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ECOLOGICAL ZONATION AS A TOOL FOR RESTORATION OF DEGRADED FORESTS IN NORTHERN MONGOLIA

ABSTRACT. We developed a geo-vegetation zonation in the Khaan Khentii massif, northern Mongolia. Our specific objective was to assess and classify the response of the tree vegetation to environmental factors operating at a coarse climatic level. We sampled forest ecosystem vegetation, climate, physiographic features, and soil properties. Our analysis included clustering, ordination, classification, and ANOVA techniques. Based on the complex data set, we identified three geo-vegetation zones: forest-steppe, montane and dark taiga zone. We characterized them based on the regional environmental factors; (1) climate as indicated by altitude, i.e., precipitation, (2) geomorphology by an index of the vertical distance to channel network and soils by O horizon thickness and soil types. Birch and aspen ecosystems were excluded as discrete zones due to their broad ecological amplitude.

The geo-vegetation zonation outlined in this paper is the first attempt at quantifying vegetation along with the environment at a macroclimatic level in Mongolia. This coarse-scale zonation provides a framework for building a comprehensive ecological classification, a background for sustainable forest management, which is currently unavailable in Mongolia and many central Asian countries. Additionally, it offers a roadmap for a comprehensive ecosystem survey and may act as an information platform and reference for current environmental issues such as forest degradation across Mongolian landscapes.

KEY WORDS: Ecological classification; Forest degradation; Sustainable management; Geo-vegetation zone; Zonal concept

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INTRODUCTION

Sustainability is a widely accepted principle in forest ecosystem management (e.g., Barbati et al. 2007). Traditionally, it has been applied through ecological classifications based on knowledge of natural vegetation and environmental conditions (usually defined by important environmental parameters) of a particular area or region (Pfister and Arno 1980; Pojar et al. 1987; Viewegh et al. 2003; Vahalík and Mikita 2011; Kusbach et al. 2017a). This vegetation-environmental relationship can be studied in different spatial-functional settings (Major 1951). It is reflected on a (i) macroscale (macroclimate – regional climate) for example, in biogeoclimatic zonation of British Columbia (Pojar et al. 1987), ecoregions (Bailey 2002), forest types (Caudullo et al. 2016), natural forest areas (Plíva and Žlábek 1986) and forest vegetation zones (Viewegh et al. 2003; Kusbach et al. 2017a), (ii) mesoscale (local climate), e.g., site series (Pojar et al. 1987), climax series (Pfister and Arno 1980), forest site complexes via edaphic series (Viewegh et al. 2003), and (iii) microscale, e.g., site types (Pojar et al. 1987), habitat types (Pfister and Arno 1980), forest site types (Viewegh et al. 2003). Forest ecological classifications exist in territories advanced in forestry such as North America, Europe, and the Asian part of Russia for decades (e.g., Kusbach et al. 2017a). These systems represent an important communication tool for the interested audience and provide an underlying framework for forest policy (decision making) and practice (ecosystem management, restoration and conservation etc.), (e.g., Kotar 1988; Barbati et al 2007; Sharik et al. 2010; Zenner et al. 2010).

For instance, in the Czech Republic, Regional Plans of Forest Development (RPFD) serve as a framework for forestry planning and legislation, practical management, nature protection and conservation, forested land evaluation, tax calculation, subsidies etc. (http://www.uhul.cz/what-we-do/regional-plans-of-forest-development). The plans have been developed for natural forest areas, regional units more or less homogeneous in natural conditions (Plíva and Žlábek 1986). The Czech Forest Ecosystem Classification (CFEC) includes additional structuring of growing conditions typical for forest vegetation zones (Viewegh et al. 2003; Kusbach et al. 2017a).

All worldwide ecological classifications were established based on expert knowledge (Haeussler 2011). While the original idea of zonality (zonality of soils sensu Dokuchaev) has been criticized as old-fashioned and "static" (Johnson et al. 1990), there is still intellectual power and potential in that idea (e.g., the zonal concept), which can serve as a feasible framework for advanced ecological classifications in areas without such systems (Haeussler 2011; Kusbach et al. 2014), especially for use in sustainable close-to-nature forest management.

Based on classic works of e.g., Morozov (1925), Pogrebnyak (1955), Sukachev (1972), Kolesnikov (1974), a tremendous amount of work was done in the field from 1970 during the Joint Russian/Soviet-Mongolian Complex Biological Expeditions and further surveys in terms of forest ecosystem classification and mapping (e.g., Unatov 1950; Lavrenko and Sokolov 1978; Grubov 1982; Karta 1983; Ulziikhutag 1989; Dulamsuren et al. 2005; Vostokova and Gunin 2005; Dorjgotov 2009). However, there is no framework and tools analogical to CFEC and RPFD on the Mongolian territory. Coarse-scale outputs - units of ecosystem surveys and maps (scales 1: 1.5-12 000 000, e.g., Vostokova and Gunin 2005; Dorjgotov 2009) do not provide a sufficient environmental stratification (at least in climate scaling as stated above) for definition of lower forest classification units. Additionally, there is no mapping of particular localities, no site-specific information except a general soil description with the Russian nomenclature (Nogina et al. 1980) used in the phytocoenological typology of Lavrenko and Sokolov (1978) with a brief description of basic forest types. These typological structures used, e.g., in Nyam et al. (2009) are obsolete and broad.

Moreover, no frequent thematic maps such as the map of existing vegetation for the Domogt Shariin Gol Company Ltd. (Kusbach et al. 2017b; Smola et al. 2019) were elaborated within sparse Mongolian descriptive forest management plans. Finally, since there is no legal framework (spatial units similar to the Czech natural forest areas and forest vegetation zones) and tools (a classification system) in Mongolia so far, it is not possible to recommend forest management and implement political decisions systematically (Kusbach et al. 2017b). In Mongolia, the forestry sector, especially forestry legislation, planning, education and extension is under development (Tsedendash 1998; Tsogtbaatar 2007; Batkhuu et al. 2011). Therefore, a formal framework (forest classification with management structures) is necessary to build besides activities such as National Forest Inventory (Altrell and Erdenebat 2016).

