it appears that seasonally frozen ground and permafrost are interspaced from Madoi to Yeniugou along the G214. Isolated patches of permafrost generally occur under wetlands above 4250–4400 m asl, and seasonally frozen ground generally occurs at dry locations. Madoi town is located on the middle and upper parts of a piedmont fluvial fan with a dry ground surface underlain by seasonally frozen ground. To the south, permafrost was found in boreholes ZK5 and K14 on the northern banks of the Yellow River and borehole K10 in Xiaoyemaling, but seasonally frozen ground was present in borehole K8 on the southern bank of the Yellow River and in borehole ZK4 on the north bank of the Hei’he River. Pit excavations also indicate that there is only seasonally frozen ground below 4250 m asl along the Hei’he River banks and at Yematan. Isolated patches of permafrost start to occur near Yeniugou (4370 m asl). Permafrost becomes continuous, and thicker above 4500 m asl For example, ground ice and permafrost are well developed from Chalaping (4800 m asl) to the Bayan Har Mountain Pass (4824 m asl) along the G214. As shown in a pit 1.3 m in depth, the permafrost table was at 0.8 m in September 1997, and a ground ice layer was found at depths of 0.8–1.3 m. Cuts for highway construction and maintenance revealed a 2 m thick ice layer immediately below the permafrost table in Chalaping. Glacial deposits and landforms such as U-shape troughs, nival and ice-scoured lakes, and periglacial manifestations of various types such as thermokarst lakes, pingos and palsas are present and on a larger scale than other sections of the highway [18, 19].

Vertical distributions of permafrost are multifaceted in the transition zone. They can generally be divided into two types: attached (the active layer can be frozen back) and detached from seasonal frost action. The latter can be further divided

Table 2. Features of frozen ground in the sources area of the Yellow River [14, 18].

Borehole	Location	Lat. (N)	Long. (E)	Elev. (m)	Depth (m) of borehole	Permafrost layer Depth (m)	Permafrost layer Thickness (m)	Vertical distribution of permafrost
ZK5	N bank of the Yellow R. S of Madoi	34°53′	98°11′	4220	88.97	1.2	10.0	Attached
ZK6	N shore of the Ngöring L., 123.9 m E of the fishery	35°05′	97°46′	4272	200.80	1.5–8.0 19.81–24.26	6.5 4.45	Two-layer
ZK7	Huangjintai Valley N of Ngöring L.	35°12′	97°43′	4472	80.01	1.3	44.27	Attached
ZK8803	Slope toe 25 km N of Ngöring L.	35°10′	97°42′	4400	171.0	1.2	18.2	
ZK8804	Interlake bar between the Ngöring L. and Wuming L.	35°01′	97°42′	4275	187.0	1.8	8.25	
ZK8805	6 km N of Ngöring L. fishery	35°08′	97°45′	4300	201.0	2.0–8.5	6.5	
No 5	Gamale lake shore	35°04′	98°05′	4239	221.3	1.2–27.7	26.5	
No 7	1 km NE of Madoi	34°56′	98°13′	4280	62.20			Seasonally frozen ground
No 8	Duogerong	34°55′	98°31′	4253	77.50	1.0–20.2	19.2	Attached
No 9	E shore, Ayonggongma Co L.	34°50′	98°08′	4216	63.57	1.2–6.3	5.1	
No 10	Yellow R. valley at Duoshixia	34°49′	98°22′	4218	155.01	1.4–19.2	17.8	
K1	N of Kariqu R.	34°54′	96°20′	4583	27.8	1.9–3.6	1.7	Two-layer
K2	S of Kariqu R.	34°53′	96°20′	4507	65.68	1.9–5.2 33.0–48.0	3.3 15.0	
K3	Sand bar between Nan Co and Ngöring L.	34°59′	97°48′	4272	89.60			Lake talik
K4	N of the Bangkaqu R.	34°44′	96°09′	4557	30.25	0.9–3.5	2.6	Attached
K5	N of the Bangkaqu R.	34°43′	96°09′	4569	92.40	17.0–36.8	19.8	Detached
K8	S of the Yellow R. at Madoi	34°52′	98°10′	4211	81.01			Seasonally frozen ground
K14	N of Yellow R. at Madoi	34°54′	98°11′	4221	46.60	4.85–13.35	8.5	Detached
K10	Xiao Yemaling	34°01′	98°08′	4294	91.85	8.05–10.40	2.35	
ZK4	N bank of the Hei'he R. along G214	34°00′	98°03′	4220	153.66			Seasonally frozen ground

