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Climate effects on the vitality of boreal forests at the treeline in different ecozones of Mongolia

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Abstract

In northern Mongolia, at the southern boundary of the Siberian boreal forest belt, the distribution of steppe and forest is generally linked to climate and topography, making this region highly sensible to climate change. Detailed investigations on the limiting parameters of forest and steppe occurrence in different ecozones provide necessary information for environmental modelling and scenarios of potential landscape change. In this study, remote sensing data and gridded climate data were analyzed in order to identify distribution patterns of forest and steppe in Mongolia and to detect driving ecological factors of forest occurrence and vulnerability against environmental change. With respect to anomalies in extreme years we integrated the climate and land cover data of a 15 year period from 1999-2013. Forest distribution and vegetation vitality derived from the normalized differentiated vegetation index (NDVI) were investigated for the three ecozones with boreal forest present in Mongolia (taiga, subtaiga, and forest-steppe). In addition to the entire ecozone areas, the analysis focused on different subunits of forest and non-forested areas at the upper and lower treeline, which represent ecological borderlines of site conditions.

The total cover of boreal forest in Mongolia was estimated at 73,818 km^2. The upper treeline generally increases from 1,800 m above sea level (a.s.l.) in the Northeast to 2,700 m a.s.l. in the South. The lower treeline locally emerges at 1,000 m a.s.l. in the northern taiga and is rising southward to 2,500 m a.s.l. The latitudinal trend of both treelines turns into a longitudinal trend in the east of the mountains ranges due to more aridity caused by rain-shadow effects. Less vital trees were identified by NDVI at both, the upper and lower treeline in relation to the respective ecozone. The mean growing season temperature (MGST) of 7.9-8.9 °C and a minimum of 6 °C was found to be a limiting parameter at the upper treeline but negligible for the lower treeline and the total ecozones. The minimum of the mean annual precipitation (MAP) of 230-290 mm y^{-1} is an important limiting factor at the lower treeline but at the upper treeline in the forest-steppe ecotone, too. In general, NDVI and MAP are lower in grassland, and MGST is higher compared to the forests in the same ecozone. An exception occurs at the upper treeline of the subtaiga and taiga, where the alpine vegetation is represented by meadow mixed with shrubs. Comparing the NDVI with climate data shows that increasing precipitation and higher temperatures generally lead to higher greenness in all ecological subunits. While the MGST is positively correlated with the MAP of the total ecozones of the forest-steppe, this correlation turns negative in the taiga ecozone. The subtaiga represents an ecological transition zone of approximately 300 mm y^{-1} precipitation, which occurs independently from the MGST. Nevertheless, higher temperatures lead to higher vegetation vitality in terms of NDVI values.

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Climate change leads to a spatial relocation of tree communities, treelines and ecozones, thus an interpretation of future tree vitality and biomass trends directly from the recent relationships between NDVI and climate parameters is difficult. While climate plays a major role for vegetation and treeline distribution in Mongolia, the disappearing permafrost needs to be accounted for as a limiting factor for tree growth when modeling future trends of climate warming and human forest disturbance.

1. Introduction

Due to the highly continental environment in northern Central Asia, Mongolia is subjected to dry and cool climate conditions. The landscape and vegetation development is highly sensitive to changes in temperature and/or precipitation. However, this is not a uniform phenomenon throughout the entire region. The intensity and impact of climate parameters on vegetation is strongly varying in space and time caused by different factors like topography, latitude and air circulation. Corresponding to the change of the climatic conditions from cold semi humid in the north to arid in the south a latitudinal zonation of the vegetation occurs, which is modified by an altitudinal zonation in the mountainous landscape (Hilbig, 1995). From north to south, these vegetation belts include taiga, subtaiga, forest-steppe, steppe, and the Gobi desert. Taiga, subtaiga, and forests in the forest-steppe ecotone represent the southern edge of the Eurosiberian boreal forest, whereas the steppes are part of the Mongolian-Chinese steppe region. The distribution of the different vegetation belts, ecozones, and treelines is controlled by air temperature, evapotranspiration, and precipitation (Walter and Breckle, 1994). Moisture conditions are regarded to be a main limiting factor for the distribution of the desert and steppes ecozones as well as for the lower boundary of mountain forests at the transition to drylands. In contrast, thermal conditions control the upper treeline and the alpine ecozone (Körner, 2012; Klinge et al., 2003, 2015; Paulsen and Körner, 2014). Both, the upper and the lower treeline of Mongolia's boreal forests represent an obvious visual boundary between biomes of highly different ecological requirements, though their actual state can be strongly influenced by human impact (Klinge et al., 2015). Trees grow and exist for several decades or centuries and establish an autochthonous microclimate below the canopy, thus forests are representing mean climatic conditions of a longer period. In contrast, the vitality of annual or perennial grasses and herbs of the steppes and meadows respond to inter-annual variation in climate conditions and the vegetation density represents small-scale periods (Bat-Oyun et al., 2016).

Mean air temperature during the growing season (MGST) is more relevant for describing the thermal environment at the upper forest line than mean annual air temperature, because temperatures from the non-growing cold season only play a minor role in tree growth (Jobbágy and Jackson, 2000; Körner, 2012; Körner and Paulsen, 2004). Based on worldwide empirical data Körner and Paulsen (2004) stated that the minimum MGST of 5.5 to 7.5 °C and the mean temperature of 6.4 °C during a period of daily temperatures >0.9 °C in a minimum growing season of 94 days (Paulsen and Körner, 2014) are better definitions for the upper treeline in a global context than the commonly used warmest month isotherm of 10 °C (Walter and Breckle, 1994). A lower treeline occurs in the semi-arid region of Central Asia between relatively humid mountain regions and arid basins. The forest distribution is generally limited by annual precipitation, which has its minimum between 300 and 200 mm y^{-1} (Dulamsuren et al., 2010a; Holdridge, 1947; Miehe et al., 2003; Walter and Breckle, 1994). Dulamsuren et al., (2010a) proved an annual precipitation between 230 and 400 mm for larch trees (*Larix sibirica*) at the lower forest boundary in northern and central Mongolia. However, additional soil water supply from upslope and from melting permafrost ice supports tree growth at lower elevations where rainfall is insufficient. Furthermore, drought periods can be temporarily bridged by the soil ice reservoir. This explains why Dulamsuren et al. (2014) found coniferous forests in regions with an annual precipitation of around 120 mm in the Altai Mountains in western Mongolia.

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Dulamsuren and Hauck (2008) and Dulamsuren et al. (2010a, 2010b) investigated the ecological conditions in the forest-steppe ecotone of Mongolia, where steppe and forest alternate in short distances. In the forest-steppe, the spatial distribution of vegetation is highly correlated with relief parameters (Hais et al., 2016; Klinge et al., 2015). Less solar radiation input causes lower temperatures and reduces the evapotranspiration pressure on north-facing slopes, leading to higher humidity, higher soil moisture, and more widespread permafrost. The higher water availability supports the growth of trees, which is Siberian larch (*Larix sibirica*) on most of Mongolia's forested area (Dashtseren et al., 2014). On south-facing slopes more solar radiation input produces hydrological conditions which are too dry for the establishment of forests and thus favor steppe vegetation (Bayartaa et al., 2007).

With respect to global climate change, the question of potential shifts in growth conditions arises. Vegetation indices like the most commonly applied NDVI (Normalized differentiated vegetation index), which are derived from multispectral satellite images (Landsat, MODIS, Spot VGT) provide information about the "greenness" and vitality of the vegetation cover. The various investigations on recent trends of climate and NDVI, which exist for the region of Mongolia state partially diverging results (Dashkhuu et al., 2015; Eckert et al., 2015; Miao et al., 2015; Poulter et al., 2013; Vandandorj et al., 2015). Instrumental climate data from weather stations in Mongolia are often discontinuous and time series of climate measurements are not available from mountain areas since climate stations are located near settlements in the basins. Thus, representative climate parameters must be modelled by different regionalization processes (Böhner, 2006). Various gridded datasets of re-analyzed climate parameters with different spatial and temporal resolution, which are mainly used for climate trend analysis, exist: e.g. CRU-TS (Harris et al., 2014), ERA-interim (Dee et al., 2011), CHELSA (Karger et al., 2016). While the quality, origin, and resolution of climate records constitute one uncertainty factor, the results and interpretations about the correlations between climate and NDVI trends occasionally suffer from disregarding the specific bio-ecological restrictions of the different vegetation zones.

