Interrelations between relief, vegetation, disturbances, and permafrost in the forest-steppe of central Mongolia

Michael Klinge1 | Florian Schneider1 | Choimaa Dulamsuren2 | Kim Arndt1 | Uudus Bayarsaikhan3 | Daniela Sauer1

1Department of Physical Geography, Institute of Geography, University of Göttingen, Göttingen, Germany
2Applied Vegetation Ecology, Faculty of Environment and Natural Resources, University of Freiburg, Freiburg, Germany
3Department of Biology, School of Arts and Sciences, National University of Mongolia, Ulaanbaatar, Mongolia

Abstract

In semi-arid central Asia, relief has a strong impact on the distribution of vegetation and discontinuous permafrost. Our aim was to analyse causal chains and interrelationships that control the spatial patterns of forest and permafrost in the forest-steppe of the northern Khangai Mountains in Mongolia. For this purpose, we conducted soil-profile descriptions, ground-penetrating radar sounding, and vegetation mapping to gain information about forest and permafrost distribution. We integrated remote-sensing analysis and field-mapping data, including soil properties, vegetation cover, forest fires and anthropogenic forest use. We developed and applied a technique for spatial delineation of permafrost distribution, based on the parameters Topographic Wetness Index (TWI), incoming solar radiation and Normalized Difference Vegetation Index (NDVI). Key outcomes of this study are that the occurrence of discontinuous permafrost within 1 m depth is limited to forest stands larger than 100 ha on north-facing slopes. Dense ground vegetation supports permafrost, whereas sandy soil texture leads to greater depth of the permafrost table. As the seasonal ice in the active layer progressively melts down during summer, meltwater interflow above the permafrost table provides additional soil moisture downslope. This process is reflected in enhanced vitality of the steppe vegetation on toe slopes below forests with permafrost. This effect can in turn be used to indirectly detect permafrost in forest stands by remote sensing. Permafrost mostly disappears after forest fires and other severe disturbances, but it may re-establish during forest regrowth. However, climate warming is presently leading to a loss of permafrost regeneration potential after disturbance, and to a shift from climate-induced and ecosystem-driven permafrost to entirely ecosystem-protected permafrost. These trends will result in a further decrease of permafrost area after forest disturbance.

KEYWORDS

forest fire, forest-steppe, geomorphology, ground-penetrating radar (GPR), Mongolia, permafrost, soil

1 | INTRODUCTION

The forest-steppe of Mongolia represents a zonal ecotone at the northern edge of the central-Asian dry belt. It is thus highly sensitive to climate change (Dulamsuren et al., 2010). Water is the main limiting factor for forest distribution in this semi-arid region. As a result of topographically induced differences of solar radiation and evapotranspiration, forests, consisting of Siberian larch (Larix sibirica), are limited to north-facing slopes, whereas mountain steppe covers south-facing slopes (Schlütz et al., 2008). In these semi-arid regions, forest
distribution on slopes is controlled by temperature at the upper treeline and by moisture at the lower treeline (Klinge et al., 2015). The Mongolian forest-steppe is characterized by discontinuous permafrost (Dashtseren et al., 2014). Permafrost also influences soil moisture, as was already highlighted by Richter et al. (1963), Kowalkowski and Starkel (1984), and Starkel (1998). Based on results of ecological studies in the forest-steppe of Mongolia, several authors suppose that soil moisture on slopes is supplemented by meltwater released from seasonal ice above the permafrost table (Dulamsuren, 2004; Dulamsuren & Hauck, 2008; Dulamsuren et al., 2010; Kopp et al., 2014). During drought events, this additional water source can be crucial for forests in semi-arid regions (Sugimoto et al., 2002, 2003; Kopp et al., 2014). Moreover, slope aspect and solar radiation lead to topographic asymmetries in soil moisture and vegetation cover that cause different geoeological conditions between north- and south-facing slopes (Pelletier et al., 2018). Iijima et al. (2012) showed that precipitation on south-facing steppe-covered slopes is completely consumed by evapotranspiration. In contrast, precipitation on north-facing forested slopes with permafrost is only partially consumed by evapotranspiration and partially contributes to river discharge. Therefore, the mountain-forest ecosystems of Mongolia represent substantial water reservoirs (Karthe et al., 2013).

The mountain forests of Mongolia are currently threatened, as the trees are suffering from enhanced drought stress (Dulamsuren et al., 2010, 2014). In addition, insufficient forest management and extensive forest exploitation by logging and wood pasture have led to forest fragmentation and deforestation (Tsogtbaatar, 2004). Fragmented forests are more sensitive to climate warming and less resilient than large forests (Khansaritoreh et al., 2017). Moreover, fires destroyed large forest areas in Mongolia over the past decades (Goldammer, 2002; Hansen et al., 2013; Nyamjav et al., 2007). Given the role of the forest ecosystems as important water reservoir, a continuation of the decrease in forest area would lead to shortage of potable water for people and livestock.

As pointed out earlier, additional water supply related to permafrost patches can make the decisive difference for tree growth in the semi-arid Mongolian forest-steppe. Therefore, permafrost distribution and the factors controlling the permafrost-distribution pattern need to be considered in order to understand the spatial differences in water supply and tree growth. Shur and Jorgenson (2007) identified vegetation, soil and hydrological conditions as the main factors controlling permafrost distribution in the region of discontinuous permafrost of Alaska. Sharkhuu (2003) as well as Sharkhuu and Sharkhuu (2012) showed (spatially differentiated) trends of permafrost degradation in Mongolia. The authors found an increase in the active-layer thickness of 0.1 to 0.6 mm yr\(^{-1}\) (1969–2002) that accelerated between 1980 and 2005. The main cause for this trend is global warming, as the mean annual air temperature (MAAT) in Mongolia increased by 1.9 K over the period 1940–2006 (Dagvadorj et al., 2009). In addition, degradation of the vegetation cover by fires, logging, and overgrazing contribute to the permafrost degradation as well (Sharkhuu & Sharkhuu, 2012).

Understanding the causal chains and interrelations between the factors that control the permafrost pattern in the Mongolian forest-steppe is essential, because of the role of permafrost for the growth of forests in this sensitive ecotone and in turn, the importance of forests in the water cycle. Therefore, we performed geomorphological field investigations and Geographic Information System (GIS) analyses in the forest-steppe of the Khangai Mountains in central Mongolia (Figure 1) in order to test the following hypotheses:

![Figure 1](image-url)  
**Figure 1** Study area. (a) Overview of Mongolia. The black frame shows the position of map b). (b) Location of the study area in the forest-steppe of central Mongolia. The vegetation zones were adapted from Klinge and Sauer (2019). The DEM was created from SRTM (Shuttle Radar Topography Mission) data. The black frame in (b) indicates the location of the study area [Color figure can be viewed at wileyonlinelibrary.com]
H1. Large forest stands on north-facing slopes (northwest–northeast) favour permafrost, whereas permafrost is absent under small fragmented forests.

H2. Meltwater from seasonal ice above the permafrost table enhances vegetation growth and vigour during summer.

H3. Forest use leads to opening of forest stands, which in turn causes deepening of the permafrost table.

H4. Permafrost disappears after extensive forest fire, but may reconstitute during tree regrowth.