into shallow (depth to present permafrost $\leqslant$8 m) and deep (>8 m), and two-layer permafrost. Along the G214, detached shallow permafrost is common. For example, it was found at three sites south of Madoi in the Yellow River valley, as well as in borehole No 3 on the northern shore of Xingxinghai south of the Yellow River, in borehole No 31 in Dayamaling, and in boreholes Nos 31, 47 and 49 south of the Hei'he River Bridge. In these areas, the permafrost table was generally detected at depths of 5–8 m, and it was less than 10 m in thickness. Sometimes, a lower layer of permafrost was encountered at depths below 17 m. For example, the lower layer of permafrost was at depths of 17–33 m in boreholes K2, K5, and ZK6 (table 2) [9].

3.2. Temperature and thickness of permafrost

Although elevational zoning of permafrost thickness and temperature dominates, latitudinal zoning is also evident in spite of the frequent disruptions from the rugged terrains and other local factors such as surface water bodies, soil types, slope orientations, and vegetation coverage. Most of the boreholes in table 2 are in intermontane valleys and basins lower than 4600 m asl. Ground temperatures were only measured in boreholes ZK5, ZK6, and ZK7 (figure 2). The thicknesses deduced from ground temperature measurements and local prevailing geothermal gradients agree well with those judged from on-site drilling cores (table 2) [9].

The permafrost thickness increases with increase in elevation as shown in boreholes ZK6, ZK8803, and ZK7 on the northern shore of the Ngöring Lake. These three boreholes, about 35 km apart, are at similar geomorphic positions, with only a difference in elevation. The permafrost is 6.5 m thick in borehole ZK6 at 4272 m asl; 18.2 m in borehole ZK8003 at 4400 m asl; and 44.3 m in borehole ZK7 at 4472 m asl. The geo-electrical sounding on the northern slope of the Bayan Har Mountains also indicates that the permafrost thickness increases at an average rate of about 13–17 m (permafrost thickness) per 100 m rise in elevation. It is possible that permafrost thickness can exceed 100 m at elevations above 5000 m asl in the Bayan Har and Buqing Mountains.

3.3. Seasonally frozen ground

The flat and dry areas in the eastern and southeastern SAYR are generally underlain by seasonally frozen ground. Meteorological data at Madoi indicate an average of MAATs during 1956–2005 of −4.0 °C, a mean annual ground surface

Table 3. Monthly average temperatures of air, ground surface and soils at Madoi during 1956–2005.

		Temperature (°C)												
		Jan.	Feb.	Mar.	Apr.	May.	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Annual average
Air		−16.8	−13.4	−8.4	−3.7	1.4	5.2	7.6	6.9	2.9	−2.5	−10.7	−15.1	−3.9
Ground surface		−14.8	−9.6	−3.9	1.8	7.1	10.6	12.4	11.9	7.2	1.2	−7.6	−12.9	0.4
Soil depth (cm)	5	−11.1	−7.6	−2.8	1.3	5.9	9.4	11.2	10.8	8.0	2.3	−3.5	−7.8	1.3
	10	−10.2	−7.0	−2.9	0.9	5.6	10.1	11.1	11.1	7.9	2.7	−3.4	−7.7	1.4
	20	−9.5	−6.8	−3.1	0.1	4.6	8.6	10.0	10.1	7.6	3.1	−2.5	−6.8	1.3
	40	−7.7	−5.7	−2.7	−0.1	3.4	7.7	8.7	8.9	6.6	2.0	−1.0	−5.6	1.2
	80	−5.1	−4.1	−2.2	−0.4	1.3	4.9	6.0	7.0	5.9	2.7	0.4	−2.7	1.1
	16	−0.5	−1.1	−0.9	−0.4	−0.2	0.0	0.5	2.0	3.9	2.9	1.2	0.3	0.6
	320	0.5	0.2	0.2	0.1	0.1	0.1	0.3	1.2	1.8	2.2	1.6	0.9	0.8