Our general objective was to reveal vegetation-environmental interactions in the macroclimate scale in northern Mongolia. We examined the relationships between tree composition and environmental variables (sensu Krajina 1965; Bailey 2002). Specific objectives were to (i) assess a response of vegetation to significant environmental factors at a level of regional climate, and (ii) suggest a spatial framework as broad forest/landscape units relatively homogeneous based on that response.

MATERIALS AND METHODS

The zonal concept

Late-seral or old-growth, usually minimally disturbed plant communities with intermediate terrain morphology and soil conditions are presumed to best reflect the influence of regional climate (Krajina 1965; Pojar et al. 1987; Bailey 2002). Local climatic, topographical and soil (topoedaphic) extreme sites such as hot steep slopes, cool, shady slopes, cold depressions or skeletal soils are disqualified and only intermediate environmental conditions are involved in application of the zonal concept and in selection of zonal sites. Together with the local extremes, also disturbed vegetation is disregarded. For details of the concept, see Kusbach et al. (2014).

STUDY AREA

The study area belongs into the Selenge and Darkhan Uul provinces in northern Mongolia. It is located in the northwest part of the Khaan Khentii massif (Fig 1). The western part of the massif belongs to the vegetation-geomorphologic province of the Daurian-Mongolian forest mountain steppe (Dorjgotov 2009). The lowest parts of the area are as low as 650–700 m a. s. l. and the highest parts reach over 2000 m a. s. l. The majority of the study area is made of uplands (800–1200 m a. s. l.). The Selenge River, the biggest river in Mongolia, with Orkhon, Eröö and Sharyn Gol River tributaries taking water from the study area to the Lake Baikal, Russia.

Mongolia is a landlocked country with climatic extremes, e.g., huge differences between summers and winters in temperatures and rainfall amounts. Winters are long, very cold and relatively dry (little snowy) affecting a relatively short vegetation period (May – September), especially in high elevations. Summers are hot and moister than cold and dry winters (e.g., Tsedendash 1995; Dulamsuren et al. 2005). Springs and falls are short. Mean annual temperature varies between -3 and -1.5ºC and mean annual rainfall between 280 and 350 mm within the study area (data obtained from the Mongolia National Agency for Meteorology and Environmental Monitoring). With increasing altitude, the amount of rainfall can reach up to 500 mm per year in the Bugant area, a part of the study area (Oyunsanaa 2011). This general macroclimatic pattern is modified by a local terrain topography causing substantial changes at a mesoclimatic level (Dulamsuren et al. 2005; Hais et al. 2016). This phenomenon of a local climate is distinctive on steep south-facing slopes with enormous temperature differences

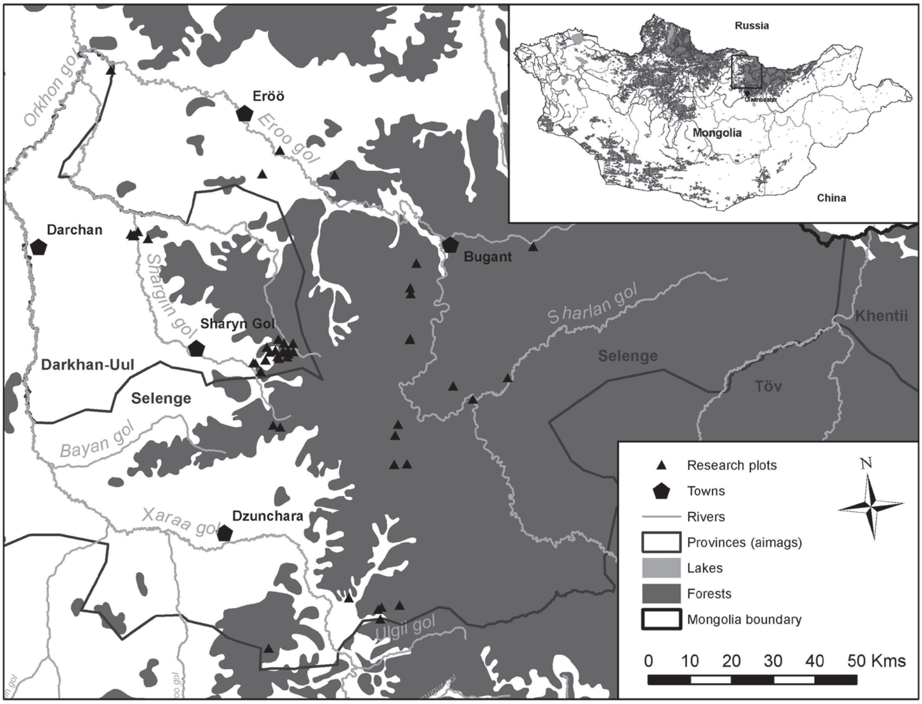

Fig. 1. The study area with locations of sample zonal sites

and usually shallow soils contrary to shady north-facing slopes with a low solar radiation. While a forest-steppe or steppe is developed on hot-dry south-facing slopes, a close-canopy forest covers cold-moist north-facing slopes (Dulamsuren et al. 2005, Mühlenberg et al. 2011).