H5. Remote sensing data can be used to locate permafrost patches and to estimate the depth of the permafrost table (corresponding to the thickness of the active layer).

Proving the hypotheses H1 to H4 was important, because these geoecological relationships have been postulated by several researchers before, but have not yet been proven in detail. Proving hypothesis H5 was relevant, as it provided the base for spatial delineation of the depth of the permafrost table based on empirical data, as an alternative approach to the use of deterministic top-down models based on climate parameters for assessing zonal permafrost distribution (Böhner & Lehmkuhl, 2005; Gruber, 2012).

2 | STUDY AREA

The study area is situated at the northern edge of the Khangai Mountains in central Mongolia, south of Tosontsengel (98°16′E/48°46′N, 1670 m above sea level [a.s.l.]) (Figure 1). It is characterized by a cold, semi-arid continental climate, with mean annual air temperature of −6°C and monthly mean temperatures between −31.7°C in January and 14.7°C in July (Tosontsengel). Most of the precipitation (220 mm yr−1) falls from May to September, with a maximum in July. It is related to low pressure cells that are driven across the region by the westerlies (Batima et al., 2005). Winters are generally dry, as an effect of the Siberian High. The given climatic conditions result in the presence of discontinuous permafrost. Permafrost mainly occurs in valley bottoms, higher mountain areas, and on north-facing slopes. Ground ice in permafrost forms only where some soil moisture is available. Otherwise, dry permafrost, that is permanently frozen ground without ice, occurs.

The highest mountains within the study area, reaching up to 3200 m a.s.l., are situated in the southern part of the study area. Mountain plateaux with cryoplanation terraces are widespread at these altitudes (Kowalkowski & Starkel, 1984; Richter et al., 1963). There, the upper treeline is at about 2500 m a.s.l. (Klinge et al., 2018). This elevation also represents the lower limit of the periglacial zone with continuous permafrost. The mountains in the northern part of the study area are lower. Their north-facing slopes are completely covered by mountain forest-steppe up to the summits. The major valleys run from south to north. At an elevation of 1600 m a.s.l., they discharge into the valley of the River Ider Gol that runs west–east. The geological basement of the study area is composed of Permian metamorphosed sedimentary and acidic plutonic rock, and Carboniferous mafic rock (Academy of Sciences of Mongolia and Academy of Sciences of USSR, 1990). Debris composed of these rock types largely covers the slopes. Sandy to silty aeolian sediments are often mixed into the rock debris, forming cover beds, that overly the rock debris.

The area south of the River Ider Gol is characterized by large, dense forests, whereas further north, steppe vegetation predominates, and forests are more fragmented (Dulamsuren et al., 2019). Forests (made up of L. sibirica) are generally limited to north-facing slopes, whereas steppe covers south-facing slopes. This clear spatial vegetation pattern is characteristic for the forest-steppe of Mongolia (Hilbig, 1995). It is the result of low precipitation (< 300 mm), high evapotranspiration and the strong difference in insolation between north- and south-facing slopes in the mid-latitudes (Schütz et al., 2008; Hais et al., 2016). In addition, groundwater-fed riparian forests occur, which are less dependent on local precipitation. Riparian woody vegetation includes willow (Salix), poplar (Populus), and larch (L. sibirica). Moreover, scattered, single old larch trees occur on Pleistocene dune fields that are widespread in the basins. During summer, there are many local forest fires (Hessl et al., 2012; Nyamjav et al., 2007). Large forest areas were destroyed by fires in 1996 and 2002. Also, anthropogenic activity causes disturbance of forests. In addition to the extraction of firewood and wood pasture by the local population, intensive forest exploitation in the study area started in the 1960s, when also a timber factory was built in Tosontsengel. In the early 1990s, industrial logging was abandoned. However, in the meantime, logging has restarted to some extent.

3 | METHODS

Two approaches were combined. Fieldwork provided site information about permafrost distribution and the depth of the permafrost table. Remote sensing and statistical correlations were used to analyse geoecological parameters and to evaluate permafrost distribution.

3.1 | Fieldwork

In July and August of the years 2017 and 2018, we dug 76 soil pits down to either the permafrost table or bedrock. Vertical soil-temperature profiles were measured at 10 cm intervals in the profile walls of 30 soil pits immediately after digging. We used a thermometer (Greisinger, G 1700) with a 10 cm robust insertion probe (Greisinger, GES 175). Sediment layers and soil horizons were described according to the Food and Agriculture Organization of the United Nations (FAO) Guidelines for Soil Description (FAO, 2006), and the soils were classified according to the World Reference Base for Soil Resources (IUSS Working Group WRB, 2015). The sub-surface structure was recorded by use of ground-penetrating radar (GPR) along 30 transects, covering different vegetation, relief and soil types. The recording tracks were positioned to run across forest boundaries, dense and open forests, as well as burned, remaining, and regrowing forests. The aim was to evaluate the differences of the permafrost-table depth between different vegetation units, as previous investigations showed the suitability of GPR for detecting permafrost in Alaska, Canada, and Mongolia (De Pascale et al., 2008; Hinkel et al., 2001; Moorman et al., 2003; Wu et al., 2009, 2012). We used a GPR SIR-4000 system by Geophysical
Survey Systems Inc. (GSSI) equipped with a 400 MHz antenna (Type: S04005). Data editing and generation of GPR images was performed using the RADAN 7 software of GSSI. The exact transect positions were determined by global positioning system (GPS, Garmin Montana 680 T). The GPR tracks were previously cleaned from stones, branches and dead trees. They were supplemented by up to 2 m deep soil pits and up to 1 m deep manual drillings in which soil temperature was measured. Depending on soil characteristics and moisture, the maximum GPR recording depth was 3–5 m.

3.2 | Remote sensing and statistical analysis

The workflow of GIS analysis, generation of a DEM (digital elevation model), and remote sensing analyses is shown in Figure A1 (Appendix). The DEM was based on TanDEM-X data (resolution 10 m × 10 m). We integrated four supervised image classifications from Landsat 8 (2013.05.14; 2015.06.20) and Sentinel 2 (2016.09.14; 2017.09.19) satellite images and visually checked and edited the forest polygons to obtain a robust forest representation. The forest area was then used to eliminate topographic distortion caused by forest from the DEM. The elevation data was gradually reduced by 3 m from the forest edges to the interiors, and a smoothing filter was applied on the elevation data inside the forest polygons. The resulting DEM was used to compute various topographic datasets (Figure A1):

- Relief parameters were calculated by the GIS module ‘Basic Terrain Analysis’ integrated into the SAGA 2.3.2 software (Conrad et al., 2015).
- The potential incoming annual solar radiation (ASRI) was calculated for the year 2017 by use of the GIS tool ‘Area Solar Radiation’ implemented in ArcMap 10.7 (ESRI).
- A hydrographic catchment delineation based on the DEM was combined with the forest-classification map to distinguish hydrologically differing forest units.

The study area was subdivided into different landscape units:

- Based on the proportions of forest and steppe, we distinguished forest-dominated areas (FDAs) and steppe-dominated areas (SDAs).
- The area, where the mountains reach above the upper treeline, was defined as high-mountain area.
- Flat areas (≤ 2° slope angle) at low relative elevations were classified as alluvial plains and basins.