Batima et al. (2005) analyzed climate station data and observed an increasing mean annual air temperature (MAAT) of 1.66 °C for Mongolia between 1940 and 2001. Eckert et al. (2015) stated that temperatures have not varied much since the year 2000. Dulamsuren et al. (2014) found a trend to warmer temperature extremes starting around 2000. Sharkhuu et al. (2007) and Sharkhuu (2003) executed measurements on permafrost distribution and active layer development in Mongolia for more than 30 years. They found a general trend of permafrost degradation, which is additionally accelerating since the 1990s. This is due to climate warming, but reinforced by a loss of vegetation due to livestock grazing in some steppe areas and tree cutting in the forests. Permafrost degradation is more intense in the Khuvsgul area than in the Khentei and Khangai Mountains.

The trends of precipitation in Mongolia are not spatially uniform. However, the observed trend can strongly depend on the specific period used for climate analysis (Erasmi et al., 2014; Giese et al., 2007). This can explain the different results between Batima et al. (2005) and Eckert et al. (2015), who analyzed the climate development in Mongolia at different time spans in the period, which was regarded in this research. While there was a positive trend in the annual precipitation found in the forest regions of northern and central Mongolia during the period from 2001 to 2011, it has been negative in the previous period between 1970 and 2001. In the driest regions of western and southern Mongolia however, no specific trends occurred at all. Based on tree-ring data, Dulamsuren et al. (2010b) documented increasing drought stress in larch trees in the Khentei Mountains, which they attributed to increasing aridity by rising summer temperatures and decreasing summer precipitation during the last 50 years. Although trees at the outer boundary of the forest stands might be better adapted to drought stress, obvious margins of dead trees surrounding the forest

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islands are recently found at many places of the forest-steppe. For the period from 1980 until 2005, Bayartaa et al. (2007) reported a strong increase in burnt forest area in Mongolia starting in 1996, which was due to very dry winter and spring seasons but may also be combined to weakened governmental management during the period of political transition. A general tendency of decreasing lake levels during the last decades in two great lakes of interior drainage in the Gobi with an catchment area south of Khangai Mountains was observed by Szumińska (2016). This lake level decline was associated with trends for reduced precipitation and increased evapotranspiration resulting from rising temperatures.

Eckert et al. (2015) analyzed the general trend of NDVI in Mongolia during the period between 2001 and 2011 using the MODIS NDVI dataset and found mostly positive trends in northern and eastern Mongolia, stable conditions in southern Mongolia, and large areas of negative trends in the northern Mongolian Altai and in the east of the Khangai Mountains. Based on the same dataset and a similar period from 2000 to 2012, Vandandorj et al. (2015) analyzed the seasonal variation of NDVI for individual vegetation zones. High variations in NDVI occur particularly in the steppe regions where the vitality and density of grassland is closely related to the amount of annual precipitation due to low stomatal control of transpiration by the grassland vegetation. Low variations in NDVI occur in forested regions, since trees exert a much stricter stomatal control of transpiration than herbs and grasses, and in the sparsely vegetated desert regions. Poulter et al. (2013) investigated the influence of recent climate trends on the forests in Inner Asia by the temporal distribution of a greening value using specific vegetation indices from remote sensing data and environmental datasets. They found a trend to earlier greening induced by increasing spring temperatures and earlier browning associated with decreasing summer precipitation. Based on these relationships they projected better future forest conditions for Mongolia until 2100. In opposite of these findings, Bayartaa et al. (2007) reported that climate scenarios would indicate a significant decrease in forest area and its total biomass for Mongolia until the middle of the 21st Century, which is in accordance with the recent trends from dendrochronological data from Mongolia (Dulamsuren et al., 2010a, 2010b, 2014; Khansaritoreh et al., 2017). Lu et al. (2014) investigated the applicability of different remote sensing-based biomass estimation approaches. They found the biomass estimation method via NDVI to be sufficient in low density forests. Dulamsuren et al. (2016) showed that the NDVI well usable to estimate the tree biomass for Mongolian forests. The best fit of linear regression was found between biomass and the mean NDVI of April for the period 1999-2013. This shows that in addition to the vegetation vitality the NDVI is a valuable indicator for tree biomass in open forest stands.

With regard to the diverse and in parts contradicting observations on climate and vegetation status, interdependencies and recent trends in Mongolia that are reported here, this study investigates the present distribution of forest areas and its relation to climate and topography based on high resolution satellite and gridded climate data. In addition to existing studies, here, the impact of climate and changes in climate parameters is studied at different spatial levels related to the zonation of ecozones. The following hypotheses were tested:

- Every ecozone has its own climatic restricted environment. The statistical correlations between NDVI and climate condition in different forest types and at the corresponding treelines reflect the specific ecological relationships and limitations.
- There are different trends of climate-induced vitality change detectable for the different ecozones and especially for the treelines as an indicator for extreme ecological site conditions.
- Forests and grasslands of the same ecozone show different trends and relations to climate and NDVI.

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2. The Study Area

Mongolia is situated in northern Central Asia in the transition zone between the Siberian taiga in the north and the Gobi desert in the south (Fig. 1). Spatially Mongolia extends from 87°45'E to 119°56'E and from 41°34'N to 52°09'N and covers a total area of 1,562,950 km^2. Wide basins of interior drainage are spread on elevations between 900 and 1500 m a.s.l. with the lowest areas below 720 m a.s.l. There are five principal mountain systems in Mongolia: The Mongolian Altai (MA) in the west (highest peak is Tavan Bogd, 4374 m a.s.l.), the Gobi Altai in the south (Ikh Bogd, 3957 m a.s.l.), the Khangai Mountains (KaM) in the center (Otgon Tenger, 3964 m a.s.l.), the Khentei Mountains (KeM) in the northeast (Asralt Kharj khan, 2799 m a.s.l.), and the Khuvsgul region in the eastern Sayan Mountains (Munkh Saridag, 3460 m a.s.l.). The mountain tops are shaped by pronounced flat surfaces at elevations between 2500 and 3500 m a.s.l. (Academy of Sciences of Mongolia and Academy of Sciences of USSR, 1990; Murzaev, 1954)

The climate of Mongolia is characterized by high continental semi humid, semiarid, and arid conditions. In wintertime, the Siberian high pressure cell produces cold and dry weather with few snowfall and mean temperatures between -15 and -30 °C (Barthel, 1983; Klinge, 2001). The main rainfall occurs from June to August during the short summer and is induced by westerlies and cyclone precipitation, with the dry season starting again in autumn. The mean summer temperatures range between 10 and 27 °C. Mean annual precipitation is lower than 50 mm in the interior basins, around 125 mm in the southern desert and up to 350 mm in the northern steppes, whereas it increases to more than 500 mm in the high mountains. There is a large annual variation in precipitation amount and period, which strongly controls the annual density of the steppe vegetation cover (Bat-Oyun et al., 2016).

According to the climatic conditions, the vegetation zones occur in a latitudinal and altitudinal order (Hilbig, 1995). Dark mountain taiga with coniferous trees (*Pinus sibirica, Picea* obovata, *Abies sibirica*) occurs as closed forests in northern Mongolia and selective in the upper KaM in central Mongolia (Dulamsuren, 2004). The subtaiga ecozone with needle and deciduous broadleaf forests (*Larix sibirica, Pinus sylvestris, Betula platyphylla*) represents a type of light taiga beneath and surrounding the mountain taiga. In northern Mongolia, the forest often extends into the valley bottoms and open grassland is restricted to intra-mountainous basins. The vegetation in central Mongolia consists of steppe grasslands in the basins and forest-steppe in the mountain area. Small areas of grassland have been converted into croplands. In this forest boundary ecotone of semiarid climate conditions, the relief controls the vegetation patterns. While the deciduous conifer forests consisting of *Larix sibirica* are primarily limited to north-facing slopes, the southern slopes are covered by steppe vegetation (Treter, 1996). The southern part of Mongolia consists of desert steppe and sparse desert vegetation. Sand dunes, as well as playas and takirs, which consist of salty and clayey sediments remaining from evaporated water in episodically existing lakes in basins of interior drainage, are widely distributed. In the high mountains, dense alpine meadow vegetation occurs between forest-steppe and the periglacial zone of frost debris. The main perennial rivers are accompanied by floodplain meadows and alluvial forests (Hilbig, 1995).

Missing forestry management and extensive forest use by tree cutting and wood pasture led to forest degradation and local deforestation in many regions of Mongolia during the last decades (Tsogtbaatar, 2004). In addition, hazardous forest fires destroyed large forest areas (Bayartaa et al., 2007; Goldammer, 2002, 2007; Hansen et al., 2013). Although it is supposed that most of the recent forest fires in Mongolia were primarily set by humans, there has to be an additional ecological exposure to fire susceptibility (Dorjsuren, 2009).