A majority of Khaan Khentii massif consists of plutonic volcanic rocks of the Palaeozoic era, usually metamorphed. These deep and thick bedrocks are combined with Quatenary deposits of loess and eolian sands in lower elevations. In wider valleys of rivers, we can meet young organic soils, alluvial deposits and marches (Geological Map of Mongolia 1998). According to the "World Reference Base for Soil Resources" (WRB 2014) supported by the field pedological experience (Kusbach et al. 2017b), Kastanozems, Chernozems, and Arenosols are the most widespread in the northwest periphery of the study area associated with the steppe zone. On the other hand, Phaeozems, Cambisols, Luvisols, Umbrisol and Fluvisols are the most common soils in the central and eastern part of the study area linked with the forested zone.

The lowest levels of the study area (around 700 – 800 m a.s.l.) are characteristic by steppe and forest-steppe vegetation dominanted by *Pinus sylvestris* with locally higher presence of *Ulmus pumila*, and shrubs *Caragana microphylla* and *Spiraea aquilegifolia*. The largest portion of the area is occupied by "light taiga" forest ecosystems dominanted by *Larix sibirica, Pinus sylvestris,* and *Betula platyphylla* (Ermakov et al. 2002). As subdominants, we can find *Populus tremula* and locally, on the south-facing steep slopes, *Ulmus pumila* with *Spiraea aquilegifolia*. In higher altitudes of the central and eastern part and on north-facing slopes of lower altitudes, stands often belong to "dark taiga" composed of *Abies sibirica, Picea obovata* and *Pinus sibirica* (e.g., Knystautas 1987). The presence of *Picea obovata, Salix spp., Populus laurifolia, Padus asiatica, Potentilla fruticosa, Betula fruticosa* and *B. fusca* is typical for alluvial vegetation (Dulamsuren et al. 2005; Kusbach et al. 2017b).

Recent dominant landscape disturbances such as timber cutting, livestock overgrazing, wildfires (mostly human-induced), and mining combined with climate change (causing desertification) result in changes of the structure and age-class distribution of forest stands and depletion and degradation of forests (Khodolmor et al. 2013; Altrell and Erdenebat 2016; Gradel et al. 2017; Kusbach et al. 2017b). In many places, where *Pinus sylvestris* or *Larix sibirica* were cut down, *Betula plathyphylla* and *Populus tremula* stands are now predominant (Dulamsuren et al. 2005; Kusbach et al. 2017b). Forests highly disturbed by overpasturing and logging are thus characterized by low and mid, exceptionally late seral stages where a forest understory including natural regeneration is usually poorly developed (Kusbach et al. 2017b; Juřička et al. 2019). Species richness along a huge altitudinal gradient is, despite intensive disturbances, very high (Dulamsuren et al. 2005; Chytrý et al. 2012).

Sampling design and data collection

In summers 2015 to 2018, we established 96 circular sample plots (225 m^2 each) along the altitudinal range in order to get a broad environmental variation of the study area. One soil pit was dug in each plot to the unweathered parent material. A stratified (based on plot vegetation physiognomy, marked as ecosystem) fixed (subjective selection) sampling design was used. (Kusbach et al. 2017b). In this study, applying the zonal concept, we selected 49 zonal sites (Fig. 1), i.e., mature forest stands with intermediate site parameters such as mid-slope position, gentle to moderate slope (< 30 degrees), loamy soils (> 50 cm deep) with coarse rock fragment content < 50 % by volume and no growing-season ground water table (Damman 1979). We thus avoided those conditions that may substantially modify overall climate, such as frost pockets, cold air drainages and steep slopes. As "mature" we considered vegetation with relatively stable composition of dominant, potential climax tree species, with a clear successional trajectory, e.g., assessed by advance regeneration of climax species (Pfister and Arno 1980; Pojar et al. 1987). True zonal sites with climax (e.g., old growth) vegetation are relatively rare in the Khaan Khentii massif because many forest ecosystems never reach potential climax due to natural disturbances such as fire (e.g., Pojar et al. 1987; Cook 1996) and anthropogenic disturbances such as logging and pasture. Therefore, we compromised this disadvantage by sampling of sites with younger but mature stands (over ca 70 years, Pfister and Arno 1980). Because of not clear status of some mature birch and aspen stands on zonal sites, we accepted them as sites without anthropogenic disturbance.

Environmental and Soil Data. We described each sample plot by a forest type (ecosystem) and environmental variables including elevation, slope aspect and slope gradient. Soil properties were assessed based on the Reference Soil Groups (WRB 2014) (Table 1). Parent material or soil substrate observed within the soil pits was verified against a geologic map (Geological Map of Mongolia 1998).

One composite soil sample from 0–30 cm was collected from a pedon in each

Table 1. Research variables used in the analysis

Climatic factors	Abbreviation	Units/Values
Total Annual Mean Precipitation	P_year	mm
Annual Mean Temperature	T_year	°C
Physiographic/geomorphometric factors		
Altitude	Alt	meters
Aspect	Aspect	values 0 - 10
Channel Network	Chan_Net	values 0 - 1000

Catchment Area	Catch_A	values 0 - 25 000
Catchment Slope	Catch_Sl	values 0 - 1
Convergence Index	Converg	values - 87 - 89
Diurnal Anisotropic Heating	Diur_Ani	values -0.6 - 0.53
Gradient	Gradient	values 0 - 1
Gradient Difference	Grad_Dif	values -1 - 1
Local Convexity	Convexit	values 0 - 0.8
Mass Balance Index	Mass_Bal	values -1 - 2
Mean Catchment Area	M_Catch	values 0 - 25 000
Midslope Position	M_Slope	values 0 - 1
Normalized Height	Norm_H	values 0 - 1
Protection	Protect	values 0 - 1
Relative Slope Position	R_slope	values 0 - 1
Slope Gradient	Slope	degrees
Slope Aspect Value	av	values 0 -1 (Roberts and Cooper 1989)
Slope Height	Slope_H	m/0 - 450
Solar Radiation	Solarrad	values 635 000 - 1 400 000
Standardized Height	Stand_H	m/0 - 1500
Topography Wetness Index	TWI	values 0 - 26
Topographic Position Index	TPI	values -11 - 12
Terrain Roughness Index	TRI	values 0 - 60
Valley Depth	Valley_D	m/values 0 - 600
Vertical Distance to Channel Network	Vert_D	values 0 - 762
Wind Exposure	Wind_exp	values 0 - 2
Geologic/Soil Factors		
Available Potassium	aK_A	milligram/100 g of soil
Available Phosphorus	aP_A	milligram/100 g of soil
Carbon Nitrogen Ratio	C/N_A	not applicable
Coarse Rock Fragment Content	skelet	% volumetric
Exchangeable Calcium	eCa_A	milligram/ekv/100 g of soil