In addition, we mapped sand dunes and sand sheets that locally occur across the study area, because they modify soil moisture and temperature, and thus the depth of the permafrost table. Sand dunes can be easily detected in satellite images, whereas sand sheets are mostly masked by vegetation. The latter were recorded exemplarily by GPS-tracking when observed in the field. In addition, the light colour of unpaved roads was used for detecting sand sheets in satellite images.

In a first step, we assigned potential permafrost occurrence to certain landscape units, based on the results of our fieldwork combined with NDVI (Normalized Difference Vegetation Index) analysis (Section 4.4). We used the NDVI of three satellite images of midsummer to determine individual NDVI threshold values (TVs) for steppe below forests with and without permafrost (Sentinel 2: 2019.07.31, TV = 0.7; 2018.06.11, TV = 0.45; Landsat 8: 2015.07.23, TV = 0.7) (Figure A1).

In a second step, we included the depth of the permafrost table in various landscape units. Stepwise regression analyses were carried out to identify correlations between the depth of the permafrost table as measured in the field, relief parameters and NDVI. We chose those parameters that showed the highest correlations and obtained specific linear regression models for different landscape units with potential occurrence of permafrost. Finally, we calculated multivariate regression terms to establish a linear model for the spatial delineation of the depth of the permafrost table. This model was validated by comparing the model-output data to the empirical input data from the study area (Figure A2).

4 | RESULTS

4.1 | Field observations on the interrelations between relief, permafrost, and water supply to forests

Usually no permafrost was observed in fragmented forests. Such forests showed no or very slow regrowth after extensive forest fire. Large forest stands on north-facing slopes usually grew on permafrost. Steppe vegetation on toe slopes below such forests was more vital, denser and greener than below forests without permafrost (Figure A3). Thus, the steppe vegetation below forests with permafrost reflected the additional moisture supply by meltwater from seasonal ice above the permafrost table during summer. We assumed that this was due to lateral meltwater flow above the permafrost table that supplemented soil moisture downslope. In addition, shrubs and deciduous trees like willow and birch occurred at these sites. This difference in vegetation vigour during summer enabled us to indirectly identify forests with permafrost also by remote sensing, based on enhanced NDVI of steppe vegetation on toe slopes below forests in satellite images taken in summer (see Section 4.4).

4.2 | Soil-temperature depth curves and depth of the permafrost table

Soil-temperature depth curves were measured in the profile walls of 30 soil pits on north-facing slopes (Figure 2). These measurements were carried out during July–August, when the thawing depth approaches its maximum (French, 2018; Yershov & Williams, 2009). Therefore, the depth where the temperature reached 0°C may serve as an approximation of the depth of the permafrost table. A generally steep temperature decrease in the upper 10 cm was followed by a more gradual decrease further down. The upper 10 cm were rich in soil organic matter and were in places covered by an organic layer, isolating the soil from the above-ground air temperature. We grouped the curves into four classes, corresponding to different site conditions (Figure 2), and calculated mean temperature gradients (excluding the upper 10 cm) for these four classes (Table 1).

Soils developed in slope debris under forest showed the lowest soil temperatures and steepest gradients (~0.09 K cm⁻¹) (Figure 2).
The permafrost table usually occurred at a depth of 50 to 100 cm (on average at a depth of 70 cm). Sandy soils under forest showed higher temperatures and a less steep temperature gradient ($0.07 \text{ K cm}^{-1}$). The temperature reached 0°C at 110–170 cm (mean: 160 cm) depth, thus on average 90 cm deeper compared to soils developed in slope debris under forest. Sandy soils under forest showed the highest surface temperatures, reaching up to 15°C. In all soil profiles under steppe and burned forest, the bedrock occurred at 80–120 cm depth, and a temperature of 0°C was not reached within this depth. Temperature decrease with depth was much more gradual in soils without forest than in soils under forests ($0.03–0.04 \text{ K cm}^{-1}$). Soil temperatures at sites without forest did not seem to approach 0°C, making the presence of permafrost unlikely.

The insulating effect of O horizons and moss covers led to considerably shallower depth of the permafrost table (Figure 3). As a mutual feedback, low soil temperatures and high permafrost table decreased biological activity and thus led to thick O horizons (and thin A horizons resulting from reduced bioturbation).

### 4.3 Permafrost distribution and sedimentological information obtained by ground-penetrating radar (GPR)

Linear reflectors in GPR images indicate distinct sedimentary boundaries. The permafrost table produces a continuous reflection that cuts through any sedimentary structures (Figures 4 and A5). Ground-ice attenuates the radar signal below the permafrost table. A reflector above the permafrost table that was running approximately parallel to the permafrost table, was interpreted as the upper limit of a moist zone. Linear reflectors that approached the soil surface in downslope
direction indicated an imbricated structure of colluvial deposits and solifluction layers. Surface-parallel structures below the permafrost table pointed to the transition zone to the bedrock. The depth of the permafrost table increased with decreasing tree density.

Two examples of GPR images (transects A and B) and their interpretation are shown in Figure 4 (transects C to F are provided in Figure A5). These transects were located on slope debris of metamorphic rock under forest. Transect A was in a pristine forest with dense ground vegetation consisting of mosses, herbs and shrubs. Logging was limited to a few patches at the lower forest boundary. Deadwood and windthrown trees were widespread. Ice-rich permafrost was found at less than 1 m depth in many soil pits.
The soils were generally moist. The shallow depth of the permafrost table of < 0.8 m was clearly visible in the GPR image. It increased to ~1 m where the forest had been opened. Moisture and ice strongly attenuated the GPR signal. Transect B was in an area of intense logging that had led to opening of the lower part of the forest stand. As captured in the GPR image, the depth of the permafrost table increased downslope, from ~1.5 m under dense forest to 3 m under steppe. The depth of the moist zone above the permafrost table increased from < 1 m depth under dense forest to more than 1.8 m depth under steppe. This trend already started in the lower part of the forest that had been opened by logging.

FIGURE 5  Landscape classification. The shaded relief is based on TanDEM-X data. The burned area was adapted from Klinge et al. (2020). FDA, forest-dominated area; SDA, steppe-dominated area [Color figure can be viewed at wileyonlinelibrary.com]
4.4 | Geographic Information System (GIS)-based delineation of vegetation and permafrost patterns

We had observed in the field (cf. Section 4.1) that steppe vegetation on toe slopes below forests with permafrost benefitted from additional soil moisture (Figure A3). Therefore, we compared the NDVI of steppe vegetation below forests in which we had detected/not detected permafrost during fieldwork, and found a clear difference. We used three suitable satellite images to determine individual NDVI thresholds for steppe vegetation below forest stands with and without permafrost. Where steppe NDVI values from all three satellite images exceeded the respective thresholds, we classified the forests above these steppe sites as forests growing on permafrost (Figure 5).

In addition, we checked forest stands for the presence of sandy sediments, as these reduced soil moisture and decreased the NDVI of the adjacent steppe below the defined thresholds, even where ice-poor permafrost was present.

This approach pointed to permafrost in < 5% of the forests in the SDA, and in > 55% of the forests of the FDA (Figure 5; Table A1, Appendix). The north-western part of the study area belongs to the SDA, whereas the north-eastern part is FDA. In both areas, we found no permafrost during fieldwork. In agreement with these field observations, also the NDVI-based approach indicated permafrost only in a few cases (Figure 5). In the central part of the study area, the sand-layer distribution substantially affected soil moisture and permafrost distribution. Sandy deposits also occurred in the western part of the FDA but not in the eastern part of the SDA.