3. Methods

An overview of the complete analysis process is illustrated in figure 2, while the single steps are described in detail below. The spatial resolution of the various basic data sets is presented in figure 3. The forested area was mapped for Mongolia and its surroundings using a maximum likelihood supervised classification of 50 Landsat 8 satellite images (spatial resolution 30 m). Images of the years 2013 and 2014 were used as a baseline, and, in areas of low quality or high cloud coverage, were supplemented by Landsat 5 images from 2009 to 2011 (spatial resolution 30 m).

The elevation of the actual treeline was calculated by selected points from a digital elevation model (DEM) of SRTM-data (spatial resolution 90 m). Points representing the treelines were established by a kernel-model which evaluates for every pixel covered by forest if (1) it lies on a slope of more than 2°, (2) there is any forested area in the surroundings in a higher or lower position, and (3) there is any woodless area representing the existence of the next vegetation zone beyond the potential forest boundary to exclude relief related distribution limits. The specific search parameters for the upper and lower treeline are given in figure 2. Körner (2012) proposes a minimum vertical range from the upper treeline (UT) to the summit to prevent the summit effect on tree development and to receive a true climatic treeline value. Due to extensive planation surfaces in the investigation area of KaM, flat mountaintops in the alpine zone widespread occur. During the analysis process, it was necessary to reduce the minimum distance between the upper treeline and more highly elevated non-forested areas to only 10 m to prevent large areas above the forests from being excluded. After visual proof and deletion of strong outlying points, a final number of 7,081 points for the UT and 5,220 for the lower treeline (LT) were used for the interpolation of the treeline surfaces applying the natural neighbor method (Watson, 1992). Subsequently, the vertical distance of the treelines, the area above and below the treeline were calculated. A buffer of 1000 m around these areas was chosen to represent the treeline boundary area, because this distance meets the spatial resolution of the Spot VGT and climate data (Fig. 3).

The distribution of the different ecozones was adapted from Gunin and Vostokova (2005). At several places the map does not match the position of the landscape elements represented in the remote sensing data. Thus, these spatial deviations were corrected to the positions of the latter. The different vegetation units were generalized to the main ecozones (desert, desert steppe, steppe, forest-steppe, subtaiga, taiga, alpine vegetation). Forests of floodplain areas, which are hydrologically favored by groundwater, were excluded from this analysis. When forest areas were found in steppe regions, those parts were changed into forest-steppe. In the upper mountains where the strong disparity between north-facing slopes with forest and south-facing slopes with steppe dissipates, the areas with slopes covered by forests in every direction were reclassified as mountain subtaiga. Subsequently, the mapped forest areas were combined with the ecozones to achieve a spatial differentiation between forested area and open grassland within the total ecozone (TE) of the forest-steppe, subtaiga and taiga. These three ecozones comprise the area under investigation in the present study. In addition, the mapped forest area was combined with digital tree spices maps provided by the NAMHEM, Ministry of Nature, Environment and Tourism, Mongolia (2009) to receive spatial tree species data.

Here, the statistical approach to use only one mean value in a period of 15 years (1999-2013) for every parameter was chosen in order to eliminate annual changes and inter-annual variations, which derive from phenology and climate variability. Thus, normalized variables representing the mean site conditions were computed and spatially analyzed. NDVI, temperature and solar radiation are directly combined to the MGS. Precipitation during the winter season is retained in the soil and additionally available during the MGS. The vegetation index from SPOT VGT satellite data was used for the time span from January 1st, 1999 to December 31st, 2013, which originally consists of SPOT-Vegetation 10-daily NDVI composites (spatial resolution 1 km). These data were aggregated to monthly values using the maximum value of the three 10 day composites. Monthly NDVI data were further aggregated to the mean of the growing season from May to September (MGS-NDVI) for the period 1999 to 2013. We used re-analyzed climate data from the CHELSA dataset with 30 arc sec resolution (approx. 1 km) (Karger et al., 2016). Monthly data from 1999 to 2013 were averaged to cover the same period as the MGS-NDVI dataset. While mean growing season temperatures (MGST) were calculated from the monthly means from May to September, the mean annual precipitation (MAP) represents the average of the total annual sum of the period from 1999 to 2013. The sum of solar radiation input (MGSR; Wh m^{-2}) for the MGS (day 121-273) was calculated based on STRM-DEM data for 2007 and was assumed to be relatively constant for the observation period 1999 to 2013.

Up to 3000 random points for both, forest and grassland area in the three ecozones and at the upper and lower forest boundary were chosen for statistical analysis (Tables 1, 2; Fig. 4). The total number of random points was reduced for treeline subunits which have only a small spatial distribution to prevent a too large point density. While the subtaiga is bordering to the meadow-steppe, the lower treeline seldom occurs in the taiga zone, because the precipitation input in these regions is mostly high enough for tree growth. For the region of Mongolia, this is true for the large basins and valleys. Nevertheless, at smaller intermountain basins and smaller valleys, which are rain shadowed by the surrounding mountains, a lower forest boundary is detectable. When including the isolated lower treeline values into the interpolation process, the lower treeline surfaces passes the larger valleys where extensive forest occurs beneath it. These areas are excluded from the treeline analysis.

For each of the three forest-bearing ecozones (forest-steppe, subtaiga, taiga), first, the total area (total ecozone, TE) is considered, then, the TE is divided into forest (f) and grassland (s) and further reduced to the 1 km boundary area of both treelines (LT, UT). This categorization leads to 18 ecological subunits, which are analyzed separately. Multiple comparison between means were calculated with Duncan's multiple range test after testing for normal distribution using SAS 9.4 software (SAS Institute Inc., Cary, North Carolina, U.S.A.). In addition to the mean values, the standard deviation specifies the variation range of the climate parameters for every subunit. Pearson and multiple correlation coefficients between NDVI, MAP, MGST, and MGSR were computed as statistical base for the interpretation of regression trends. Due to the high amount of random points, it was opposed to perform a t-test because the significance level (p-value) is always <0.05. The correlations at the level of the TE are used to analyze the controlling climatic conditions and the environmental range with respect to the ecology of the entire ecozone. In contrast, the treelines represent boundaries of forest distribution at the ecological limits and it is hypothesized that changes in climate or environmental conditions at these boundaries lead to an alteration of the treelines.

4. Results

4.1 Treeline distribution

The actual total area of Mongolian southern boreal forest was estimated at 73,818 km^2 (Dulamsuren et al., 2016). The spatial ratio of forested areas related to the total ecozone areas and in the 1 km boundaries at the treelines are given in Table 3. While the approximate forest portion is 40 %, low forest densities occur at all LTs and in the TE of the forest-steppe. Figure 5 shows the forest distribution, the treelines, the vertical distance of the forest belt, and the area beyond the treelines in northern Mongolia. The forest area surrounding the Mongolian border was additionally mapped to receive continuous treeline values crossing the administrative border, but the Siberian region further to the north was omitted. No treeline continuance is indicated in the southern part of Mongolia due to missing boreal forests in the desert. The treeline distribution in western Mongolia generally corresponds to the results from Klinge et al. (2003), who investigated forest distribution in the Altai Mountains based on topographic maps.

Large areas above the UT occur in the MA, in the southern part of KaM and east of Lake Khuvsgul. In the KeM areas above the treeline in >2500 m a.s.l. are small. The UTs show a general increase from 2200 m a.s.l. at the Mountains in the North of Uvs Nur and from 1800 m a.s.l. south of Lake Baikal to 2700 m a.s.l. in the southern parts of the MA and the KaM (Fig. 5a). In the southwestern side of the MA the UT increases steeply from 2100 to 2600 m a.s.l. in a northeastern direction. In the large mountain systems of the MA and KaM the UT stays in a relative constant altitude between 2400 and 2600 m a.s.l. Northeast of KaM, the UT has an explicit longitudinal direction and a UT depression of up to 800 m occurs in the basin of the Selenga River. It was verified using the forest cover change data of Hansen et al. (2013) that the extraordinary low UT in 1800 m a.s.l. is not related to burnt forest. Large areas below the LT exist in the great basins and along the main river valleys, but they are also present in the intermountain basins (Fig. 5b). In northern Mongolia, the LT disappears in the large valleys and forests extend continuously into the valley bottom. However, a distinct LT is still present in intermountain basins. Concordant with the increasing aridity the LT is generally rising southward from 1000 to 2500 m a.s.l. in eastern Mongolia. The steep gradient of >1200 m height at the north- and southwestern edges of the Altai Mountains is due to the enhanced capture of rainfall at the western ranges of the Altai and the increasing aridity in the MA.

