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Vegetation classification of *Stipa* steppes in China, with reference to the International Vegetation Classification

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Abstract

Aims: The vegetation classification system of China (China-VCS) is not completed. *Stipa* steppes are the most important steppes in China. Here we made optimal use of available plot data to classify *Stipa* steppes into associations in a way that is consistent with International Vegetation Classification. **Study Area:** the Songnen Plain, Inner Mongolian Plateau, Loess Plateau, Tibetan Plateau, and the northwest mountain areas of China. **Methods:** We used 1337 plots to partition the *Stipa* steppes of China into clusters using hierarchical clustering. Supervised noise clustering was used to improve the classifications at the group, alliance, and association levels. Non-metric multidimensional scaling ordination was used to visualize the homogeneity of plots within each cluster, and we overlaid site and climatic vectors. Diagnostic species were identified for each cluster using Indicator Species Analysis. **Results:** We defined five biogeographic groups, 26 alliances, 91 associations, and 12 communities of *Stipa* steppes of China. The *Stipa*-dominated alliances in the framework of the current China-VCS were verified, but the four vegetation subformations of Tussock Steppe were not completely supported by this study. **Conclusions:** This is the first systematical and comprehensive classification for *Stipa* steppes in China based on plot data. Our classification used a set of dominant species and diagnostic species to define biogeogrpahic groups, alliances and associations, ensuring compatibility with the International Vegetation Classification.

Taxonomic reference: Flora Reipublicae Popularis Sinicae, Flora of China

Abbreviations: AMT = Annual Mean Temperature; AP = Annual Precipitation; China-VCS = vegetation classification system of China; IVC = international vegetation classification; MTCQ = Mean Temperature of Coldest Quarter; MTWQ = Mean Temperature of Warmest Quarter; NC = noise clustering; NMDS = non-metric multidimensional scaling; PDQ = Precipitation of Driest Quarter; PS = Precipitation Seasonality; PWQ = Precipitation of Wettest Quarter; TS = Temperature Seasonality

Keywords

alliance, association, China, *Stipa*, steppe, vegetation classification

Introduction

Understanding the regional variation in plant community composition is essential for developing strategies of natural resource management and conservation, and for planning ecological restoration programs (Faber-Langendoen et al. 2014; De Cáceres et al. 2015; Franklin et al. 2015, 2018). Vegetation classification summarizes the spatial and temporal variation of vegetation using a limited number of vegetation types (De Cáceres et al. 2015).

There is increasing interest in developing internationally agreed standard approaches for vegetation classification (De Cáceres et al. 2015, 2018; Franklin et al. 2016). Many countries, such as USA, UK, the Czech Republic, New Zealand, South Africa and Mongolia, have developed their plot-based national vegetation classifications using standardized classification procedures and quantitative methods (Hilbig 1995; De Cáceres et al. 2018).

Based on the phytocoenological-ecological approach, the vegetation classification system of China (China-VCS) was developed in 1980 (ECVC 1980) and revised in 2014 (Chen et al. 2014; Guo et al. 2018) and 2020 (Guo et al. 2020). In the latest revision of China-VCS, the upper level units of the previous classfication systems were revised, and the corresponding English terms of all units were also revised (Fang et al. 2020; Guo et al. 2020), to some extent, making it more compatible with current international standards, such as the International Vegetation Classification (Faber-Langendoen et al. 2014). The main principles for vegetation classification include vegetation physiognomy and structure, dominant species, floristic composition, dynamics, and environmental attributes. For natural/semi-natural vegetation, there are three levels including eight units in the hierarchical framework of China-VCS: upper level (Vegetation Formation Group, Vegetation Formation, and Vegetation Subformation), middle level (Alliance Group, Alliance, Suballiance), and lower level (Association Group, Association) (Suppl. material 1: Table S1.1). Among these, the Vegetation Formation, Alliance and Association are the main upper, middle and lower levels, respectively. In this system, nine vegetation formation groups and 48 vegetation formations were defined, and 23 natural and semi-natural vegetation formations were further classified into 81 vegetation subformations (Guo et al. 2020). However, this vegetatation classification at the upper levels was mainly based on expert opinion, dominant species and their growth forms; there is no systematic census of alliances and associations for the entire country due to the lack of adequate supporting plot data (Guo et al. 2018; Fang et al. 2020).