The combination of temperature measurements in soil pits with permafrost information from GPR measurements led to a database of 115 plots with empiric data for the depth of the permafrost table.

Stepwise regression analyses showed the closest relationships with the depth of the permafrost table for the following three parameters (Table 2):

- Topographic Wetness Index (TWI), a topographic parameter that depicts the accumulation of soil water and slope deposits in the relief;
- Potential incoming ASRI, used for estimating diurnal warming intensity as influenced by topography;
- Mean NDVI of 16 multispectral satellite images (2013–2018), integrating site-specific vegetation conditions for the entire growing season, and inter-annual variability in moisture availability.

These three parameters represent independent variables. They were derived from different databases and relate to ecological conditions favouring permafrost. The applicability of these three parameters for permafrost delineation agrees with findings reported by Etzelmüller et al. (2006). The strongest correlation with NDVI was obtained by using the average NDVI of 16 satellite images from the growing seasons of the period 2013–2018, whereas individual NDVI datasets from Landsat 8 and Sentinel 2 yielded weaker correlations.

Two multivariate regression terms were used for delineating the depth of the permafrost table in areas with (F₂) and without forest (F₁). A multiple correlation coefficient of \( r^2 = 0.58 \) (Table 2) was determined for sites without forest (including the classes steppe, burned forest and areas with ongoing tree succession). The correlation for the 81 forested sites was much weaker (F₁, Table 2). Excluding forests on sandy soils resulted in an increase of the multiple correlation coefficient to \( r^2 = 0.26 \) (F₃). The lacking correlation for forests on sandy soils (F₃) indicated that factors not considered here controlled the depth of the permafrost table at these sites. Therefore, we generally applied the regression for forests on slope debris F₂ for estimating

| Table 2 | Correlation statistics of multivariate regressions between depth of the permafrost table and the parameters ASRI (potential incoming annual solar radiation), TWI (Topographic Wetness Index), and mean NDVI (mean Normalized Difference Vegetation Index of 16 satellite images) of different geoeological units (F₁–F₄). Root mean square error (RMSE) refers to the relationship between measured and calculated depths of the permafrost table |
|---------|---------------------------------------------------------------|
| Geologic unit | F₁: Sites without forest | F₂: Slope debris under forest | F₃: Sandy soil under forest | F₄: All sites under forest |
| Number of samples (n) | 34 | 53 | 28 | 81 |
| Determination coefficient \( r^2 \) | 0.58 | 0.26 | 0.06 | 0.06 |
| Permafrost table depth | | | | |
| Arithmetic mean (cm) | 184 | 96 | 160 | 118 |
| Maximum/minimum (cm) | 380/75 | 200/40 | 200/73 | 200/40 |
| RMSE (cm) | 40.4 | 26.4 | 23.3 | 40.3 |
| Mean NDVI | | | | |
| \( p \) Value | 0.00 | 0.00 | 0.31 | 0.39 |
| Mean value/standard deviation | 0.43/0.05 | 0.51/0.02 | 0.52/0.02 | 0.51/0.02 |
| ASRI | | | | |
| \( p \) Value | 0.01 | 0.02 | 0.32 | 0.04 |
| Mean value/standard deviation (kW h m\(^{-2}\)) | 1141/57 | 1045/47 | 1064/85 | 1051/63 |
| TWI | | | | |
| \( p \) Value | 0.04 | 0.01 | 0.27 | 0.24 |
| Mean value/standard deviation | 4.97/0.74 | 4.22/0.41 | 4.35/0.61 | 4.27/0.49 |
the depth of the permafrost table in forests and then added 1 m to the permafrost-table depth for forests on sandy soils. This adjustment was based on our field observation that the permafrost table was up to 1 m deeper in sandy soils compared to soils in slope debris (cf. Section 4.2). Subsequent validation of the delineated depth of the permafrost table including all 115 plots yielded a correlation coefficient of $r^2 = 0.58$ between empirical and modelled data (Figure A2).

The final delineation of permafrost distribution and depth of the permafrost table was achieved by combining the qualitative relationship between forests with permafrost (Figure 5) and the quantitative results of the linear regression terms for landscape units in which permafrost occurs (Figure 6). The maximum depth was set to 300 cm, as this depth represented the maximum penetration depth of the 400 MHz GPR antenna and the maximum sediment thickness on the slopes. Thus, possible occurrences of permafrost at more than 300 cm depth were not considered.

Permafrost in the steppe area was limited to the direct vicinity of large forests. The depth of the permafrost table there was between 200 and > 300 cm. Permafrost was absent on south-facing slopes and in most basin areas. North of Tosontsengel, permafrost was scarce.

**Figure 6** Delineated permafrost distribution and calculated depth of the permafrost table in the study area. The shaded relief is based on TanDEM-X data. No permafrost was identified in the non-coloured areas [Color figure can be viewed at wileyonlinelibrary.com]
Under fragmented forests, permafrost occasionally occurred below 150 cm. Sandy soils under forest had permafrost starting between 200 and 300 cm. Inside large and dense forests, the depth of the permafrost table generally decreased downslope, from 200 cm on the upper slopes to < 50 cm at the lower forest boundary. On the mountain crests in the FDA, the permafrost delineation pointed to absence of permafrost or deep permafrost table (~300 cm).

Permafrost was widespread under peat and swampy meadows in the alluvial plains. This is in accordance to observations by Shur and Jorgenson (2007) in the zone of discontinuous permafrost of Alaska. However, no permafrost was found in floodplains near rivers and under riparian forests. Dunes in the basins, and the periglacial zone in the highest mountains were not included in this study.

5 | DISCUSSION

5.1 Soil properties and vegetation controlling permafrost distribution and depth of the permafrost table

The observed influence of relief and soil texture on the depth of the permafrost table can be explained as follows. Three soil-physical parameters control permafrost-table depth in the region of discontinuous permafrost in semi-arid environments. These are thermal conductivity, thermal capacity and water content. Soil moisture and ground ice increase thermal conductivity. The high thermal capacity of ground ice makes ice-rich permafrost more resilient to thawing, compared to dry permafrost, because of the heat that is required to melt the ice. Soil texture is important, too, as water can easily infiltrate into sandy material, but sand has a low water holding capacity. Thus, the upper 10 cm of a dry, sandy soil quickly warms up, whereas the low thermal conductivity of dry sand limits soil-temperature changes at greater depth.

The influence of vegetation cover was also investigated by Dashtseren et al. (2014). Based on soil-temperature measurements in the forest-steppe region of the Khentii Mountains in northern Mongolia, they suggested that mountain-steppe supports only seasonally frozen ground, whereas a forest cover maintains permafrost, as it reduces soil exposure to insolation, and thick organic layers occurring under forest additionally insulate the soils from high summer air temperatures. The authors concluded that active-layer thickness is controlled by summer temperatures. Thermal conductivity of organic layers and mosses substantially changes with their water content. During winter, a wet organic layer (having high thermal conductivity) promotes soil freezing. During summer, a dry organic layer (having low thermal conductivity) reduces soil warming. In winter, the insulating effect of a snow cover controls soil temperature in seasonally frozen ground (Dashtseren et al., 2014; Lehmkuhl & Klinge, 2000; Zhang, 2005). Zhang (2005) suggested a snow-cover thickness of 40 cm as optimum thickness for insulating soils from low air temperatures. A thinner snow cover allows for propagation of low temperatures into the soils in winter, whereas a thicker snow cover persists longer during spring, delaying the beginning of insolation of the soil. Due to the stable Siberian high-pressure cell during winter, snow-cover thickness in Mongolia does generally not exceed 10–15 cm (Nyamjav et al., 2007), and its spatial distribution in Mongolia is limited (Middleton et al., 2015). However, in certain years an extensive snow cover occurs, leading to episodic hazardous events known as Dzuud.