The potential forested area in central Mongolia, which is left between the resulting large areas beyond the treelines, is small from top-down view. However, the spatial expansion of forests has a particular vertical component (Fig. 5c). The altitudinal extension of the forest belt reaches its highest amount of up to 1000 m in the northwestern subtaiga and taiga regions. In the mountain forest-steppe of the central MA, the western KaM, and in the mountains at Lake Khuvsgul, the altitudinal extension of forests decreases below 400 m. In the southeastern part of the MA, the UT and LT converge and the forest belt thins out so that the steppe directly passes over to the alpine zone. Due to the extraordinary low UT, thin forest belts also occur in the area northeast of the KaM and in the southwestern part of KeM. This can be related to human impact by wood cutting in a more populated region. Main precipitation is transported by the westerlies and while the western side of the Altai Mountains is humid, the dry central MA and the Valley of the Great Lakes, which is located east of the MA, are directly situated in its rain shadow. This causes an extraordinary high LT and the small vertical extension of the forest belt in this region (Klinge et al., 2003). The southern side of the KaM is still arid, but its northern part and particularly the KeM receive more precipitation coming from the northeast along the Selenga river depression. The tree species composition of the different ecozones and subunits is given in Figure 6. Siberian larch (*Larix sibirica*) is the dominant tree species in Mongolia. However, the cedar (*Pinus sibirica*) fraction increases particularly at the UT of the subtaiga and taiga where the precipitation limit is less important. Additionally, birch (*Betula platyphylla*), aspen (*Populus tremula*), and pine (*Pinus sylvestris*) trees are occurring at all LTs.

4.2 Climate parameters of different ecozones

The zonal statistics for the climate parameters and MGS-NDVI in different ecozones and subunits are given in Table 1 and the correlation matrix between MGS-NDVI, MAP, MGST, and MGSR is presented in Table 2. Fig. 4 illustrates the frequency distributions and linear regressions between these parameters. The average MAP of the TE forests generally increases from 266 mm y^{-1} in the forest-steppe to 339 mm y^{-1} in the subtaiga and 357 mm y^{-1} in the taiga (Table 1). Due to the hydrological limitation, the MAP at the LT is lower than the respective average of the TE. This is also true for all forest subunits at the UTs, where the MAP is about 30 mm y^{-1} lower than the mean average of the TE forests. This aspect is due to the lower temperatures in higher mountains, which reduce the

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evapotranspiration pressure. Interestingly, the average MAP at the UT of the forest-steppe is even lower than at the LT. However, sites with extremely low MAP below 190 mm y^{-1} (Fig. 4a) must be related to additional water supply. The grassland has predominantly lower mean values of MAP than the forests of the corresponding subunit. This general trend inverts at the UTs of the subtaiga and taiga, while there are nearly equal values at the LTs of the forest-steppe and taiga.

The average MGST in all three TEs are very similar between 11.0 and 11.7 °C. However, the maximum of 16 °C in the taiga is lower than in the forest-steppe and subtaiga where it is up to 18 °C (Fig. 4b). While all mean values of MGST at the LTs equate to the TE values, the UTs show frequency maxima of the MGST between 7.5 and 8.9 °C (Table 1). With the exception of the UT in the subtaiga and taiga, in all subunits, the grasslands have similar or slightly higher temperatures as the forests of the same unit. This phenomenon of an inversion of the general trend at the UT of the subtaiga and taiga occurs simultaneously to the MAP. Here, the grassland is not represented by mountain meadow steppe but by alpine shrub and meadow vegetation, which is provoked by a cold but more humid climate. The MGST of all TEs and LTs shows similar frequency distributions with wide value ranges and slightly higher values at the LTs (Fig.4b). However, the narrow and uniform frequency distributions of all UTs indicate that the MGST is the main controlling parameter for forests distribution at the UT with an absolute minimum value of 6 °C. A considerable portion of MGST at the UTs occurs between 10 and 13 °C, which is marginal in the forest-steppe and subtaiga but becomes more important in the taiga.

4.3 Relationship between climate and NDVI in different ecozones

The mean values of MGS-NDVI in Table 1 show only slight variation between the ecozones and subunits. The values increase from forest-steppe to taiga and are higher in the forested area compared to the grassland of the same subunit. The inverse trends of relation between forest and grassland of the same subunit, which occur for MAP and MGST at the UT of subtaiga and taiga, do not exist for the NDVI. The frequency distributions of MSG-NDVI for the subunits in the forest-steppe are nearly similar but clearly separated in the other ecozones (Fig. 4c). The UTs have the lowest and the TEs have the highest NDVI values, which is generally due to less favorable ecological site conditions at the forest boundaries. In Table 2 most of the TEs show good correlations between NDVI and the climate parameters ($r = 0.44$-0.71), with an obvious exception of the MAP in the taiga TE. Linear regressions of the relief parameter MGSR are omitted in Fig. 4, because MGSR is only weakly correlated to the NDVI in all subunits.

In accordance with the correlation coefficients given in Table 2, the linear fit of the regressions between MGS-NDVI, MAP, and MGST, which are shown in Fig. 4, illustrates the relationship and potential susceptibility of the ecozones and corresponding treelines to changes in climatic conditions. There are mostly low correlations between MGS-NDVI and MAP at most subunits. The only exceptions are the TE and the LT of the forest-steppe and particular the LT in the forest subunit of the taiga. However, the gradients of linear regression indicate potential relations between NDVI and MAP for all LTs and particularly for all subunits in the forest-steppe (Fig. 4a). Both, the correlation values and the linear regressions between MGS-NDVI and MGST (Fig. 4b) indicate strong dependencies for all subunits; the UT of the forest-steppe is an exception from this rule, since only weak correlation was found. However, the steep gradient of the linear regressions at all UTs accentuates the temperature as the main limiting parameter with increasing influence towards the taiga. Presupposing that at least precipitation, temperature and solar radiation input control the vitality of the vegetation and the treeline distribution but with different intensities for every subunit, the multi-regression correlations between NDVI and MAP, MGST, and MGSR are generally higher. However, the combination of the two climate parameters MAP and MGST shows the best

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correlations with the NDVI, while the combination of all three parameters only leads to a marginal improvement (Table 2).

The high positive correlations between MAP and MGST and the high negative correlation between MGST and MGSR in the TE and at the LT of the forest-steppe indicate a specific environmental interrelation and potential auto-correlation effects between these two climate parameters in the semiarid climate zone. This is due to the fact that in the forest-steppe the increasing atmospheric vapor pressure deficit, which results from higher temperatures, must be compensated by more precipitation, on the one hand, and by less solar radiation input, on the other hand. However, the weak correlation between MAP and MGST in all subunits of the subtaiga and taiga indicate a climate independent factor. This is notably attributable to permafrost distribution as a supplemental ecological parameter, which is not included in our regression models but modifies the soil hydrological regime. Regression gradients between MAP and MGST of the TEs change from the strong positive trend in the forest-steppe into a less precipitation-dependent trend in the subtaiga and then into a negative trend in the taiga (Fig. 4d). The increasing MAP produces more humid climate in the taiga and makes vegetation vitality in the TE less dependent on precipitation limits. Low temperatures as zonal climatic parameter become a dominating limit for tree development towards higher latitudes. Concordant to the transformation of ecological conditions, the physiological constitution of trees and the tree species composition changes from drought-adapted to low-temperature adapted but more drought sensitive individuals.

5. Discussion

The lower boundaries of the distribution curves (Fig. 4a) and the standard deviation of the MAP (Table 1) indicate that an approximate MAP of 190 mm y^{-1} can be regarded as the minimum amount of direct rainfall for tree development in Mongolia. Sites with lower MAP values, occurring in parts of the forest-steppe, are favored by additional soil water supply from upslope area or melting permafrost ice, which can support tree growth under these dry conditions (Dulamsuren et al., 2014). The annual amount of precipitation is highly varying in the steppes region and the permafrost layer aids to bridge dry years by accumulating soil water during more humid years (Sugimoto et al., 2002). The vegetation vitality as expressed by the NDVI is generally lower in the forest-steppe than in the subtaiga and taiga. This fact proves the extreme ecological limitations of the forest-steppe ecotone. The recently emerging margins of dead trees around the forest islands are apparently induced by the trend of increasing temperature, insufficient precipitation, and missing soil water storage from disappearing discontinuous permafrost.