Exchangeable Magnesium	eMg_A	milligram/ekv/100 g of soil
Organic Carbon	C_A	%
Soil Substrate	substr	not applicable, categorical
Soil Type	stype	not applicable, categorical
O horizon thickness	Ohor	centimeters
A horizon thickness	Ahor	centimeters
Soil Depth	depth	centimeters
Soil Texture	stext	1-sandy, 2-loamy, 3-clayey
Soil pH	pH_A	1-14 pH scale
Soil Organic Matter	som_A	%
Total Nitrogen	totN_A	%

pit. The fine soil fraction (a particle size < 2 mm) was analyzed for physical and chemical attributes such as soil texture classes (sand, loam, clay) using the feel-method (Thien 1979), pH (1:1 soil in water, Corning pH analyzer), total organic C, total N (LECO CN analyzer, Leco Corp., St. Joseph, MI), exchangeable cations Ca, Mg, K (Holmgren et al. 1977), and available P (Olsen et al. 1954) (Table 1).

In order to detect a site environmental character, we calculated common geomorphometric indices expressing thermic regime of terrain relief, done by its openness and protection of a locality by surrounding relief, and characterizing terrain by hydrological processes. We calculated indices available in the SAGA GIS software for each sample plot (Table 1). We used the Digital Terrain Model (DTM) with a spatial resolution 30×30 m transformed into the coordinate system UTM (the zone north, tier 48). The DTM data derived from the ASTER GDEM (Global Digital Elevation Model) were resampled to achieve: (1) a feasible compromise between a geographical extent of landscape-level units considered and a grain (a pixel size) characterizing an appropriate level of detail of terrain topography, and (2) faster calculation of the indices. Our aim was to filter out microsites (different microclimate or soil moisture conditions).

Climatic data. Climatic data in a form of raster data of annual mean air temperature and total annual mean precipitation with resolution of 900×600 m were generated using the free of charge Worldclim database (www.Worldclim.com) and interpolated from available climatic stations for the sample sites. Quality climatic data are not available in Mongolia due to a thin network of weather stations and plots (Kusbach et al. 2017b).

Data analysis

We performed the following analytical steps: (1) ordination of the sample plots/ecosystems based on environmental data; (2) cluster analysis of ecosystems based on important environmental variables examined in the ordination; (3) discriminant analysis of clusters based on important environmental variables; (4) analysis of variance (ANOVA) of environmental data with clusters. The total dataset was comprised of 49 zonal sites, 26 geomorphic indices, and 21 other environmental variables (including climate and soil).

We used principal components analysis (PCA) ordination to determine the relative importance of the environmental variables and interpret principal components (PC) associated with zonal sites. In the first PCA run, we distinguished among

26 geomorphic indices calculated for each sample plot. Orthogonal rotations and correlation type of a cross-products matrix were used to derive independent, mutually uncorrelated PCs (Lattin et al. 2003). We checked for outliers during the PCA run. Significance of PCs was tested using a Monte Carlo randomization (based on proportion-based p-values for each PC). In order to find the relationship of the variables with the PCs and interpret PCs, we calculated correlation coefficients (loadings) with each ordination axis: the linear (parametric Pearson's *r)* and rank (nonparametric Kendall's *tau*) relationships between the ordination scores and the variables. Our use of *r* and *tau* is suggested to be more conservative than p-values for the null hypothesis of no relationship between ordination scores and variables (McCune et al. 2002). We set the threshold for *r* and tau > 0.4 (e.g., Hair et al. 2013). Based on the first PCA run, we selected significant geomorphic indices, which were used together with the environmental variables (climate and soil) in the next PCA run.

To associate the ecosystems with important environmental factors obtained in the PCA, we performed cluster analysis. We used Ward's (1963) linkage method with Sorensen (Bray-Curtis coefficient) distance as suggested by McCune et al. (2002). We transformed the variables with |skewness|>1, standardized the data by adjustment to standard deviate (z-scores) and checked the dataset for outliers. A clustering dendrogram was scaled by a distance objective function (Wishart 1969). Resulting clusters were hereafter considered analytical classes.

Random Forests analysis (Breiman 2001), a machine-learning bootstrapping method, was used to identify the most important environmental variables associated with meaningful clustering to highlight cluster differences. Random Forests is accurate, combines many classification trees, and determines variable importance (e.g., Chen et al. 2004). Results were produced for all classes including among-class partial misclassification errors (taken from the RF confusion matrix). Important factors (the most influential when assigning classes to observations in the RF algorithm) were ranked in the RF variable importance analysis according to Mean Decrease Accuracy and Mean Decrease Gini. For the machine-learning training (to grow a 'forest'), we used ntree = 1000 (a number of trees as a function in R) and mtry = 1, 2 and 3 (a number of variables randomly used at each split) (Liaw and Wiener 2002).

Using the most important factors obtained from Random Forests classification and PCA, we confirmed differences between the clusters/classes by the Kruskal-Wallis test (one way non-parametric ANOVA). Finally, using results of the first two PCA runs and meaningful clustering, we displayed broad landscape units as the zones in the third PCA run.