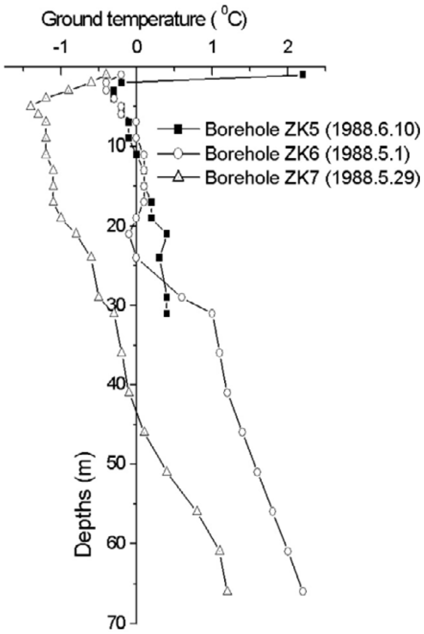

Figure 2. Ground temperature curves at boreholes ZK5, ZK6, and ZK7 [9].

temperature of +0.3 °C, and an accumulative period of subzero (including 0 °C) average daily air temperatures ranging from 192 to 207 days. The monthly average air temperatures are above 0 °C from May to September, when occasionally daily average air temperatures can still dip below freezing. The accumulative period with subzero minimum ground surface temperatures ranges from 300 to 320 days. The maximum depths of frost penetration vary from 2.2 to 2.4 m. It is evident that the mean annual ground surface temperature was 4.3 °C warmer than the MAAT during the period from 1956 to 2005 (table 3).

4. Degradation of frozen ground

4.1. Evidence

The degradation of frozen ground is evident in the SAYR. This is based the following observations:

(1) A decrease in the areal extent of permafrost, and relative increase of seasonally frozen ground and taliks from recently thawed permafrost. For example, Huang'he'yan and Madoi town were all underlain by permafrost before the 1970s [19]. Repeated investigations and surveys for urban planning and construction projects showed that permafrost under these two towns had largely disappeared after the 1990s. At present, the boundary of permafrost near Madoi town has shifted westwards by about 15 km; the lower limit of permafrost in foothills to the north has risen to 4350 m asl from 4250 m asl; at Huang'he'yan in the south, the permafrost boundary also moved northwards by 2 km.

(2) Detached permafrost layer(s) has/have been discovered in many places in the eastern SAYR. The depths to the permafrost table have increased, and the talik thickness has increased. For example, talik has reached a depth of about 5 m in Xiaoyemaling.

(3) Data from boreholes, excavation pits, and water wells indicate that the lower limit of permafrost has risen by 50–80 m compared with the 1980s. For example, it rose from 4320 to 4370 m asl at Yeniugou along G214, and from 4270 m asl to more than 4350 m asl on the slope north of Madoi.

(4) The averages of maximum frost penetration depths were 2.4 m in the 1980s and 2.2 m in the 1990s. During the 1980s–1990s, the average soil temperatures at depths of 0.05–3.2 m rose by 0.3 °C. Water temperatures in many wells in Madoi town also rose from 0.8 °C in the 1980s to 1.5 °C in the 1990s. This may suggest a similar warming trend of ground temperatures at similar depths (figure 3; table 4).

(5) Many pingos generally near the lower limit of permafrost thawed and collapsed in the lower parts. They migrated upslope in wetlands as a result of upslope thawing of permafrost. In addition, solifluction and retrogressive thaw slumps were observed.

The general trend of permafrost degradation is a transition from continuous to discontinuous, and to isolated patches of permafrost, thinning of permafrost layers, reduction in the area of permafrost, conversion of some permafrost islands or

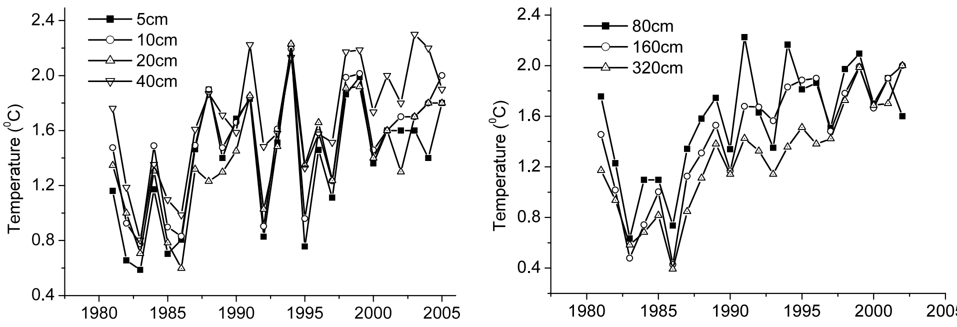

Figure 3. Changes in mean annual soil temperatures at the Madoi Meteorological Station during 1981–2000.