The proportion between predominant open grassland area and forest islands in the southern forest-steppe changes towards northern latitudes with the expansion of forest area. In the large valleys of the taiga and subtaiga in northern Mongolia, where trees are not limited by water scarcity, a LT does not exist. However, inside the dense woodland of the southern Siberian taiga, the grassland occurs in intra-mountainous basins where precipitation is extraordinarily low (Dulamsuren et al., 2005; Gunin et al., 1999; Hilbig, 1995) and thus a LT is present. The high correlation of the detected LTs to MAP in the taiga ecozone proves the more natural than human-induced existence of this forest distribution boundary and its susceptibility to aridification. This conclusion is supported by ecophysiological, dendrochronological, and palynological studies from such areas (Dulamsuren et al., 2009a; 2010b; Schlütz et al., 2008).

The correlation between NDVI and MGST at the UT is strong in the taiga and subtaiga regions (Table 2). At the UT of the forest-steppe region, precipitation is a concurrent limiting factor at higher elevations. While a MGST of 6 °C tends to be the general minimum temperature for tree growth in the study area, at some places at the UT of the subtaiga, trees occur at MGST as low as 4 °C (Fig. 4b).

At these locations, the low MGST is associated with high MAP of roughly 350 mm y^{-1} (Fig. 4d). At the low temperature range between 6-8 °C, the linear regressions between MAP and MGST at the UT show that, at these cold sites, different MAP conditions exist simultaneously for the different ecozones (Fig. 4d). In the forest-steppe at 6 °C MGST, MAP is approximately 200 mm y^{-1}, whereas it amounts to c. 320 mm y^{-1} in the subtaiga and 400 mm y^{-1} in the taiga. This combination between both low precipitation and temperature is most extreme at the LT of the forest-steppe. In the range of 6-8 °C MGST, MAP tends to be below the tree growth minimum of 190 mm y^{-1}, which emphasizes again the impact of permafrost, as the permafrost is also associated with low temperatures.

Differing frequency distributions show that the NDVI at the UT and LT is generally lower than in the TEs of the taiga and subtaiga, except for the forest-steppe (fig 4c). The low NDVI values indicate low vegetation vitality. This suggests that forests composing treelines in the taiga and the subtaiga and the complete forest-steppe ecotone are exposed to physiological stress. Reports of increased drought stress, reduced stemwood formation, reduced forest regeneration and increased tree mortality especially in the *Larix sibirica*-dominated forest-steppe ecotones of Inner Asia support this conclusion (Dulamsuren et al., 2010a; 2010b; 2013; Liu et al., 2013). Future climate warming with increased summer drought will change dominating tree species from *Larix sibirica* to *Pinus silvestris* in places of the forest-steppe (Dulamsuren et al., 2009b). Forests in the taiga receive generally more precipitation and thus have thus developed higher stand densities and are also home to more water-demanding dark taiga tree species (Dulamsuren, 2004; Dulamsuren et al. 2010a).

6. Conclusion

Using high resolution remote sensing and climatic data enables to specify the climatic framework of the three forest-bearing ecozones in Mongolia and to indicate additional factors for vegetation growth. Differing tendencies in the NDVI distribution between forest and grassland of the same subunits, which are mainly controlled by different photosynthetic activity, vegetation density, and seasonal growth, were also found. However, with respect to the small-scale variation of the vegetation and the ground resolution of the NDVI-data a spatial overlap producing mixed data values cannot be totally avoided.

In summary, the ecological relationship between climatic parameters and forest or treeline distribution can be verified by the NDVI as indicator for vegetation vitality. But site conditions like permafrost distribution, soil parameters and hydrology play an important role for vegetation vitality, too. The statistical results presented in this work are adequate to be used for projection and modeling of potential forest development on the one hand or for vegetation based refinement of climate data on the other.

We conclude that rising temperatures induced by global warming will finally lead to less tree vitality and forest degradation in the forest-steppe, subtaiga, and taiga as well. Even a simultaneous increase of precipitation will be consumed by more evapotranspiration. The observed recent increase of forest greening indices from remote sensing data and stemwood increment found in several places is combined to increasing summer temperature but also promoted by additional soil water supply from melting permafrost. However, disappearing permafrost and increasing drought stress on less drought-tolerant trees can subject hazardous distortion to forests in the future. For all LTs and for the TE of the forest-steppe, rising temperatures will lead to tree mortality, the reduction of forested area, and shifting of the LTs. Even a contemporaneous increasing precipitation cannot totally compensate for the disappearing permafrost because this leads to insufficient soil water during dry years. The existence of the widespread dead tree margins at forest islands proves that this trend is already ongoing concurrent to the temperature increase during the last decades. Unadapted trees suffering from drought stress are increasingly vulnerable to insect calamities and mortality and less resistance to many of the recent forest fires.

Research on NDVI trends and climate change in Mongolia is often lacking detailed spatial separation of the different ecozones. Every ecozone has its own temporal and ecological environment, which produces different trends in remote sensing derived vegetation indices. The local climatic and soil site conditions induce the growth of physiologically adapted trees and tree species. A climatic change will lead to more or less vitality but in the limited physiological range of the individuals. Forest dynamic and forest development from the biological point of view means change in the vegetation structure and biodiversity, which cannot be exclusively modeled by greening indices (Miao et al., 2015; Poulter et al., 2013). For future investigation on vegetation development in relation to climate trends, it is strictly necessary to consider the ecological transitions. It was shown, that the creation of a detailed landscape stratification and of small scaled ecological classifications can assist to incorporate spatial and temporal transitions of vegetation units in environmental modelling or projection.

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Tables:

Table 1: Arithmetic mean ± standard deviation of different climate parameters (MAP: Mean Annual Precipitation, MGST: Mean Growing Season Temperature, MGS-NDVI: Mean Growing Season Normalized Differentiated Vegetation Index) and vegetation units (Subunits are TE: Total Ecozone, LT: Lower Treeline, UT: Upper Treeline, s: portion of grassland, f: portion of forest). Within one row, mean values sharing a common uppercase letter, do not differ significantly (P≤0.05, Duncan's multiple range test, $df_{model} = 2$).Within one subunit (forest-steppe, subtaiga, taiga), mean values sharing a common lowercase letter, do not differ significantly (P≤0.05, Duncan's multiple range test, $df_{model} = 5, 13295$).

Subunit	Forest-steppe	Subtaiga	Taiga
	MAP (mm y^{-1})		
TE_f	266±62 Aa	339±70 Ba	357±69 Ca
TE_s	256±63 Ab	309±68 Bbe	331±73 Cb
LT_f	251±60 Ac	294±60 Bc	292±56 Bc
LT_s	253±62 Abc	286±57 Bd	290±53 Bc
UT_f	231±52 Ad	305±72 Be	333±80 Cbd
UT_s	227±54 Ae	314±73 Bb	339±80 Cd
	MGST (°C)		
TE_f	11.0±2.1 Aa	11.7±2.3 Ba	11.1±1.4 Ca
TE_s	11.6±2.5 Ab	11.7±2.7 Ba	11.1±1.7 Ca
LT_f	11.5±2.2 Ab	12.1±2.6 Bb	11.5±1.7 Ab
LT_s	12.1±2.3 Ac	12.8±2.4 Bc	11.7±1.6 Cc
UT_f	8.4±0.8 Ad	7.9±1.2 Bd	8.9±1.3 Cd
UT_s	8.4±0.9 Ad	7.5±1.2 Be	8.5±1.3 Ce
	MGS-NDVI		
TE_f	0.51±0.08 Aa	0.60±0.08 Ba	0.63±0.06 Ca
TE_s	0.47±0.08 Ab	0.55±0.09 Bb	0.55±0.09 Cb
LT_f	0.46±0.08 Ab	0.54±0.08 Bc	0.58±0.09 Cb
LT_s	0.44±0.08 Ac	0.51±0.08 Bd	0.55±0.08 Cc
UT_f	0.44±0.06 Ac	0.47±0.07 Be	0.51±0.09 Cd
UT_s	0.42±0.07 Ad	0.44±0.08 Bf	0.47±0.09 Ce

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Table 2: Correlation matrix showing Pearson and multiple correlation coefficients (r) between NDVI, climate, and relief parameters for different ecozones and subunits. (MAP: Mean Annual Precipitation, MGST: Mean Growing Season Temperature, MGS-NDVI: Mean Growing Season Normalized Differentiated Vegetation Index, MGSR: Mean Growing Season Solar Radiation Input, subunits are TE: Total Ecozone, LT: Lower Treeline, UT: Upper Treeline, s: portion of grassland, f: portion of forest)