Ishikawa et al. (2018) calculated a mean active-layer thickness of 300 to 400 cm for the zones of continuous and discontinuous permafrost in Mongolia. Wu et al. (2009, 2012) used GPR to detect the permafrost table under steppe in a basin near Ulaanbaatar, where it occurred at depths between 200 and 400 cm. In the forest-steppe of northern Mongolia, Kopp et al. (2014) reported permafrost at 70 cm depth under forest on north-facing slopes, whereas permafrost was absent on south-facing slopes under steppe and in burned forest areas. Our observations of a permafrost-table depth between 50 and > 300 cm in the northern Khangai Mountains match well with these findings.

5.2 Influence of fire and forest exploitation on permafrost

The main factors controlling permafrost and their effects in the various geoeological units of the forest-steppe are summarized in Table 3. As discussed in the previous section, forests promote permafrost. As a positive feedback mechanism, meltwater released from seasonal ice above the permafrost supports them to persist through droughts and fire events. Selective logging and non-lethal forest fire lead to a lowering of the permafrost table, whereas clear-cutting and severe forest fires lead to permafrost degradation (Shur & Jorgenson, 2007). Fires destroyed many of the large forests in the high-mountain area (Figure 5). In the burned areas, permafrost has largely disappeared. In contrast to large closed forests, forest fires can less easily propagate across small, fragmented forests. This explains why forest fires are less extensive in the steppe-dominated area. Relief strongly controls the

| Ecological parameter | Pristine forest | Degraded forest | Steppe | Burned forest | Forest succession |
|----------------------|-----------------|-----------------|--------|---------------|------------------|
| Canopy shading       | high            | low             | no     | no            | high             |
| Ground vegetation    | dense mosses, grasses, shrubs | sparse grasses | sparse grasses | sparse grasses, herbs, shrubs | sparse grasses |
| Organic layer        | thick           | shallow         | missing| missing       | shallow          |
| Thermal insulation   | high            | medium          | low    | low           | medium           |
| Permafrost table     | shallow         | deep            | missing| missing       | deep/missing     |
| Physical soil conditions | cool/wet      | warm/dry        | hot/dry| hot/dry       | cool/dry         |

Table 3 Geoeological factors controlling soil moisture and permafrost distribution in different vegetation units
pattern of forest disturbance and regrowth after fire (Figure A4a). For instance, larch trees on toe slopes and in depressions, where soil moisture is enhanced, often survive forest fires (Dorjsuren, 2009). Such patches of remaining trees form nuclei of forest regrowth. They are often surrounded by belts of different tree generations (Figure A4a). From there, forest regeneration slowly proceeds into the burned area, as larch seeds do not spread very far, and seedlings mainly grow near their parent trees (Dugarjav, 2006). The shading effect and moist soils under deadwood and remaining living trees improve the conditions for seedlings (Figure A4d).

Because of the mutual positive feedback between forest and permafrost, the speed and spatial pattern of this forest regeneration process also controls permafrost re-establishment. Fedorov et al. (2017) showed for a disturbed larch forest in the zone of continuous permafrost in Yakutia that permafrost regenerates with the succession of vegetation. According to Nyamjav et al. (2007), it may take up to 200 years until a forest regenerates to its state prior to the fire. In the semi-arid environment of our study area, larch seedlings require several consecutive moist years, allowing them to root deep enough to survive also a drier year. This explains the strong age grouping of larch forests in the Altai Mountains reported by Sommer and Treter (1999). They argued that dry years and fires often destroy several generations of seedlings, before a tree generation can finally establish.

Soil moisture plays a decisive role for both, forest regrowth and permafrost re-establishment. In Alaska, Jorgenson et al. (2013) found that permafrost in silty soils even persisted after forest fire, due to high water capacity and ice content of these soils, whereas permafrost in sandy and gravelly soils mostly disappeared after fire. Kopp et al. (2014) and Lange et al. (2015) compared soil moisture and water fluxes under pristine forests, burned forests and steppes on south-facing slopes in the Khentei Mountains. They found high infiltration of precipitation into soils under intact and burned forests. The permafrost layer under intact forests retained the moisture in the soils. Without permafrost, the water was lost through deep percolation. The authors assumed a short-term water loss under burned forests due to permafrost degradation. On south-facing steppe-covered slopes, Lange et al. (2015) observed that water infiltrated only a few centimetres into the soil and then evaporated.

Permafrost re-establishment after forest disturbance differs considerably between the zones of discontinuous and continuous permafrost. In the zone of continuous permafrost, soils usually have high water and ice contents. After forest disturbance, the soils warm up. The released meltwater is perched above the permafrost table, increasing the thermal conductivity of the soil, which in turn results in partial permafrost degradation (Fedorov et al., 2017). In the region of discontinuous permafrost in semi-arid Mongolia, soil moisture is limited, with strong relief-controlled differences, leading to spatially differing permafrost re-establishment after forest disturbance.

Based on our field observations, we suggest the following causal chains: Abundant deadwood maintains soil moisture, allowing for dense tree succession after fire, in turn supporting permafrost re-establishment. Without deadwood, tree regrowth and, thus, permafrost re-establishment, are hampered (Figure A4c). Hence, with respect to the permafrost formation-degradation scheme of Shur and Jorgenson (2007), discontinuous permafrost in our study area is in-between climate-induced, ecosystem-driven and ecosystem-protected. Under natural conditions without climate warming, permafrost would re-establish contemporaneously with forest regrowth. However, permafrost already disappeared in small fragmented forests. Dead-tree margins at the edges of many forest stands point to ongoing soil-moisture decrease, induced by climate warming (Figure A4b). With climate warming, permafrost in this region will become totally ecosystem-protected and will thus not regenerate after forest disturbance any longer. Zhang et al. (2011) modelled the larch-taiga permafrost system in Siberia under climate warming. They predicted that this coupled system cannot persist if warming exceeds 2°C. Tchekabova et al. (2009) modelled potential vegetation changes across Siberia based on climate-change scenarios, predicting a decrease of forest areas and a northward shift of the present Siberian biomes. Aridity and increased tree mortality would trigger more frequent and more severe wildfires, in turn accelerating permafrost disappearance.

6 | CONCLUSIONS

Combining remote sensing, field measurements and statistical analyses enabled us to locate permafrost patches and to estimate the depth of the permafrost table in the central-Mongolian forest-steppe. The most significant correlations were found between permafrost-table depth and TWI, potential ASRI, and mean NDVI. These parameters allow for predicting permafrost-table depth. Sandy soil texture, however, may lead to a 100 cm deeper permafrost table, contributing to drier conditions in sandy soils under forest compared to soils developed in slope debris.