Table 4. Decadal averages of mean annual soil temperature (°C).

	Soil temperatures (°C) at depths (cm)						
Decades	5	10	20	40	80	160	320
1980s	1.17	1.30	1.10	1.41	1.24	1.02	0.90
1990s	1.50	1.58	1.60	1.79	1.84	1.76	1.49
Warming	0.33	0.28	0.50	0.38	0.60	0.74	0.59

patches into seasonally frozen ground or taliks. Permafrost degrades more rapidly in the east than in the west. It has resulted in reduction of vegetation types and grassland desertification.

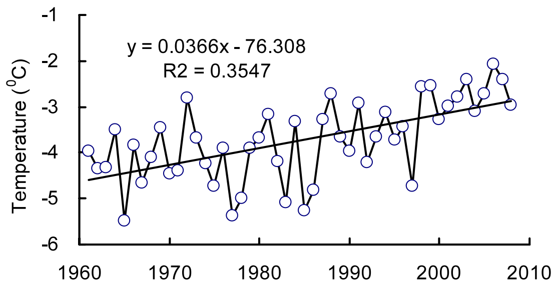

Figure 4. Changes of mean annual air temperature at Madoi in the SAYR during 1950–2006.

4.2. Causal analysis

Frozen ground degradation is complicated and has many causes, but rising air temperatures are the most basic reason. The MAATs have been increasing from 1955 to 2005 (figure 4). The increase in MAATs was at an average rate of 0.02 °C yr^{-1} during the mid-1980s and late 1980s. In particular, the MAAT was −2.6 °C in 1998, the largest positive departure of 1.4 °C from the 51-year average. The MAAT average in the 1990s was 0.6, 0.7 and 0.4 °C warmer than those in the 1960s, 1970s and 1980s, respectively. The period between 2001 and 2005 was 0.8 °C warmer than those in the 1960s. Increases in MAAT decadal averages were 0.6–0.7 °C, and the warming occurred in all seasons, but the warming in winter was the largest (+0.9 °C), followed by those in autumn (+0.8 °C), summer (+0.4 °C) and spring (+0.3 °C).

The decadal averages of mean annual ground surface temperature increased from −0.1 °C in the 1960s to +0.8 °C in the 1990s (table 5). Changes in air temperatures showed an apparent seasonality. The warming in winter is the most striking, followed by those in summer and autumn. The warming in the 1980s mainly occurred in autumn and winter. Since the 1990s, the warming rates slowed in winter and autumn, but accelerated in spring and summer. At the same time, evaporation increased.

Changes in air and ground surface freezing and thawing indices are important in analyzing the accumulative changing trends of frozen ground. During 1961–2000, the freezing indices were decreasing, and the thawing indices were increasing at Madoi (table 6), indicating a warming trend both in the cold and warm seasons and a heat accumulation in soils [20]. Since the 1980s, the mean annual ground surface temperatures changed from subzero to above zero, and the ratio of thawing index to freezing index decreased from 1.63 to 1.56. This suggests that climate warming had an increasing effect on frozen ground degradation.

5. Ecological and environmental impacts of degrading permafrost

The persistent presence of frozen ground can effectively retard, reduce, or even prevent soil moisture and surface waters from downward and lateral permeation [21]. It can also re-enrich with various nutrients on the bottom of the active layer or above seasonally frozen ground for plant growth during thawing seasons. As a result, alpine meadows usually flourish in valleys and basins.

During the past few decades, climate warming, overgrazing, unplanned mining, over-harvesting of herbaceous medicine plants and damage by rodent activities have resulted in severe degradation of grasslands in the SAYR. Degradation of frozen ground has further accelerated the degradation of grasslands and other environmental deterioration. The degrading or degraded frozen ground alters the habitats for flora and fauna through changing or changed heat, moisture and nutrient regimes in soils, causing ecological chain reactions.