Subunit	Forest-steppe	Subtaiga	Taiga	Forest-steppe	Subtaiga	Taiga	Forest-steppe	Subtaiga	Taiga	Forest-steppe	Subtaiga	Taiga
	MGS-NDVI / MAP			MGS-NDVI / MGST			MGS-NDVI / MGSR					
TE_f	0.58	0.44	0.22	0.49	**0.62**	0.55	-0.15	-0.24	-0.09			
TE_s	0.57	0.38	0.19	0.49	0.55	0.57	-0.26	-0.17	-0.18			
LT_f	0.53	0.33	0.51	0.56	0.52	**0.60**	-0.09	-0.20	-0.18			
LT_s	0.55	0.39	0.39	**0.61**	0.52	0.46	-0.29	-0.29	-0.30			
UT_f	0.34	0.11	0.34	0.31	0.59	**0.71**	0.22	0.19	0.08			
UT_s	0.42	0.10	0.33	0.25	0.55	**0.66**	0.15	0.17	0.08			
	MGS-NDVI / MAP ; MGSR			MGS-NDVI/MGST ; MGSR			MGS-NDVI / MAP ; MGST			MGS-NDVI / MAP ; MGST ; MGSR		
TE_f	0.58	0.47	0.24	0.51	**0.62**	0.56	**0.62**	**0.71**	**0.64**	**0.63**	**0.72**	**0.65**
TE_s	0.58	0.41	0.26	0.50	0.56	0.58	**0.62**	**0.67**	**0.68**	**0.63**	0.67	**0.68**
LT_f	0.53	0.36	0.52	0.59	0.52	0.60	**0.60**	0.56	**0.72**	**0.63**	0.57	**0.72**
LT_s	0.56	0.43	0.42	0.61	0.52	0.50	**0.64**	0.58	0.57	**0.65**	0.58	0.58
UT_f	0.36	0.24	0.35	0.37	**0.60**	**0.71**	0.43	**0.62**	**0.74**	0.45	**0.64**	**0.75**
UT_s	0.42	0.21	0.34	0.30	0.56	**0.66**	0.47	0.58	**0.69**	0.47	0.59	**0.69**
	MAP / MGSR			MGST / MGSR			MAP / MGST					
TE_f	-0.23	-0.16	0.05	-0.54	-0.48	-0.29	0.50	0.16	-0.18			
TE_s	-0.29	-0.05	0.01	**-0.67**	-0.42	-0.26	0.47	0.00	-0.28			
LT_f	-0.22	-0.21	-0.16	-0.46	-0.47	-0.24	**0.63**	0.23	0.20			
LT_s	-0.37	-0.29	-0.41	-0.58	-0.44	-0.23	**0.65**	0.24	0.12			
UT_f	0.25	-0.18	0.01	0.05	0.11	0.04	0.12	-0.11	0.18			
UT_s	0.20	-0.10	-0.05	0.00	0.12	0.16	0.11	-0.15	0.17			

Table 3: Spatial ratios of forest area (f) and total area of different ecozones and corresponding treelines. (TE: Total Ecozone, LT: Lower Treeline, UT: Upper Treeline)

area km^2	TE	TE_f	$\%_f$	LT	LT_f	$\%_f$	UT	UT_f	$\%_f$
Forest-steppe	62,678	17,983	28.7	17,275	3,894	22.5	3,525	1,822	51.7
Subtaiga	87,648	38,747	44.2	7,558	2,135	28.2	3,168	1,341	42.3
Taiga	31,710	17,088	53.9	1,234	401	32.5	949	495	52.2
Sum	182,036	73,818	40.6	26,067	6,430	24.7	7,642	3,658	47.9

Figures:

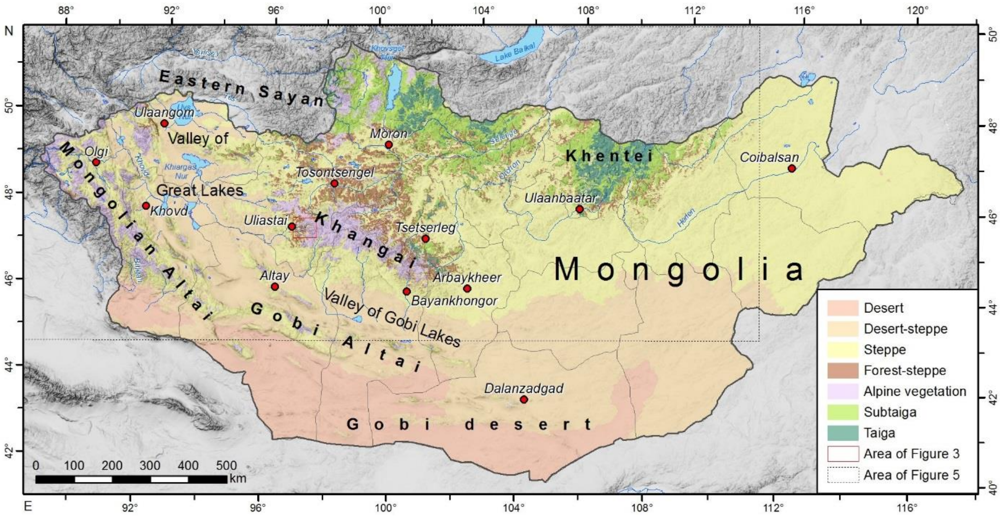
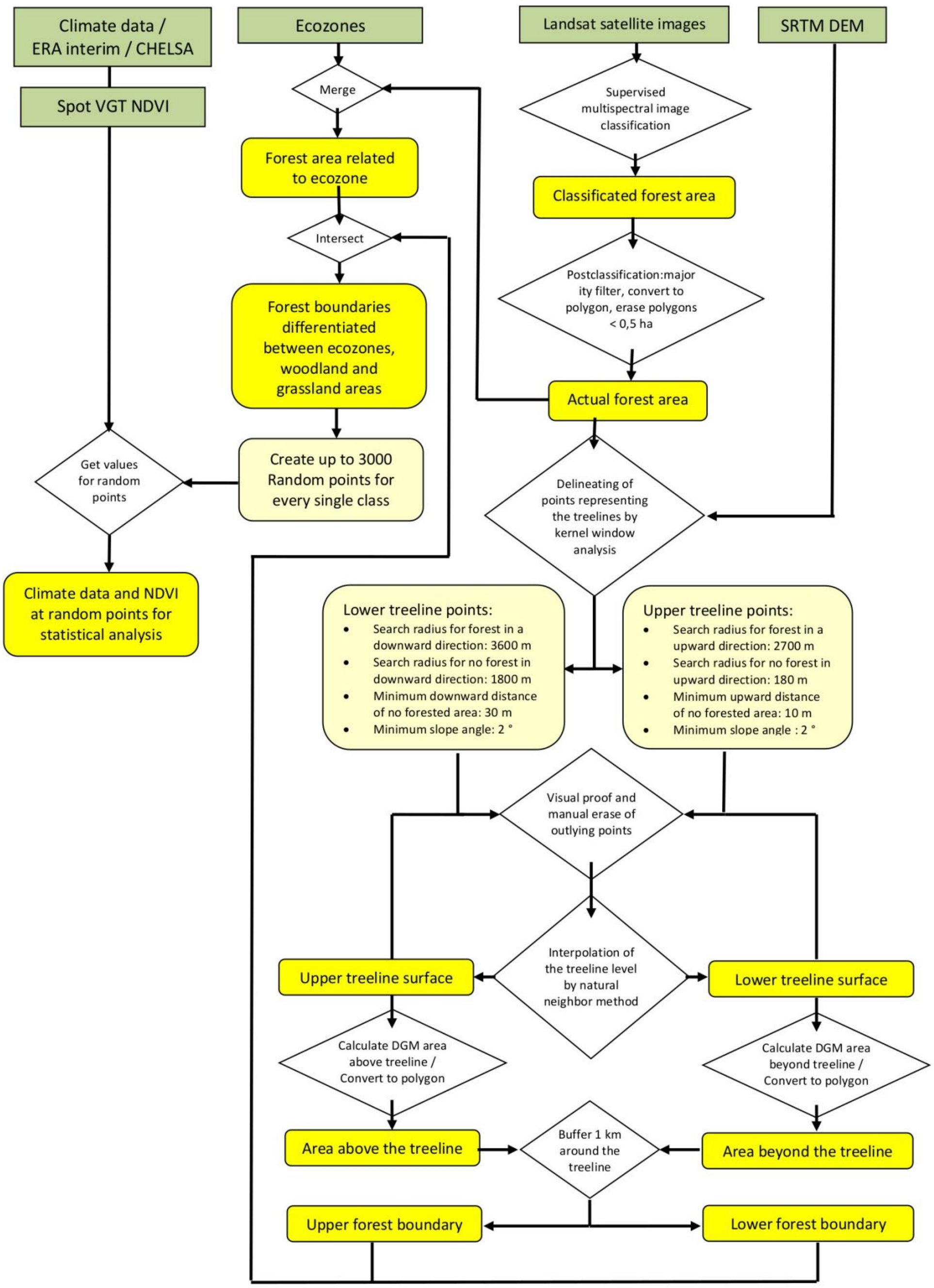


Figure 1: The vegetation zones of Mongolia (modified from Gunin and Vostokova, (2005) and Landsat 8 supervised classification).