The hypothesis that discontinuous permafrost in our study area is limited to large forests on north-facing slopes and directly adjacent steppes was verified. Permafrost was not encountered in small fragmented forests, even on north-facing slopes. We found that scattered patches of peat support permafrost, whereas no permafrost occurs in riparian forests.

Forests and permafrost form a mutually interlinked ecological system in the cold, semi-arid forest-steppe environment. Canopy shading of forests, and insulation of soils by organic layers and moss covers favour permafrost formation and preservation in large forest stands. Shallow depth of the permafrost table prevents deep percolation of meltwater from seasonal ice, thus keeping this important moisture reservoir available for tree roots. Progressive melting of ground ice replenishes soil moisture over summer and may support trees especially during summer droughts. Lateral meltwater flow above the permafrost table also enhances the vitality of steppe and broadleaf vegetation on the toe slopes, below the forests.

Opening of forest stands by logging decreases the shading effect and the amount of tree litter. This leads in turn to thinning of the insulating organic layer, enhanced soil warming and drying, and thus, deepening of the permafrost table and potential loss of permafrost. Thus, intense forest exploitation leads to drier conditions and increases the forests’ vulnerability to drought and risk of fire. At sites with unfavourable soil conditions, clear cutting may lead to irreversible loss of permafrost and a shift to permanent steppe vegetation.

We found that permafrost has mostly disappeared after extensive forest fires in the study area. Tree regrowth and permafrost reconstitution, however, are highly variable, depending on the site conditions. At sites with favourable geoeological conditions, such as concave relief positions, permafrost and some trees may persist after fire. These sites form nuclei, from where dense tree succession may take
place where large forests existed previously. In contrast, disturbed forests in the steppe-dominated area, where no permafrost is present today, hardly recover after fire. Under the currently ongoing climate warming, permafrost in the central-Mongolian forest-steppe is in transition from climate- and ecosystem-triggered (active formation) to ecosystem-preserved (passive). Fragmented forests in the steppe-dominated area still persist without permafrost, but they will most likely disappear after fire or logging. Large forest stands still enable permafrost reconstitution after disturbance, but they will lose this ability in the course of climate warming.

DATA AVAILABILITY STATEMENT
This study used satellite data that were publicly available from US Geological Survey (USGS) Earth Resources Observation and Science (EROS) Centre (https://earthexplorer.usgs.gov/). The dataset produced in the present study is available from the corresponding author on request.

ACKNOWLEDGEMENTS
The authors thank Daramragchaa Tuya from the Tarvagatai Nuruu National Park (Tosontsengel Sum, Zavkhin Aimag, Mongolia) for her invaluable support of our research. The authors also express gratitude to their Mongolian colleagues Amarbayasgalan, Enkhjargal, Enkh-Agar, and Munkhtuya. The authors greatly appreciated their hospitality and help with the fieldwork. Thanks also go to the German students Jannik Brodthuhn, Janin Klaassen, Tino Peplau, and Tim Rollwage for their great support in soil and vegetation mapping during the fieldwork in Mongolia. Valuable comments by Michael Fritz helped to improve the manuscript and were highly appreciated.

The German Aerospace Centre (DLR) liberally provided the TanDEM-X data for the study area (DEM_FOREST 1106). The research project was funded by the Deutsche Forschungsgemeinschaft (DFG), project number 38546042.

CONFLICT OF INTEREST
The authors declare that there is no conflict of interest.

ORCID
Michael Klinge https://orcid.org/0000-0001-5374-9363
Florian Schneider https://orcid.org/0000-0001-8286-3237
Uudus Bayarsaikhan https://orcid.org/0000-0003-1303-4739

REFERENCES
Academy of Sciences of Mongolia. (1990) Academy of Sciences of USSR. Ulan Batar, Moscow: National Atlas of the Peoples Republic of Mongolia.
Batima, P., Natsagdorj, L., Gomblauudev, P. & Erdenetsetseg, B. (2005) Observed climate change in Mongolia. AIACC Working Papers, 12, 1–25.
Böhner, J. & Lehnhukh, F. (2005) Environmental change modelling for central and high Asia: Pleistocene, present and future scenarios. Boreas, 34(2), 220–231.
Conrad, O., Bechtel, B., Bock, M., Dietrich, H., Fischer, E., Gerlitz, L. et al. (2015) System for Automated Geoscientific Analyses (SAGA) v. 2.1.4, Geoscientific Model Development, 8(7), 1991–2007. https://doi.org/10.5194/gmd-8-1991-2015
Dagvadorj, D., Natsagdorj, L., Dorjiyurev, J. & Namkhainyam, B. (2009) Mongolia Assessment Report on Climate Change 2009. Ulaanbaatar, Mongolia.

Dashtsuren, A., Ishikawa, M., Ilijima, Y. & Jambaljav, Y. (2014) Temperature regimes of the active layer and seasonally frozen ground under a forest-steppe mosaic, Mongolia. Permafrost and Periglacial Processes, 25(4), 295–306. https://doi.org/10.1002/ppp.1824
De Pascale, G.P., Pollard, W.H. & Williams, K.K. (2008) Geophysical mapping of ground ice using a combination of capacitive coupled resistivity and ground-penetrating radar, Northwest Territories, Canada. Journal of Geophysical Research, 113(F2), 68.
Dorjsuren, C. (2009) Anthropogenic succession in larch forests of Mongolia (in Russian), Biological Resources and Natural Conditions of Mongolia, 50, 1–260.
Dugarjav, C. (2006) Larch forests of Mongolia (in Mongolian). Bembi San: Ulan Batar.
Dulamsuren, C. & Hauck, M. (2008) Spatial and seasonal variation of climate on steppe slopes of the northern Mongolian mountain taiga. Grassland Science, 54(4), 217–230. https://doi.org/10.1111/j.1744-697X.2008.00128.x
Dulamsuren, C., Hauck, M., Khishigjargal, M., Leuschner, H.H. & Leuschner, C. (2010) Diverging climate trends in Mongolian taiga forests influence growth and regeneration of Larix sibirica. Oecologia, 163(4), 1091–1102. https://doi.org/10.1007/s00442-010-1689-y
Dulamsuren, C., Hauck, M. & Leuschner, C. (2010) Recent drought stress leads to growth reductions in Larix sibirica in the western Khentey, Mongolia. Global Change Biology, 16, 3024–3035.
Dulamsuren, C., Khishigjargal, M., Leuschner, C. & Hauck, M. (2014) Response of tree-ring width to climate warming and selective logging in larch forests of the Mongolian Altai. Journal of Plant Ecology, 7(1), 24–38. https://doi.org/10.1093/jpe/rtt019
Dulamsuren, C., Klinge, M., Bat-Enerel, B., Ariunbaatar, T. & Tuya, D. (2019) Effects of forest fragmentation on organic carbon pool densities in the Mongolian forest-steppe. Forest Ecology and Management, 433, 780–788. https://doi.org/10.1016/j.foreco.2018.10.054
Etzelmüller, B., Heggem, E.S.F., Shakhnou, N., Frauenfelder, R., Kåå, A. & Goulden, C. (2006) Mountain permafrost distribution modelling using a multi-criteria approach in the Hövsgöl area, northern Mongolia. Permafrost and Periglacial Processes, 17(2), 91–104. https://doi.org/10.1002/ppp.554
FAO. (2006) Guidelines for soil description. Rome: Food and Agriculture Organization of the United Nations.
Fedorev, A.N., Iwahana, G., Konstantinov, P.Y., Machimura, T., Argunov, R.N., Efremov, P.V. et al. (2017) Variability of permafrost and landscape conditions following clear cutting of larch forest in central Yakutia. Permafrost and Periglacial Processes, 28(1), 331–338. https://doi.org/10.1002/ppp.1897
French, H.M. (2018) The periglacial environment. Hoboken, NJ: Wiley Blackwell.
Goldammer, G. (2002) Fire situation in Mongolia. International Forest Fire News, 26, 75–83.
Gruber, S. (2012) Derivation and analysis of a high-resolution estimate of global permafrost zonation. The Cryosphere, 6(1), 221–233. https://doi.org/10.5194/tc-6-221-2012
Hais, M., Chtryt, M. & Horsák, M. (2016) Exposure-related forest-steppe: A diverse landscape type determined by topography and climate. Journal of Arid Environments, 135, 75–84. https://doi.org/10.1016/j.jaridenv.2016.08.011
Hansen, M.C., Potapov, P.V., Moore, R., Hancher, M., Turubanova, S.A., Tyukavina, A. et al. (2013) High-resolution global maps of 21st-century forest cover change. Science (New York, N.Y.), 342(6160), 850–853. https://doi.org/10.1126/science.1244693
Hessl, A.E., Ariya, U., Brown, P., Byambasuren, O., Green, T., Jacoby, G. et al. (2012) Reconstructing fire history in central Mongolia from tree-rings. International Journal of Wildland Fire, 21(1), 86. https://doi.org/10.1071/WF10108
Hilbig, W. (1995) The vegetation of Mongolia. Amsterdam: SPB Academic Publishing.
Hinkel, K.M., Doolittle, J.A., Bockheim, J.G., Nelson, F.E., Paetzold, R., Kimble, J.M. & Travis, R. (2003) Detection of subsurface permafrost...
features with ground-penetrating radar, Barrow, Alaska. Permafrost and Periglacial Processes, 12(2), 179–190. https://doi.org/10.1002/ppp.369