The randomForest and ANOVA analyses were carried out in the program R 3.0.0 (R Core Team, 2014). PC-ORD 6 (McCune and Mefford 2011) was used for PCA ordination and clustering. ArcGIS 10.3 (ESRI, Redlands, LA, USA) software with the Spatial Analyst superstructure and SAGA GIS software (Institute of Geography, University of Hamburg, Hamburg, Germany) were used for the calculation of the geomorphic indices.
Taxonomy and nomenclature of vascular plants followed Grubov (1982).

RESULTS

We identified the following parent materials and substrates on the zonal sample plots: alcalic granite, para-gneiss, metaquartzite, basic methamorphite, loess, eolian sand, and delluvial deposits.

We identified these soil groups on the zonal sample plots: Arenosols, Cambisols, Chernozems, Kastanozems, Phaeozems, Luvisols, and Umbrisols (WRB 2014).

We calculated correlations (r) among 26 geomorphic indices and kept only indices with a strong r > 0.8. The first PCA ordination (49 plots, geomorphic indices) resulted in three significant PCs (p = 0.001), explaining respectively 31, 21 and 11 % of the total variance within the geomorphic indices (Appendix A). The most important principal component (PC1) was highly associated with macroclimatic indices; Stand_H (r = -0.9, tau = -0.7), R_Slope (r = -0.8, tau -0.7), Norm_H (r = -0.8, tau = -0.6), Alt (r = -0.7, tau = -0.5). PC1 was interpreted as a macroclimate gradient. PC2 was associated with Terrain Roughness (0.9, 0.7), Catchment Slope (0.8, 0.7), Slope (0.6, 0.6), and Protection (0.7, 0.6) (Table 1, Appendix A). We interpreted this as a topographically based soil moisture gradient. (Appendix A).

For the next PCA step, we kept only macroclimatic indices following the zonal concept conditions. We added 21 climatic and soil factors and ran the second PCA. The second PCA (49 plots, 28 environmental factors) resulted in three significant PCs (p = 0.001), explaining respectively 31, 13 and 10 % of the total variance within the environmental factors (Appendix B). As in the first PCA run, the most important principal component (PC1) was associated with macroclimatic indices. PC1 was interpreted as a macroclimate gradient. PC2 was highly associated with soil factors, Soil Organic Matter (r = 0.6, tau = 0.5), Organic C (0.6, 0.5), and pH (0.5, 0.4). We interpreted this as a soil properties gradient (Appendix B).

In the cluster analysis (47 plots - without two plot outliers, 13 significant environmental factors in the second PCA), there was a stable three-cluster solution based on the distance objective function and information retained (stability of the three-cluster solution was indicated by the longest horizontal distances of clusters' branches). There was considerable similarity in environmental factors between physiognomically different ecosystems such as *P. sylvestris*, *B. platyphylla* and *P. tremula* (Fig. 2).

The Random Forests classification identified those environmental factors most strongly associated with this three-cluster solution. Four environmental factors were identified as important discriminating the clustering of sites. In order of importance by Mean Decrease Accuracy and Mean Decrease Gini in brackets, we chose two morphometric indices - Vertical Distance to Channel Network (23.1, 5.3), Altitude (21.8, 5.2), one soil factor - O horizon thickness (16.5, 2.8) and one climatic factor - Total Annual Mean Precipitation (10.3, 1.5). The ranking of variable importance was quite stable for solutions with three variables randomly used at each split (mtry function in R), and 1000 trees used to grow a "forest" (ntree function in R, Liaw and Wiener 2002). "Out-of-bag" estimate of error rate as a measure of misclassification was 4 %.

Kruskal-Wallis test confirmed overall significant differences among the zones in: Vertical Distance χ-squared value = 34.6, Altitude = 35.7, O horizon thickness = 22.0, Total Annual Mean Precipitation = 20.1 (Fig. 3). We designated low elevation *P. sylvestris* and *U. pumila* forests into the forest-steppe zone, mid elevation *P. sylvestris*, *B.*

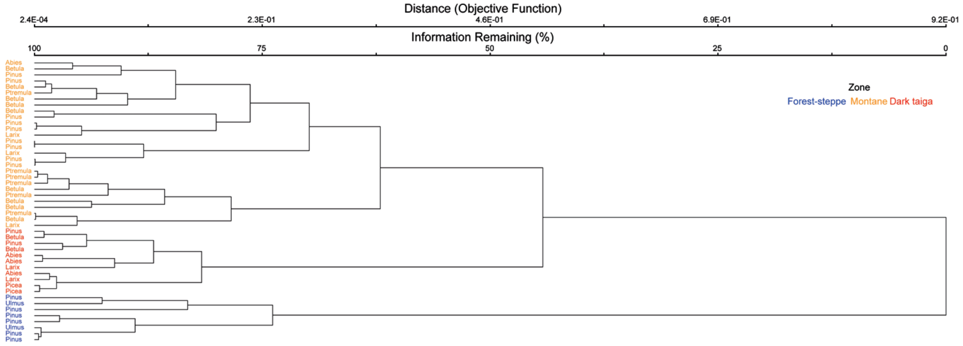

Fig. 2. The cluster analysis dendrogram with the stable and feasible three-cluster solution. ***Abies = Abies sibirica, Betula = Betula platyphylla, Larix = Larix sibirica, Picea = Picea obovata, Pinus = Pinus sylvestris, P. tremul = Populus tremula, Ulmus – Ulmus pumila***