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551 Figure 2: Processing workflow for treeline delineation, NDVI and climate analysis.

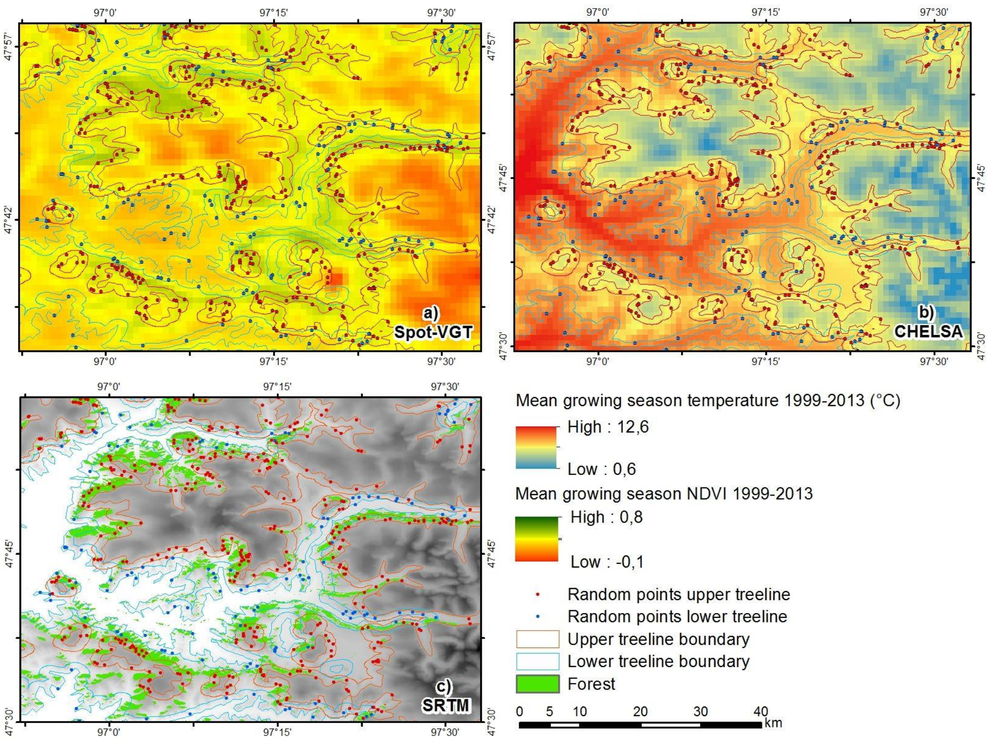

Figure 3: Examples for the spatial resolution of the different data: (a) mean growing season NDVI 1999-2013, (b) mean growing season temperature 1999-2013, (c) upper and lower treeline boundary from Landsat and SRTM data.

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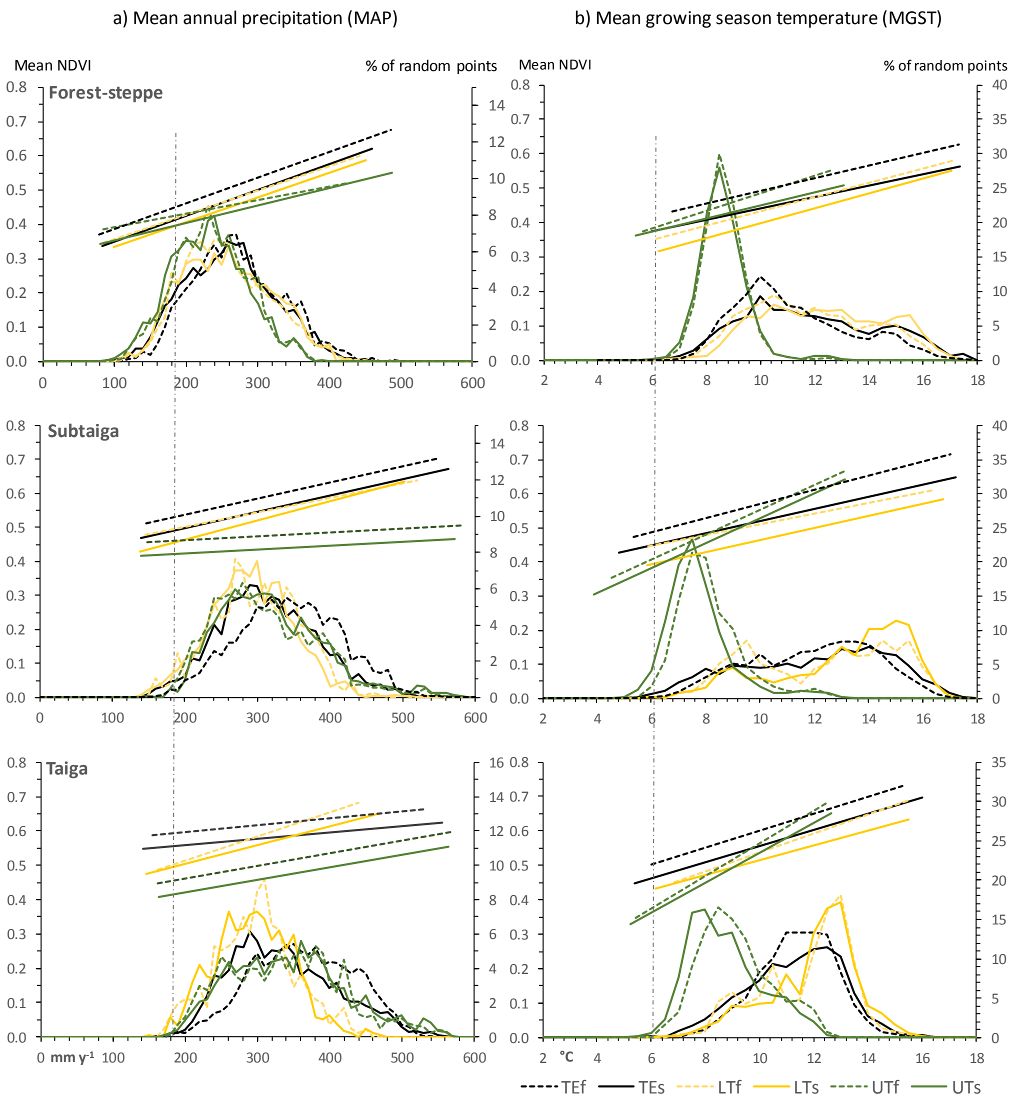

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557 Figure 4 (continued)