Ilijima, Y., Ishikawa, M. & Jambaljav, Y. (2012) Hydrological cycle in relation to permafrost environment in forest-grassland ecotone in Mongolia. (in Japanese with English abstract). Journal of Japanese Association of Hydrological Sciences, 42, 119–150.

Ishikawa, M., Jamvaljav, Y., Dashtseren, A., Sherkhnu, N., Davaa, G., Ilijima, Y. et al. (2018) Thermal states, responsiveness and degradation of marginal permafrost in Mongolia. Permafrost and Periglacial Processes, 29(4), 271–282. https://doi.org/10.1002/ppp.1990

IUSS Working Group WRB. (2015) World reference base for soil resources 2014, update 2015. International soil classification system for naming soils and creating legends for soil maps. Rome: Food and Agriculture Organization of the United Nations.

Jorgenson, M.T., Harden, J., Kanevskiy, M., O’Donnell, J., Wickland, K., Ewing, S. et al. (2013) Reorganization of vegetation, hydrology and soil carbon after permafrost degradation across heterogeneous boreal landscapes. Environmental Research Letters, 8(3), 35017. https://doi.org/10.1088/1748-9326/8/3/035017

Karine, D., Maley, M., Kopp, B.J., Minderlein, S. & Hülsmann, L. (2013) Assessing water availability and its drivers in the context of an Integrated Water Resources Management (IWRM): A case study from the Kharaa River Basin, Mongolia. Geokööko, 34(5–6), 5–26.

Kharasintoreh, E., Dulamsuren, C., Klinge, M., Ariunbaatar, T., Batburev, P., Schlütz, F. et al. (2018) Thermal states, responsiveness and degradation of marginal permafrost in Mongolia. Permafrost and Periglacial Processes, 29(4), 271–282. https://doi.org/10.1002/ppp.1990

Klinge M, Schneider F, Dulamsuren C, Sommer M & Treter U. (1999) Die Lärchenwälder der Gebirgswaldsteppe of marginal permafrost in Mongolia. Earth Surface Processes and Landforms, 107, 183–192.

Klinge, M. & Sauer, D. (2019) Spatial pattern of Late Glacial and Holocene of marginal permafrost in Mongolia. Environmental Research Letters, 6(2), 024003. https://doi.org/10.1088/1748-9326/6/2/024003

Pelletier, J.D., Barron-Gafford, G.A., Gutiérrez-Jurado, H., Hinckley, E.L.S., Istanbulluoglu, E., McGuire, L.A. et al. (2018) Which way do you lean? Using slope aspect variations to understand critical zone processes and feedbacks. Earth Surface Processes and Landforms, 43(5), 1133–1154. https://doi.org/10.1002/esp.4306

Richter, H., Haase, G. & Barthel, H. (1963) Die Golezterrassen. Petermanns Geographische Mitteilungen, 107, 183–192.

Schütz, F., Dulamsuren, C., Wieckowska, M., Mühlenberg, M. & Hauck, M. (2008) Late Holocene vegetation history suggests natural origin of steppe in the northeastern Mongolian mountain taiga. Palaeogeography, Palaeoclimatology, Palaeoecology, 261(3–4), 203–217. https://doi.org/10.1016/j.palaeo.2007.12.012

Sharkhnu, N. (2003) Recent changes in the permafrost of Mongolia. In: Phillips, M., Springman, S.M. & Arenson, L.L. (Eds.) Proc. 8th Int. Conf. Permafrost, 21–25 July 2003, Zurich, Switzerland. Lisse: Swets & Zeitlinger. 95–102. https://doi.org/10.1007/978-94-007-3866-7_17

Shur, Y.L. & Jorgenson, M.T. (2007) Patterns of permafrost formation and degradation in relation to climate and ecosystems. Permafrost and Periglacial Processes, 18(1), 7–19. https://doi.org/10.1002/ppp.582

Sommer, M. & Treter, U. (1999) Die Lärchenwälder der Gebirgswaldsteppe in den Randgebieten des Uvur-Beckens. Die Erde, 130, 173–188.