Steppe vegetation in China, which is an important component of Eurasian steppe, extends from the northeast to southwest of the country across 23° latitude (28°-51°N). Steppes occur extensively on the Northeast Plain, on the Inner Mongolian Plateau and the Loess Plateau, in the extensive mountain areas of northwestern China, and on the Tibetan Plateau, along substantial precipitation and altitude gradients, with a wide range of temperatures (ECVC 1980; ECVMC-CAS 2007; Li et al. 2019; Qiao 2019). Extensive vegetation survey and classification has been done for steppes in the relevant region, such as Russia and Mongolia, and the steppe alliances and associations were comprehensively described (Lavrenko and Karamysheva 1993; Hilbig 1995, 2000, 2009; Wesche 2005; Ermakov 2006; von Wehrden et al. 2009; Zemmrich et al. 2010). An equivalent systematic classification of Chinese steppes is needed to facilitate Chinese vegetation study and classification, grassland ecosystem management and also international communication. Grasses of the *Stipa* genus are the most common and dominant constituents of steppe vegetation (Hamasha et al. 2012). According to the latest China-VCS, *Stipa* steppe (Alliance Group) includes 22 alliances identified by different *Stipa* species dominating the communities. These *Stipa* alliances are assigned into four vegetation subformations (i.e., Tussock Meadow Steppe, Tussock Typical Steppe, Tussock Desert Steppe, and Tussock Alpine Steppe), which belong to the vegetation formation "Tussock Grassland" of the vegetation formation group " Herbaceous Vegetation" (Guo et al. 2020; Suppl. material 1: Table S1.2). However, this classification was mainly based on expert opinion, community distribution ranges and ecological context but not on a plot data-based numerical analysis. Only a few studies have investigated the community characteristics of a small number of *Stipa* steppe alliances and conducted an association classification based on dominant species (Yang et al. 2014; Qiao et al. 2017a, b, 2020; Zhao et al. 2018; Zhu et al. 2018; Lu et al. 2020). Moreover, some *Stipa* species are very similar and hard to distinguish. In previous vegetation surveys and studies, many species were falsely identified, particularly when it came to distinguishing between some *Stipa* species and their varieties, such as between *Stipa tianschanica* var. *gobica* and *Stipa tianschanica* var. *klemenzii*, *Stipa subsessiliflora* var. *basiplumosa* and *Stipa subsessiliflora*, and *Stipa roborowskyi* and *Stipa purpurea*, which further resulted in incorrectly documenting the characteristics of these *Stipa* steppes (ECVC 1980; IMNSEG-CAS 1985; Yang et al. 2014; Qiao et al. 2017a; Zhu et al. 2018).

In this study, we used 1337 plot data from extensive field surveys across the distribution area of *Stipa* steppes in China to conduct a systematical quantitative vegetation classification for *Stipa* steppes of China. Three aims are addressed: (1) To examine the validity of the *Stipa*-dominated steppe alliances and vegetation subformations; (2) to refine the classification of *Stipa* steppes to assocation level; (3) using the *Stipa* steppe as an example, we discuss how to improve the compatibility of the Chinese vegetation classification with the International Vegetation Classification (IVC) since the China-VCS and EcoVeg approaches have many similarities (Liu et al. 2019; Faber-Langendoen et al. 2020). Both approaches have eight nested hierarchical classification levels for natural/semi-natural vegetation and use similar principles and criteria for the assignment of vegetation types, including major growth forms (physiognomy), vegetation structure, species composition or floristics, and ecological context (Faber-Langendoen et al. 2018, 2020; Guo et al. 2018, 2020). Physiognomy plays a predominant role at the upper levels and floristics at the lower levels in both classification systems. Floristic definitions of types at lower levels in the EcoVeg approach are based on 'characteristic species combinations', which include diagnostic, constant and dominant species (Faber-Langendoen et al. 2018). However, lower levels in the China-VCS emphasize dominant species in multiple strata, based on species' relative abundances (or Importance Values). The association, alliance, and vegetation subformation levels of the China-VCS are somewhat similar to the association, alliance, and division levels of EcoVeg, respectively (Liu et al. 2019; Faber-Langendoen et al. 2020).