Degradation of permafrost results in an increase in thickness of seasonally thawed layers, or detached permafrost, or even further to seasonally frozen ground, and the retreat of seasonally frozen ground, thus reducing the frost penetration depth and period. As a result, soil moisture contents, particularly at plant root levels, critical for maintaining alpine

Table 5. Decadal averages of mean annual and seasonal air and ground surface temperatures (°C).

Decade	Decadal averages of mean annual and seasonal air temperatures					Decadal average of mean annual ground surface temperatures
	Annual	Spring	Summer	Autumn	Winter	
1960s	−4.2	−3.6	6.6	−3.6	−16.0	−0.1
1970s	−4.3	−3.7	6.7	−3.9	−16.5	−0.1
1980s	−4.0	−3.9	6.6	−3.2	−15.4	0.5
1990s	−3.6	−3.3	7.0	−2.8	−15.1	0.8
1960–2000	−4.0	−3.8	6.6	−3.5	−15.9	0.23

Table 6. Decadal averages of mean annual air and ground surface temperatures, freezing index (FI; °C d) and thawing index (TI; °C d) at Madoi, and their differences (TI − FI; °C d) and ratios (TI/FI) at Madoi [20].

Indices	Averages for air					Averages for ground surface				
	1960s	1970s	1980s	1990s	1960–2000	1960s	1970s	1980s	1990s	1960–2000
MAAT (°C)	−4.22	−4.27	−3.94	−3.64	−4.02	−0.08	−0.09	0.46	0.83	0.28
FI (°C d)	2274	2252	2155	2050	2183	1657	1619	1330	1470	1519
TI (°C d)	1082	1106	1171	1217	1144	2093	2184	2176	2286	2185
TI − FI (°C d)	−1192	−1146	−984	−833	−1039	436	565	846	816	666
TI/FI	0.48	0.49	0.54	0.59	0.52	1.26	1.34	1.63	1.56	1.45

meadow vegetation, are either reduced or depleted due to resultant lower water table or lateral drainage. At the same time, the soil temperature rises and its seasonal and inter-annual variability also increases. This may greatly affect those species of short-rooted plants and flora and fauna adapted to cold air and soil environments in alpine meadows, and consequently the plant biodiversity, community compositions, and eventually stability of ecosystems. For example, frozen ground near Madoi has been degrading since the 1980s, and the ground water table has been lowered to depths of 6–10 m, with a regional fall of 2–3 m during past 20 years. Landscapes around the town have been turned to sandy land or even to desert from alpine steppes [14]. Piedmont plains at the interception of the Niutoushan Hill between the Sisters Lakes and on the northern shore of the Ngöring Lake were excellent pastoral lands prior to the 1980s. Wetlands were formed in warm seasons by creeks seeping from the suprapermafrost water at the toes of slopes. The water flows were sharply reduced after the 1980s due to the elevation of the positions of springs and lowered suprapermafrost water table as a result of permafrost degradation. Accordingly, surface water supplies and soil moisture availability have been reduced, and in many places, water supplies have been completely cut off, resulting in transitions from paludal or typical alpine meadows to alpine steppes.

During thawing seasons, alpine meadows play important roles in controlling flash floods by ground storage and modulating surface runoffs and soil water supply. Mats or cushions formed by paludal meadow vegetation and root systems can buffer the splashing of raindrops or hailstones on otherwise bare ground surfaces, and absorb them in the vegetation–root–soil systems. This enables the reduction and retardation of surface runoffs, and slow percolation of water into the underlying soil layers for later use by biological communities.

Permafrost degradation has led to changes from the paludal alpine meadows to typical alpine meadows and/or steppes, to changes in plant root structures and vegetative coverage, to a reduced retention, modulation, and storage of rainfall and snow-melt and ice-melt water by vegetation, and to an increased surface evaporation. The continual lowering of the ground water table changes the original hydraulic channels and runoff conditions, and alters the original water equilibrium such as in supplies, runoff, discharge and annual budgets. These result in a weakening or loss of the functions of vegetation for moisture retention and storage. In some areas, a lowered ground water table might reverse the supply–discharge relationships of surface water bodies and ground water. For example, when the suprapermafrost water table is lowered to a level below local water levels in rivers and lakes, they supply water to ground water, resulting in reduced river flows, low lake levels, reduction in the area of lakes or even dried lakes. During 1950–2004, the water levels at the Sister Lakes were lowered by 3.1–3.5 m [14].