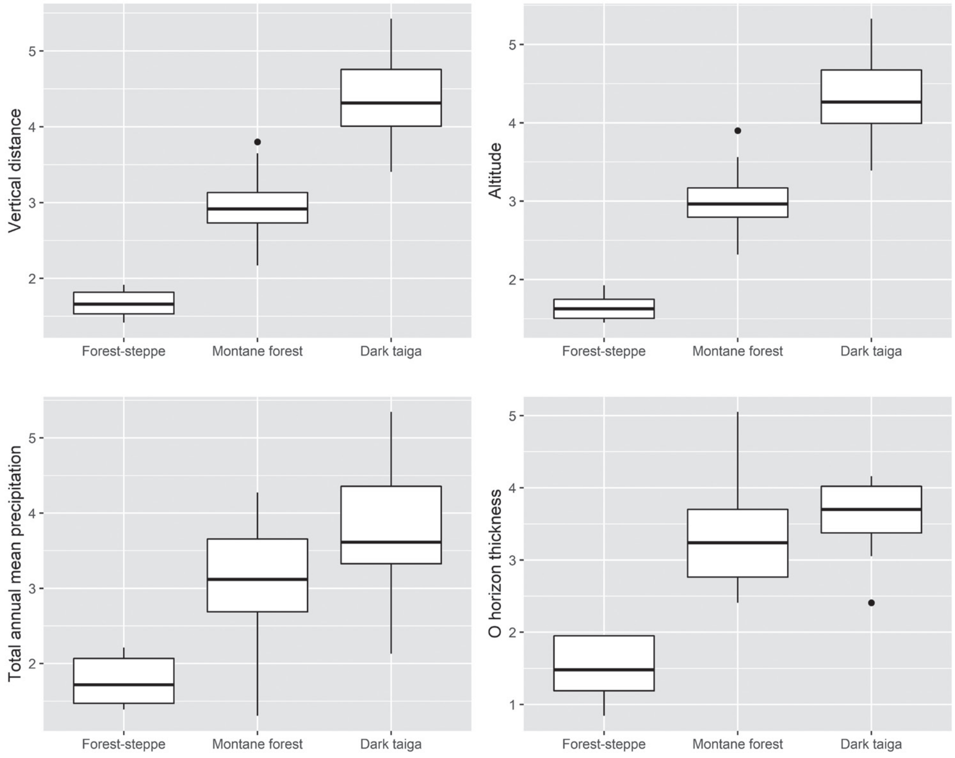

Fig. 3. Geo-vegetation zones and their significant relationship with the most important environmental factors. For all factors p< 0.001

platyphylla, P. tremula and *L. sibirica* forests we referred to as the montane zone, and high elevation *L. sibirica, A. sibirica, Picea obovata* forests to as the dark taiga zone (Fig. 2). We set up thresholds for the important factors.

Using the most important factors obtained in the Random Forests classification, we constructed a biplot of ecosystems with influential factors in the environmental space in the final PCA run. PC1 was the macroclimatic gradient, p = 0.001. Envelopes clearly delineated the three distinguish zones (Fig. 4).

DISCUSSION

Geo-vegetation zonation

Hilbig and Knapp (1983) presented an altitudinal-based stratification of the lower and upper montane belt in the Khentii Mountains, extended by vegetation classification and floristic description of Dulamsuren et al. (2005). Similarly, ecosystem mapping for the whole territory of Mongolia (Vostokova and Gunin 2005) offers information on "mesoecosystems" characterized by an ecotope (terrain relief and surface deposits with soil-plant cover in matrix setting) in a basic scale of 1: 8 000 000. Although this mesoscale mapping is supported by "detailed field surveys in stationary field areas" (no scales of those middle-scale maps are provided), this approach differs from ours using the zonal concept. While there is some consistency between the altitudinal structure of forests in Vostokova and Gunin (2005) (scale 1: 8 000 000), and our suggested zonation, Vostokova, Gunin and others (2005) distinguished the forest ecosystems, altitudinal zones and ecosystem types without clear interconnection. They used basic physiognomy for ecosystem and zone naming, e.g., dark taiga, pseudotaiga, subtaiga etc. (similarly to e.g., Korotkov 1976; Tsedendash 1995; Tsogtbaatar 2004; Dulamsuren et al. 2005) and exceptionally an edificator information, e.g., larch, pine forest for the types. No information on a successional status or disturbances was provided. Other environmental factors except a descriptive relief and soil typing (probably Nogina et al. 1980) stayed unclear.

Our analysis revealed a strong altitudinal pattern based on a broad ecological range of data (climate, geomorphology, soil and vegetation). To our best knowledge, our study is the first attempt to ecologically discriminate vegetation along a relatively comprehensive environmental gradient and quantify significant factors at a macroclimatic level in the Khentii massif. That means the study is data driven, we did not rely on traditional expert knowledge typical for all major worldwide ecological classification systems. We distinguished three **geovegetation zones** characterized by the environmental thresholds: the forest-steppe, montane and dark taiga zone (Fig. 2, 4, Table 2). These zones occur as stacked, vertical belts with distinct climatic, geomorphologic and soil differences. However, when examined in detail, the boundary between these zones is not so abrupt because of local topography, which modifies vegetation at a mesoclimatic level (Dulamsuren et al. 2005; Kusbach et al. 2017b).

In lower elevations, the forest-steppe zone is linked to the true steppe zone without a real tree cover (Karamysheva and Khramtsov 1995). *P. sylvestris* parklands and *U. pumila* woodlands characterize the zone. Since these ecosystems experience frequent wildfires (Goldammer 2002; Oyunsanaa 2011), *Pinus* can be considered the potential climatic climax species because there is no shade tolerant tree species within the zone (Pojar et al. 1987; Kusbach et al. 2017b). Successional status of *U. pumila* is poorly understood. A heterogeneous substrate and rich steppe (mostly grass) understory vegetation under open canopy forests (Dulamsuren et al. 2005) are reflected by fertile Chernozems, Kastanozems, Phaeozems and Arenosols (almost no O horizon, a thick A horizon rich in soil organic matter and organic carbon). The zone is warmer and drier than the montane zone (Table 2, Fig. 3, 4). Therefore, in general, the forest cover does not exceed 50 % of the total zone area. This cover can be seen almost exclusively on north, northeast-facing slopes within this zone.