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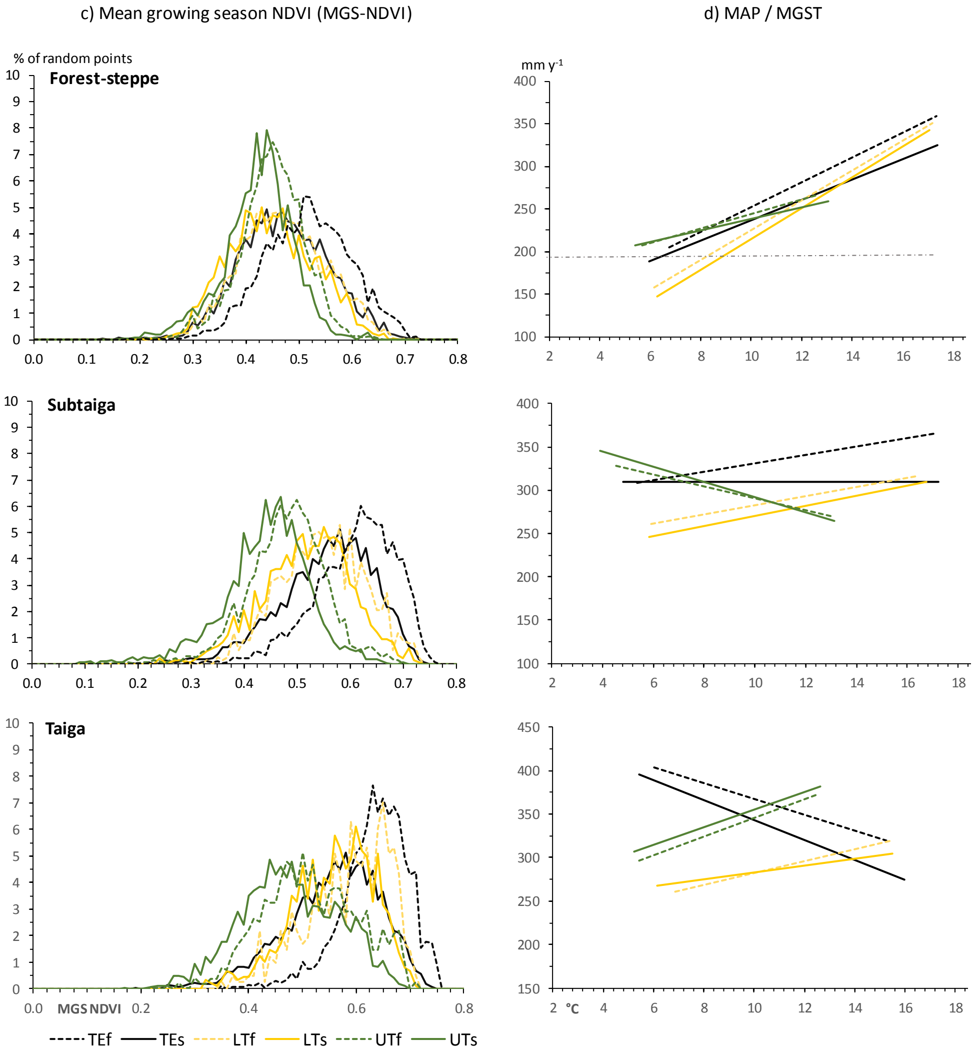

Figure 4: Mean annual precipitation (MAP) and mean air temperature during the growing season (MGST) related to the mean growing season NDVI of random points of different ecozones (values averaged for the investigation period 1999-2013). The straight lines are representing the linear regressions between climate parameters and NDVI. The distribution curves represent the frequency of random points (%). Dashed lines represent forest values (f); continuous lines represent grassland values (s); yellow colors represent lower treeline values (LT); green color represents upper treeline values (UT) and black colors represent the total ecozone values (TE). Vertical grey dashed lines indicate the deduced minimum values for tree growth.

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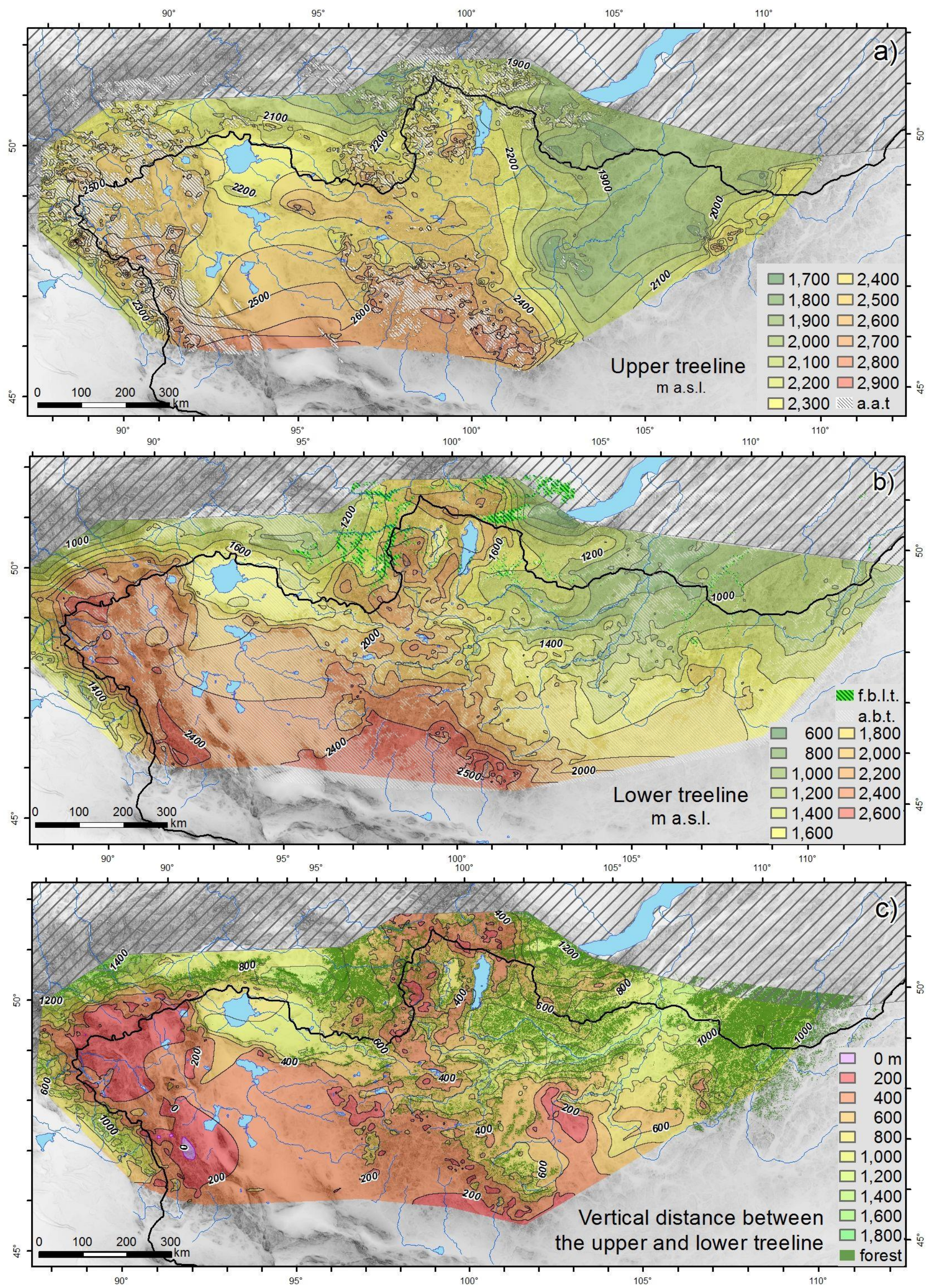

Figure 5: Treeline distribution maps of Mongolia: (a) upper treeline, (b) lower treeline, (c) vertical distance between upper and lower treeline (a.a.t. = area above the upper treeline, a.b.t. = area beneath the lower treeline, f.b.l.t. = forest below the lower treeline)

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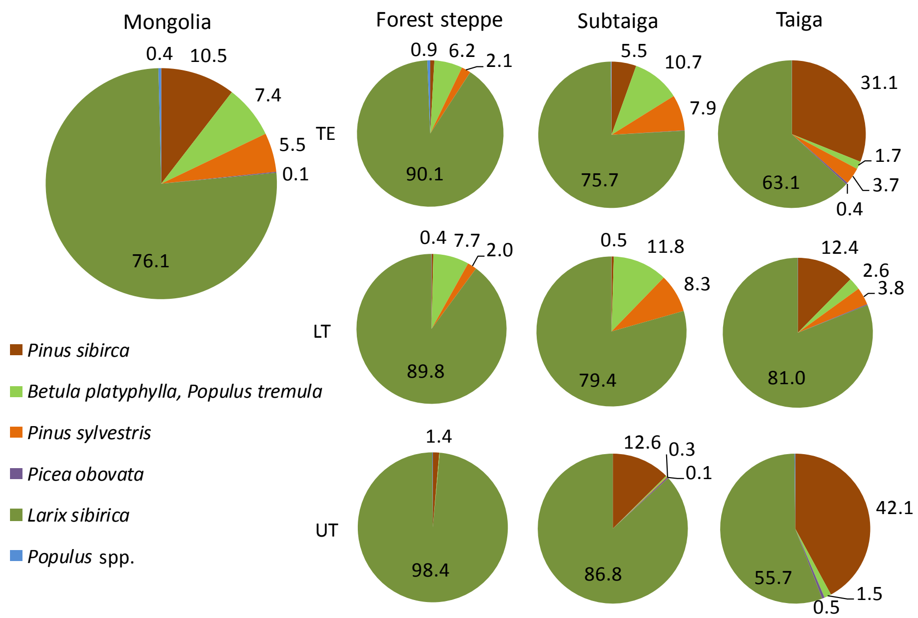

Figure 6: Tree species composition in the boreal zone of Mongolia and in the subunits of three different ecozones. The tree species distribution was adapted from Data provided by NAMHEM, Ministry of Nature, Environment and Tourism, Mongolia (2009)

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