Study area and methods

Plot collection and vegetation survey

Stipa steppes of China occur extensively on the Northeast Plain, the Inner Mongolian Plateau, Loess Plateau and Tibetan Plateau, and in the mountain areas of northwestern China. The locations of the 1337 plots recorded in this study cover the entire distribution areas of *Stipa* steppes in China (Fig. 1). We acquired plot data from two Chinese government launched national programs, "the Compilation of the Vegetation Monographs of China" (vegetation program) and "Strategic Priority Project of Carbon Budget" (carbon program), and all plots had *a priori* assignments to existing *Stipa* steppe alliances allocated by the investigators based on dominant species. We also collected some plots from the west of Mongolia as *Stipa* steppes are continuously distributed on the Mongolian Plateau (Hilbig 1995; von Wehrden et al. 2009). Both programs conducted extensive vegetation surveys on the main vegetation alliances using similar standard methods. In grasslands, the vegetation program used inventory plots of 20 m × 50 m, and then randomly established 3–5 subplots of 1 m × 1 m for intensive vegetation survey. Within each subplot, cover (percentage), height (cm), and density (number m^{-2}) of each plant species was measured and aboveground biomass (g m^{-2}) was also sometimes determined by harvest methods. Averages of these measurements for each plot were calculated from the subplot data. The carbon program used inventory plots of 100 m × 100 m, and then established 10 subplots of 1 m × 1 m along a diagonal line, of which five were treated as intensive subplots. Within each of the five intensive subplots, height, density, and aboveground biomass of each species were measured. At the same time, total cover, mean height and total aboveground biomass in each of the other five subplots were measured. We used data from the five intensive subplots to calculate averages for each plot. All species were identified according to Flora Reipublicae Popularis Sinicae (FRPS, i.e., Flora of China in Chinese version; ECFRPS 1959–2004) and Flora of China (ECFC 1994–2013). We standardized and established unique taxonomic names for each plant species prior to analysis. We removed unknown taxa and retained those that were identified to species level only. We treated *Poa sphondylodes* and *P. attenuata* as *Poa* sect. *Stenopoa* since they are very difficult to identify. Some genus-level taxa were retained because of their high abundance and constancy in plots.