Degrading permafrost has increased thaw settlement, sudden ground failures due to excessive differential thaw settlement, or retrogressive thaw slumps, solifluction, and soil erosion on slopes with fine-grained deposits and adequate soil moisture. The original structures of soil strata and plant roots systems have been damaged. The repeated freeze–thaw cycling differentially sorts soil particles: coarser grains move upwards and onto the ground surface. Once the soils are exposed on the ground surface, they become subject to land desertification, sand/dust storms, or other aeolian actions, enhancing soil erosion. Pastoral lands damaged due to overgrazing are hard to restore, and eventually they become desert if the overgrazing persists. The area of the desertified land has reached about 7841 km^2, and accounts for 31% of total land area in the SAYR [14].

The degrading or degraded permafrost has deepened the active layer, increased soil temperatures, and reduced the soil moisture contents. This has improved the physical conditions for rodent activities such as burrowing. As a result, rodents invade in larger numbers and reproduce at a more rapid rate, causing further damage to pastoral lands. The areas affected by rodents reached 224 925 km^2, or 65.2% of total areal extent of pastoral lands in Modoi county in 1998 [10]. Slightly affected grasslands have a lower productivity and a change in dominating plant species. Severely affected grasslands are transformed, resulting in the extensive appearance of 'black soil land' [22, 23]. Rodent hazards have become one of the major reasons for deteriorating eco-environments in the SAYR.

Permafrost degradation may also have contributed to the decline in the size of lakes and wetlands through increased water storage and improved hydraulic channeling. According to remote sensing data, the total lake area was 1227 km^2 in the 1960s and 1177 km^2 in 2000, i.e., there was a reduction of 50 km^2 over the past 40 years [14]. The area of wetlands was 3895 km^2 in the early 1980s, and 3247 km^2 in the 1990s, i.e. there was a reduction of 648 km^2 of total area or an annual rate of loss at about 59 km^2 [24]. As a result, their functioning for water retention and storage, flood modulation and control, and preservation of species biodiversity has declined. The aquatic habitats shrank, aquatic biodiversity decreased, and the communities became smaller and more vulnerable. All these factors have adverse impacts on biological and community structures, abundance and the survival of rare and endangered species.

Permafrost degradation has caused the desertification of pastoral lands. The ground surface conditions have been changed, resulting in higher albedo. This alters heat and radiation budgets and reduced the convection of the near-surface atmosphere, resulting in a drier and warmer local climate with increased evaporation and more consumption of water resources. On the other hand, degraded pastoral land reduces the water supply to ground water from precipitation, and surface runoffs, and lessens the modulation and storage functions of soils for water resources. These processes destabilize spatiotemporal dynamics in precipitation, evaporation and runoffs, and could further reduce water resources and cause the deterioration of water and soil environments.

The vertical distribution of grassland degradation indicates that barren land resulting from degrading grasslands mainly occurs at elevations of 4100–5200 m asl [25, 26]. It is most severe at 4300–5000 m asl, where the areal extent of grasslands accounts for 2.4–7.5% of that at 4100–5200 m asl. This coincides with the belt of warm ($>-1\,^\circ$C) permafrost, where its degradation has been most striking. Therefore, the degradations of permafrost and grasslands are spatially symbiotic, indicating interdependent, interactive and synchronous relationships.

6. Conclusions, prospects, and recommendations

The following conclusions can be drawn.

(1) A mosaic distribution of frozen ground was formed and continues to exist in the SAYR. As a result of its marginal nature, permafrost is either vertically attached or detached from the frost penetration. The detached permafrost can be further divided into shallow, deep and two-layer permafrost. In general, permafrost is warm, thin, and thermally unstable.

(2) Since the 1980s, permafrost has been in general undergoing degradation due to climate warming and increasing human activities. Permafrost degradation has been more striking around the Sisters Lakes and in the east. The lower limit of permafrost has risen by 50–80 m. The maximum frost depths decreased by about 0.2 m. The general trend of permafrost degradation is manifested by thinning and shrinking of permafrost and the transformation of discontinuous permafrost to isolated patches of permafrost, sometimes to seasonally frozen ground.