Larix sibirica, Pinus sylvestris, and *Betula platyphylla* are the climatic climax species for the montane zone, which consists of close canopy forests (Fig. 2, 4). Nevertheless, these ecosystems also experience frequent wildfires. Higher potential productivity of prevailing Phaeozems, (less Kastanozems) is indicated not just by higher precipitation, thick O and A horizons with a high amount of soil organic matter (organic carbon), but also by modest pH and presence of important macronutrients Ca, Mg, P and K that were insignificant in the analysis. The zone is cooler and moister than the forest-steppe zone (Table 2, Fig. 3, 4, Appendix B). Therefore, in general, a forest cover is higher than 50% of the total zone

Table 2. Identification of the geo-vegetation zones. Zones' differences are significant for all factors (p = 0.001). For factor abbreviations, see Table 1

Zone	Altitude (m a.s.l.)	Vertical_D (m)	Precip (mm)	O hor (cm)	Substrate	Soil groups
	Mean (range)					
Forest-steppe	803 (753-875)	61 (6-119)	304 (299-309)	1.3 (0.5-2)	sand, loess	Kastanozems
						Phaeozems
Montane	1130 (975-1379)	333 (177-549)	319 (298-331)	6.5 (3-20)	gneiss	Phaeozems
					granite	Kastanozems
Dark taiga	1391 (1090-1744)	590 (322-918)	327 (308-347)	7.8 (3-11)	gneiss	Cambisols
					granite	Umbrisols

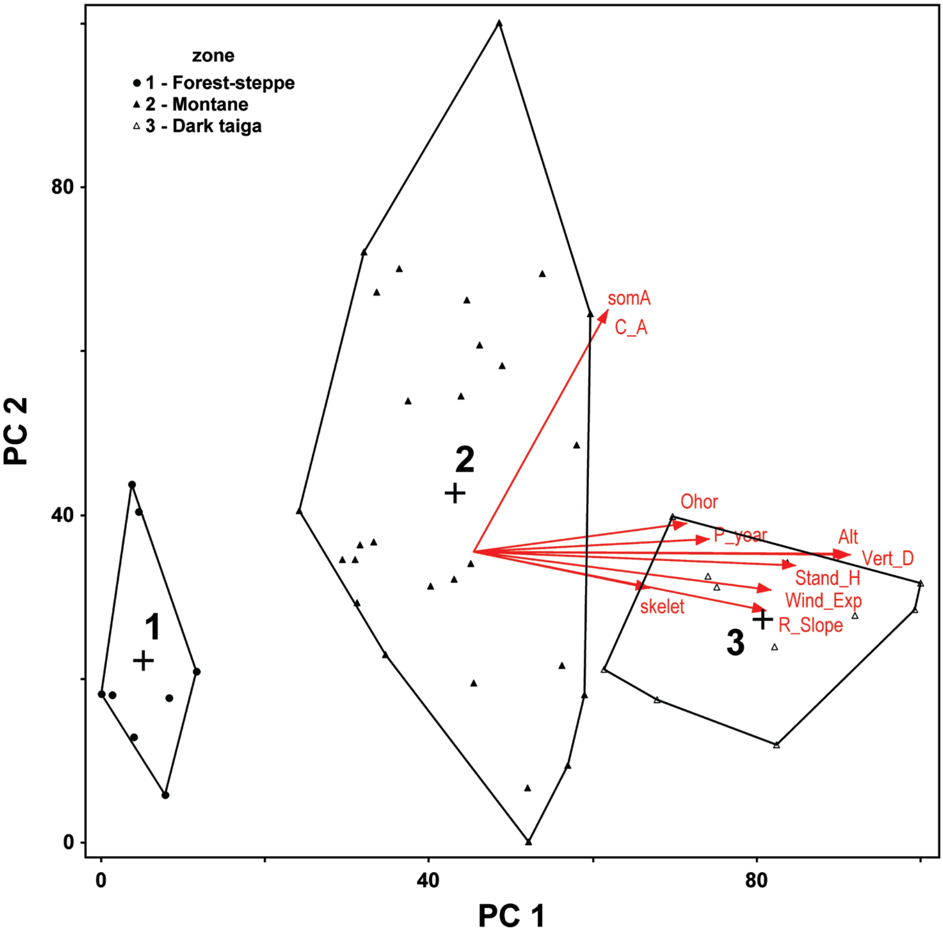

Fig. 4. Biplot of the final PCA run with a clear macroclimatic gradient (PC1) and the geo-vegetation zones. For the vector labels, see Table 1 in the text

area. In lower, more accessible parts of the zone, *B. platyphylla* tends to be more abundant than *L. sibirica* or *P. sylvestris* due to logging (since late 1960s up to now), which favored removal of valuable conifers (Dulamsuren et al. 2005; Kusbach et al. 2017b). High intensity logging limits the regeneration of *Pinus* in this area, reduces seedling numbers and creates conditions that are suitable only for the regeneration of deciduous tree species (Gerelbaatar et al. 2019). Thus, the conifers' return into these parts is problematic due to the absence of seed trees, poorly developed or missing natural regeneration and often overgrazing. Artificial planting is usually necessary in those broadleaved ecosystems (Kusbach et al. 2017b; Juřička et al. 2019).