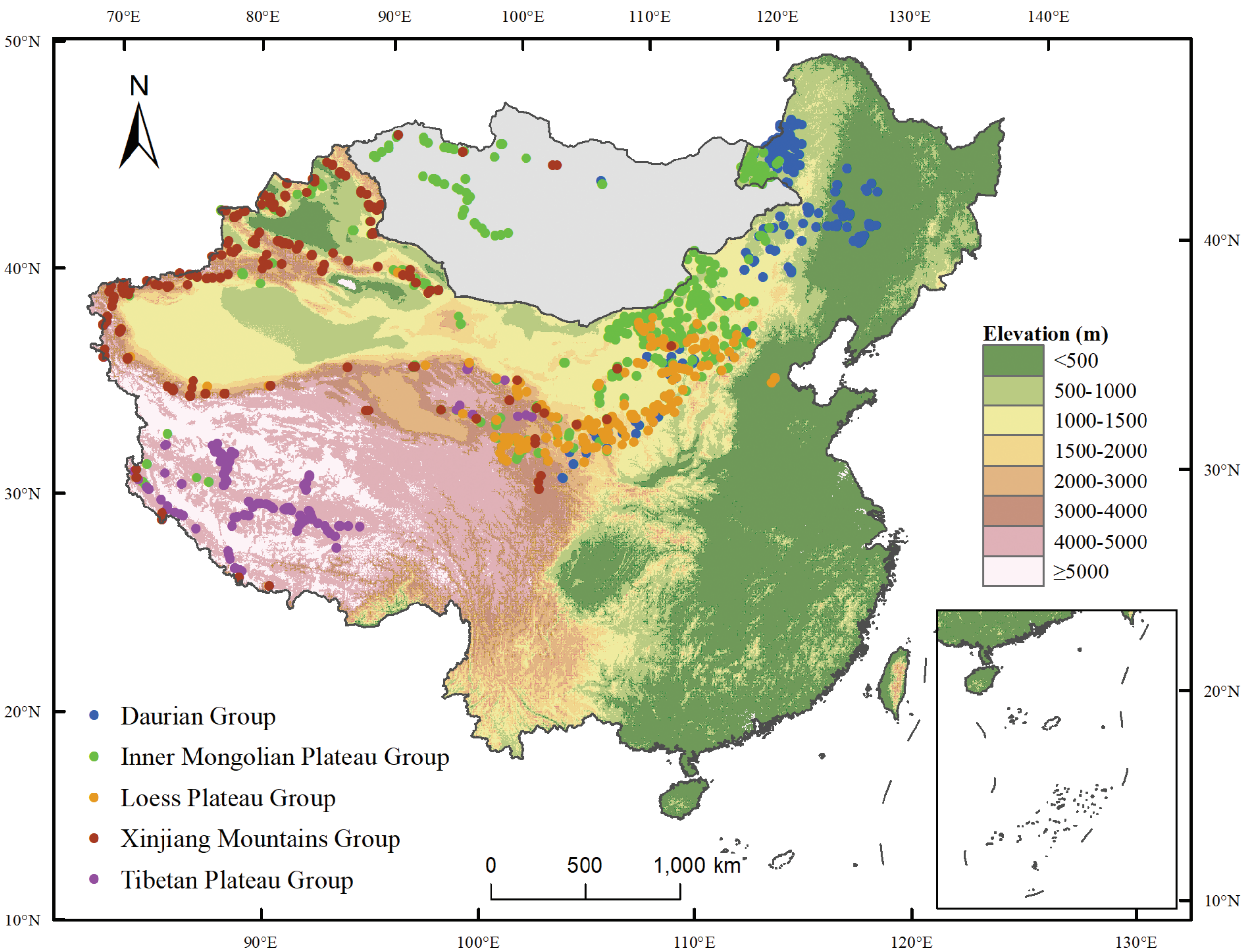

Figure 1. Map showing plot locations of *Stipa* steppes. Plots are highlighted by five biogeographic groups based on hierarchical clustering.

Using plot geocoordinates, we extracted bioclimatic variables for each study site from climate grids with a spatial resolution of 30 arc-seconds (Hijmans et al. 2005). The grid data were downloaded from WorldClim (http://www.worldclim.org/). The climatic variables included Annual Mean Temperature (AMT), Temperature Seasonality (TS), Mean Temperature of Warmest Quarter (MTWQ), Mean Temperature of Coldest Quarter (MTCQ), Annual Precipitation (AP), Precipitation Seasonality (PS), Precipitation of Wettest Quarter (PWQ), and Precipitation of Driest Quarter (PDQ).

Data analysis

Multivariate analyses were conducted using species relative abundance (Importance Value, IV), which was calculated from relative cover and relative height for the data collected by the vegetation program and calculated from relative aboveground biomass and relative height for the data collected by the carbon program. The IV of each species in one plot was calculated as: IV=(relative cover or relative biomass + relative height)/2. The relative cover of each speces was calculated as: the cover of each species/the sum of cover of all species×100%, and the relative biomass and height were calculated in the same way. Our previous study revealed that the aboveground biomass was highly related with cover in *Stipa* steppes, and vegetation classification based on cover and aboveground biomass data yielded comparable results (Liu et al. 2019). Therefore, in this study, we combined the two data sets of Importance Value to get a whole data set (1337 plots × 1261 species). The data matrix was log(x+1) transformed to improve "normality" (Peck 2016).