(3) As a result of permafrost degradation, the ground water table has been lowered and lakes and wetlands have shrunk in area, resulting in a degradation of grassland ecosystems. The degradation of grasslands may result in land desertification. Many factors have contributed to changes in ecological environments. They include climate warming and drying, permafrost degradation, increasing rodent activities, and anthropogenic factors. Permafrost degradation further accelerates the degradation of grasslands. These environmental factors interact and are interdependent. A self-fulfilling vicious cycle inevitably results in an environmental deterioration, of which the vital issue is the declining water resources, particularly the water availability in near-surface soil layers.

Two aspects need to be urgently studied to understand the mechanisms and for the effective remediation of the deteriorating environments.

(1) Observations indicate that river runoffs and near-surface soil moisture contents have been decreasing recently, but precipitation and evaporation have not changed remarkably. Partial decay of permafrost is supposed to release some soil moisture from the melting of ground ice. It is possible that climate warming might enhance potential evaporation, but the lowered ground water table may offset the actual evapotranspiration. The logical result of the combined effects of many factors, an increase in river runoffs, has yet to be observed. The question is, where has the water gone? Shallow permafrost contains large amounts of ground ice, but it is not necessarily 'excessive ice'. Therefore, upon thawing, most of the ice-melt water goes into the unsaturated vadose zone. It is also possible that in the areas of shallow or two-layer permafrost, as a result of thawed or thawing permafrost layer(s), the suprapermafrost water can be converted into intra-permafrost or subpermafrost water and stored in lower depressions or basins for long-term hydrological cycles, instead of being released to short-term hydrological cycling. Although the spatiotemporal scales of ground ice in participating in the hydrological cycle are scientifically important, they have not been explored before. Studies on permafrost hydrology need to focus on mechanisms of major processes in water cycling, such as dynamic

changes in the evapotranspiration, precipitation retention and percolation, runoff generation and phase changes in response to ground freezing–thawing. Permafrost eco-hydrogeology is still rarely studied and poorly understood. Thus, the answers to these basic questions are at best speculative. The urgent issue now is to investigate and understand the state of hydrogeology and conversions of 'five waters' (ground water, surface water bodies, precipitation, evapotranspiration, and ground ice). It is basic for the remedial measures to increase and preserve the badly needed water for the near-surface soils and plant roots, and to rehabilitate the deteriorating environments.

(2) Since 2003, the governmental programs of 'Returning to grasslands from grazing' and 'Ecological protection in the Three Rivers sources' have been implemented by evacuating local inhabitants, limitation of grazing, and artificial rain-making. The ecological environments in the SAYR have shown signs of recovery. Water flows and levels in rivers and lakes have indicated a slow, but gradual increasing trend. If these remedial measures and programs can be sustained, they may alleviate the anthropogenic impacts on the fragile and sensitive ecological environments. However, in spite of the fact that the roles of people and cattle in the ecosystems on the QTP are poorly understood so far, and the actual effects of this passive and adaptive mitigation would be limited. These costly remedial measures cannot be sustained due to complicated cultural conflicts. Therefore, more active measures should be sought after for ecological remediation, such as the upper route for the West Line of the Water Diversion Program from the Yangtze River to the Yellow River. Although the major concern for the program is to relieve the water shortage in the upper streams of the Yellow River, it can also be valuable in improving ecological functions in the SAYR.

Therefore, it is recommended that:

(1) Special funding should be established for basic research and monitoring systems in national key eco-environmental remediation programs. Before rushing into implementing costly programs, visionary, strategic and tactical research and experiments relating to the damaged ecological environments and their remedial effects should be conducted, validated and improved in order to achieve the goals in eco-environmental management, protection and rehabilitation in an integrated, more effective and practical way.

(2) Under the auspices of a coordinated endeavor by state ministries, research organizations, local governments, and service agencies, stations, transects, profiles and networks for monitoring climate, frozen ground, hydrology and hydrogeology, and eco-environments should be established in the SAYR. On the basis of ground-based measurements, GIS/RS-integrated modeling and forecasting of water/ice cycling, eco-hydrogeological effects of permafrost degradation and experiments with more active human intervention, and the validation of their effects can be accomplished.

(3) Research on the eco-hydrogeological effects of degrading permafrost needs long-term, integrated, systematic and multidisciplinary research. It involves many key system questions and answers in many scientific and engineering fields. The goals of these studies should aim at providing a solid scientific basis and practical solutions for national key projects for ecological rehabilitation and engineering construction, in order to provide infallible ecological and water safety for China.

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