Abies sibirica, Pinus sibirica and *Picea obovata* are shade-tolerant and climatic climax tree species of the dark taiga zone, which together with *Betula platyphylla* and *Populus tremula* consist of close canopy forests (Fig. 2, 4). In the highest elevations, we identified Cambisols and Umbrisols (Phaeozems only under broadleaved spp.). The zone is indicated not just by higher precipitation, thick O and thinner A horizons with a high amount of soil organic matter (organic carbon), but also by lower pH and amount of important macronutrients Ca, Mg, P and K. The zone is cool and moist (Table 2, Fig. 3, 4, Appendix B). In general, the forest cover is close to 100 % of the total zone area. Because of lower accessibility of the zone, its vegetation is relatively untouched. Five of our six dark taiga sites were found in an old-growth, never logged forest.

Birch and aspen communities are off the geo-climatic zonation

The ecological amplitude of *Betulla platyphylla* and *Populus tremula* is extremely broad compared to conifers. In our study area, this amplitude is represented by birch's (1) large altitudinal range, from low azonal sites within the forest-steppe zone (ca 750–800 m a.s.l.) through zonal sites within the montane zone, up to 1473 m a.s.l. within the dark taiga zone, and (2) heterogeneous geomorphology, as indicated by occurrence on diverse substrates and soils (Fig. 2, 3, Table 2). The wide range of climate and geomorphology/soils is associated with large differences in nutrient availability among soils in birch-dominated sites. Birch and aspen occur on rich sites with surpluses of humus and macronutrients such as N, K, Ca, and Mg. It also occurs on relatively poor and more acidic sites in high altitudes, where some macronutrients may be deficient (especially the bases Ca, Mg) (Appendix B). On the other hand, rather than a reflection of the environment, birch-dominated stands in the area are mostly a result of human-induced disturbances such as logging for a valuable conifer timber. Additionally, considerable environmental similarity between physiognomically different ecosystems such as *B. platyphylla, L. sibirica, P. sylvestris,* and *P. tremula* (Fig. 2) may suggest successional stages of these ecosystems. They, being close in environmental factors, might be distinguished by other than these factors, e.g., disturbance. For example, there was no single environmental factor, important at the level of regional climate that can discriminate birch and aspen ecosystems (secondary small-leaved forests, Vostokova and Gunin 2005) as discrete geo-vegetation zones (Kusbach et al. 2014). Thus, these ecosystems are azonal, driven by disturbance regimes either anthropogenic (logging) or natural (fire).

Implications for management

In Mongolia, the forestry sector is under development (Tsogtbaatar 2007; Batkhuu et al. 2011). Except the Resolution by the Parliament of Mongolia No. 49, the State Policy on Forest adopted in May 14, 2015, and the Law on Forest updated in 2012, lower level guidelines (using tools analogical to CFEC and RPFD in the Czech Republic) important for starting of sustainable forest management are missing. A state of forests, highly exposed to depletion and degradation especially in a forest-steppe buffer zone is alarming (Vostokova and Gunin 2005; Batkhuu et al. 2011; Kusbach et al. 2017b). Forests generally grow in extreme conditions with low productivity, poor regeneration capacity and over-harvesting (Gerelbaatar et al. 2019). The state forest policy should be changed towards detailed legislation based on ecological and sustainable principles (Altrell and Erdenebat 2016). In regions without earlier ecological classification systems such as Mongolia, our approach has considerable potential for the development of ecologically sound classifications. We suggest that management and ecosystem studies should be viewed in the context of a comprehensive ecological classification (e.g., Haeussler 2011). This framework will facilitate detailed ecosystem structuring at lower ecosystem levels e.g., for a site discrimination.

For example, the geo-vegetation structuring suggested in our analysis was used in development of the first forest management plan in Mongolia based on ecological principles (Smola et al. 2019). Forest management of the forest property of the Domogt Shariin Gol Company Ltd. was recommended for forest development types, the units designed for important landscape environmental gradients. Besides relatively "static" properties (Kusbach et al. 2014), also dynamic indicators (disturbances such as fire) influencing forest ecosystems were considered. Resulting forest development types and subtypes were further structured for age of forest stands (Smola et al. 2019).

At the beginning of regular sustainable management of forests, the systematic classification framework and management guidelines such as CFEC and RPFD, are, within the expert lacking settings of the Mongolian forestry sector, absolutely necessary. The geo-vegetation zonation suggested here, should be expanded and further tested on greater objective data sets, e.g., data coming from the national inventory (Altrell and Erdenebat 2016). Moreover, the forest ecological classification will serve as a reference platform for recent ecological issues such as global climate change resulting in potential changes of ecosystems and important communication tool within and between ecosystem research and management (e.g., Kotar 1988; Kusbach et al. 2014). Besides, it will provide a framework for practical interpretations and decisions such as collecting, organizing and reporting ecological information, e.g., in wildlife, timber, soil and water management, biodiversity, restoration and conservation (e.g., Zenner et al. 2010; Čermák et al. 2019; Smola et al. 2019).

CONCLUSIONS

Based on complex data and multivariate statistics, we identified three geo-vegetation zones in the study area: (i) forest-steppe, (ii) montane and (iii) dark taiga. The zones were defined as areas with a similar potential overstory composition in climatic climax in order to provide a coarse-scale framework for building comprehensive ecological classification. Our results are in compliance and specify earlier botanical studies of the region. However, we quantified significant factors, set up macroclimatic environmental limits and characterized these zones by macroclimate, geomorphology, and soils represented by O horizon thickness and soil types. Birch and aspen ecosystems were excluded as the discrete zones from the zonation due to their great ecological amplitude, successional status and predominantly disturbance-based origin.

The geo- vegetation zonation outlined in our study is to our best knowledge, the first attempt at quantifying vegetation along with the environment at a macroclimatic level in Mongolia. A comparable framework is missing in Mongolia, similar approach can be applied elsewhere in central Asia: (i) for development of forest management framework and (ii) as an information platform and reference for current environmental issues in Mongolian landscapes.

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