We first deleted the species that only occurred once and then deleted 31 plot outliers based on the outlier analysis procedure in the PC-ORD 7 software (Sørensen distance, with 2.0 sd cutoff). We used the remaining data set of 1306 plots × 893 species for further analyses. We calculated a Sørensen dissimilarity matrix and used agglomerative, hierarchical clustering with flexible-beta group linkage (β = -0.25) on this data set. We then used silhouette width and partana ratio to determine the optimal number of clusters, using the stride procedure in R (Optpart library; Roberts 2016). Silhouette width compares the mean similarity of each plot to plots in its own group with the mean similarity to plots in the most closely related group, while partana ratio compares the mean similarity within clusters to the mean similarity among clusters. We first partitioned the data set into five biogeographic groups based on multivariate classification. We then used non-metric multidimensional scaling (NMDS) ordination in PC-ORD to visualize the homogeneity of plots within each group. NMDS was performed based on Sørensen dissimilarity, with 250 runs for the Monte Carlo test for significance for the number of axes. The variation explained by the axes was calculated in PC-ORD, using Sørensen distance for original space and Euclidean distance for ordination space. Then, we re-ran the same analytical procedure to classify each group into clusters at a level of resolution appropriate to the alliance concept in the China-VCS, and each alliance was separately classified into associations or communities. The final cluster with a sample size ≥ 4 was classified as an association, while the final cluster with a sample size < 4 was classified as a community type.

Supervised noise clustering (NC) was used to improve the classifications at the group, alliance, and association level, using results of the previous hierarchical clustering for *a priori* group memberships (Liu et al. 2019). To cast the priori classification into the new NC framework, we first calculated the cluster centroids in the space of the Chord distance and then determined the degree of membership of each plot to each cluster according to two NC parameters, the fuzziness coefficient (m) and the distance to the Noise class (δ) (De Cáceres et al. 2010; Wiser and De Cáceres 2013). The m value was set to 1.1 and δ varied for each classification level, such that 10% of plots were assigned to the noise class (Wiser and De Cáceres 2013). Based on the results of NC, we re-assigned every plot to the cluster with the highest fuzzy membership. Following NC, we re-ran the NMDS procedure to visualize the homogeneity of plots within each cluster and overlaid site and climatic vectors. Indicator species were identified at group, alliance and association levels, using the Indicator Species Analysis of Dufrêne and Legendre (1997) and Monte Carlo randomization tests (1000 permutations) to establish statistical significance, in PC-ORD (McCune and Grace 2002). Indicator value was calculated based on species' relative abundance and frequency among clusters. We selected species with the maximum indicator value at type I error < 0.05 from Monte Carlo tests as indicator species for a specific group, alliance and association.

Results

Classification of *Stipa* Steppes into five biogeographic groups

Our clustering protocol classified the whole data set into five groups that corresponded well to five biogeographic regions of China, i.e., the Daurian region in the northeastern China, the Inner Mongolian Plateau, the Loess Plateau, the mountain areas in Xinjiang, and the Tibetan Plateau (Fig. 1). The differences among these regions are very obvious, in terms of climate and species composition, especially in terms of dominant species.

NMDS ordination of the whole data set (1306 plots × 893 taxa) yielded a two-dimensional NMDS solution that accounted for 29.1% of the compositional variation in the data set (Fig. 2). Plots representing the five biogeographic groups were clearly categorised into discrete clusters in this ordination, with some overlap between the Inner Mongolian Plateau Group and Loss Plateau Group. Axis 1 separated plots of the Tibetan Plateau Group and

Xinjiang Mountains Group from the other three groups, while Axis 2 separated plots of the Daurian Group and the Tibetan Plateau Group from the other three groups. Biplot overlays for temperature (AMT and MTWQ) and altitude (Alt) suggested an associated environmental gradient of increasing temperature and lower elevation with compositional variation on Axis 1. Biplot overlays for precipitation (AP and PWQ) suggested an associated rainfall gradient with compositional variation on Axis 2.