Sterkel, L. (1998) Geomorphic response to climatic and environmental changes along a Central Asian transect during the Holocene. Geomorphology, 23(2-4), 293–305. https://doi.org/10.1016/S0167-9800(98)00011-7

Sugimoto, A., Naito, D., Yanagisawa, N., Ichiyamagi, K., Kurita, N., Kubota, J. et al. (2003) Characteristics of soil moisture in permafrost observed in East Siberian taiga with stable isotopes of water. Hydrological Processes, 17(6), 1073–1092. https://doi.org/10.1002/hyp.1180

Sugimoto, A., Yanagisawa, N., Naito, D., Fujita, N. & Maximov, T.C. (2002) Importance of permafrost as a source of water for plants in east Siberian taiga. Ecological Research, 17(4), 493–503. https://doi.org/10.1046/j.1440-1733.2002.00506.x

Tcherebakova, N.M., Parfenova, E. & Soja, A.J. (2009) The effects of climate, permafrost and fire on vegetation change in Siberia in a changing climate. Environmental Research Letters, 4(4), 45013. https://doi.org/10.1088/1748-9326/4/4/045013

Tsogtbaatar, J. & Ichihara, C. (2000) Deforestation and reforestation needs in Mongolia. Forest Ecology and Management, 171(1), 57–63. https://doi.org/10.1016/S0378-1127(00)00228-5

Tsogtbaatar, J. & Ichihara, C. (2000) Deforestation and reforestation needs in Mongolia. Forest Ecology and Management, 171(1), 57–63. https://doi.org/10.1016/S0378-1127(00)00228-5

Wu, T., Wang, Q., Watanabe, M., Chen, J. & Battogtogh, D. (2009) Mapping vertical profile of discontinuous permafrost with ground penetrating radar at Nalikha depression, Mongolia. Environmental Geology, 56(8), 1577–1583. https://doi.org/10.1007/s00254-008-1255-7

Wu, T., Wang, Q., Zhao, L., Du, E., Wang, W., Batkhishig, O. et al. (2012) Investigating internal structure of permafrost using conventional methods and ground-penetrating radar at Honhor basin, Mongolia. Environmental Earth Sciences, 67(7), 1869–1876. https://doi.org/10.1007/s12665-012-1629-8

Yershov, E.D. & Williams, P.J. (2009) General Geocryology. Cambridge: Cambridge University Press.

Zhang, N., Yasunari, T. & Ohta, T. (2011) Dynamics of the larch taiga-permafrost coupled system in Siberia under climate change. Environmental Research Letters, 6(2), 24003. https://doi.org/10.1088/1748-9326/6/2/024003

Zhang, T. (2005) Influence of the seasonal snow cover on the ground thermal regime: An overview. Reviews of Geophysics, 43(4), 1.
APPENDIX A.

Results of GPR analyses

In the GPR images, the depth of the permafrost table is detectable as a distinct continuous reflector cutting through any sedimentary structures (Figure A5). The depth of the permafrost table increases with decreasing tree density. Transects A and B in Figure A5 are on slope debris of metamorphic rock under forest. Transect A lies in a pristine forest with dense ground vegetation consisting of mosses, herbs and shrubs. Logging is limited to a few patches at the lower forest boundary. Deadwood and windthrown trees are widespread. Ice-rich permafrost was found at less than 1 m depth in many soil pits. The soils were generally moist. The shallow active layer of < 0.8 m under the dense forest is also visible in the GPR image. The depth of the

---

**FIGURE A1** Flowchart illustrating input and output data, and the GIS-analysis process flows. The uppermost boxes list all data sources. Multispectral satellite images (blue), digital elevation data (grey), intermediate data (green), output data (yellow), final delineation of permafrost occurrence (pink) [Color figure can be viewed at wileyonlinelibrary.com]

**FIGURE A2** Relation between measured and calculated depths of the permafrost table. Depths of the permafrost table under steppe and under forest were calculated by the equations obtained for steppe (F1) and for forest on slope debris (F2). Therefore, 100 cm were added for the 28 forest plots on sandy soils, because our field observations had revealed a generally deeper permafrost table for sandy soils. The black dotted line indicates the linear regression of all 115 plots and the correlation coefficient (p < 0.005); the green dotted line indicates the linear regression of the 81 forest plots and the correlation coefficient (p < 0.005) [Color figure can be viewed at wileyonlinelibrary.com]
permafrost table increases to about 1 m where the forest has been opened. The high water and ice content strongly attenuate the GPR signal. Transect B is in an area of intense logging that caused an opening of the forest stand in the lower part. As shown in the GPR image, the depth of the permafrost table, as well as the depth of the moist zone above it, decreases downslope from < 1 m depth under the dense forest along the open forest to more than 1.8 m depth under steppe. The reflector signals in the sediment display an imbricated structure of several colluvial layers.

Transects C and D are located on a toe slope with regrowth of young and dense-growing larch trees after a forest fire ~20 year ago (Hansen et al., 2013). Transect C is on sandy material, which shows imbricated sediment structures and a development similar to transects A and B. The permafrost table in profile C is at 1 m depth. The corresponding reflector in the GPR image slightly shifts from 0.8 m depth under the remaining forest along the young forest to more than 1.2 m depth under steppe. The soil above the permafrost table was dry at the time the soil pits were dug. High ice content attenuates the radar signal below the permafrost table. Transect D is situated on glacial till, which contains abundant granite boulders causing numerous hyperbolas in the GPR image. Few distinct reflectors might indicate different moraine layers in the lower part and colluvial layers in the upper part. The permafrost table was identified at 2–2.5 m depth under forest regrowth and at > 3 m depth in the area where no tree regrowth takes place yet.

Transects E and F in Figure A5 are on sandy soil, in the transition zone from forest to steppe. The depth of the permafrost table increases from ~1.5 m under dense forest to 3 m under steppe. This trend already starts with the opening of the forest at the lower forest boundary. An approximately parallel reflector occurs above the permafrost table. It can be interpreted as the upper limit of a moist zone. Although the soils predominately consist of aeolian sand, the sediment includes colluvial sandy and stony layers and horizons with carbonate accumulation. In the GPR image, the reflectors that approach...
FIGURE A5  GPR images with interpretation of sedimentary structures, permafrost table and vegetation cover. The transects run along slopes at the lower forest boundary. The inclinations of the GPR images were adjusted to the mean gradient of the slopes. (a) Pristine forest on soils developed in slope debris, (b) forest with logging on soils developed in slope debris, (c) forest on sandy soils, in the process of regrowth after forest fire, (dd) forest on glacial till, in the process of regrowth after forest fire, (e,f) forest on sandy soils influenced by logging, (g) horizontal transect from a dead-tree margin into a forest [Color figure can be viewed at wileyonlinelibrary.com]

TABLE A1  Dimensions (km²) of the calculated landscape units in the study area

| Vegetation                  | SDA  | FDA  | HMA  | Alluvial plain |
|-----------------------------|------|------|------|----------------|
| Forest without permafrost   | 79   | 387  | 11   | Forest 7       |
| Forest with permafrost      | 4    | 487  | 75   | Peat 26        |
| Steppe                      | 1.050| 2034 | 1709 | Steppe 464     |
| Sum                         | 1.133| 2.908| 1795 | 497            |

Note: SDA, steppe-dominated area; FDA, forest-dominated area; HMA, high-mountain area.
the soil surface in downslope direction indicate an imbricated structure of colluvial layers. Periglacial processes during the late Pleistocene and early Holocene, and slope-wash processes after destructive fire events led to the formation of cover beds and colluvial layers on the slopes. Surface-parallel structures below the permafrost table indicate the transition zone to the bedrock.

Transect G runs horizontally from a rocky ridge with shallow, stony soils, bordering a small forest stand with dead-tree margin, into a slope depression in the centre of the small open forest. In the left part of the GPR image, reflector signals indicate bedrock. Wide hyperbolas point to boulders, but no permafrost table can be identified. In the right part of the image, layered slope sediments, a permafrost table, and a moist zone above the permafrost table are indicated by respective reflector signals and signal attenuation below. Due to the absence of ground ice that would provide a supplementary water reservoir and due to the low soil water capacity, trees growing on the shallow stony soils at the forest margins are seriously affected by droughts.