The Daurian Group mainly occurs on the Song-Liao Plain and the eastern Hulun Buir Plateau, and the eastern Xilingol Plateau. The Daurian region lies in the transitional zone between typical steppe and forest regions and has a high proportion of mesophytes due to good water availability. The AMT is 3.1°C and the AP is 382 mm. This group is mainly indicated by *Stipa baicalensis*, *Stipa grandis*, *Leymus chinensis*, *Carex pediformis*, *Lespedeza davurica*, and *Filifolium sibiricum* (Table 1).

The Inner Mongolian Plateau Group mainly occurs on the western Hulun Buir Plateau, the western Xilingol Plateau, the Ulan Qab Plateau, the Ordos Plateau, the loess hills on the south of Yinshan Mountain, and the western Mongolian Plateau. It is the most widespread and representative steppe in the temperate zone of China. The AMT is 3.2°C and the AP is 228 mm. Along with the decrease of precipitation from east to west, vegetation gradually changes from typical steppe to desert steppe. This group is mainly indicated by *Stipa tianschanica* var. *gobica*, *Stipa sareptana* var. *krylovii*, *Stipa tianschanica* var. *klemenzii*, *Stipa caucasica* subsp. *glareosa*, *Allium polyrhizum*, and *Convolvulus ammannii.*

The Loess Plateau Group mainly occurs from the northern Loess Plateau to the Ordos Plateau. The vegetation is highly fragmented due to intensive reclamation and afforestation. This group lies in the warm-temperate zone and many compositional species prefer warm environments. The AMT is 6.1°C and the AP is 313 mm. The indicator species mainly include *Stipa breviflora*, *Stipa bungeana*, *Leymus secalinus*, and *Cleistogenes songorica*.

The Xinjiang Mountains Group mainly occurs in the steppe zones of the Altai Mountain, Tianshan Mountain, Kunlun Mountain, Aljin Mountain and Qilian Mountain, and most of the plots belong to Middle Asian subregion. The AMT is 1.6°C and the AP is 189 mm. This group receives a higher winter and spring precipitation than the other four groups and usually has a thriving ephemeral synusia in early-spring. It is mainly indicated by *Stipa caucasica*, *Stipa orientalis*, *Stipa sareptana*, *Seriphidium* spp., *Festuca ovina*, and *Krascheninnikovia ceratoides*.

The Tibetan Plateau Group mainly occurs on the Qiangtang Plateau, in the upper valley of Yarlung Zangbo river, and in the alpine steppe zone of the Qilian mountain. The AMT is -2.6°C and the AP is 211 mm. To prevail in the cold, arid and windy climate at high altitudes, plants usually have specialized morphological traits, such as a cushion-shape, curly leaf, densely covered with pubescence, and well developed cuticle. This group is mainly indicated by *Stipa purpurea*, *Stipa subsessiliflora* var. *basiplumosa*, *Carex moorcroftii*, and *Krascheninnikovia compacta*.

Classification of the Daurian Group

Our clustering protocol classified this group (188 plots × 411 taxa) into two clusters corresponding to the alliance level of the China-VCS, i.e., *Stipa grandis* steppe alliance and *Stipa baicalensis* steppe alliance (Table 2). NMDS ordination of this group yielded a two-dimensional NMDS solution that accounted for 75.2% of the compositional variation in the data set (Fig. 3). Plots representing the two alliances were clearly grouped into discrete clusters in this ordination. Axis 1 separated plots of the two alliances. Biplot overlays for longitude (Long), latitude (Lat), altitude (Alt), and MTCQ suggested an associated northeastern environmental gradient of decreasing winter temperature and lower elevation with compositional variation on Axis 1.

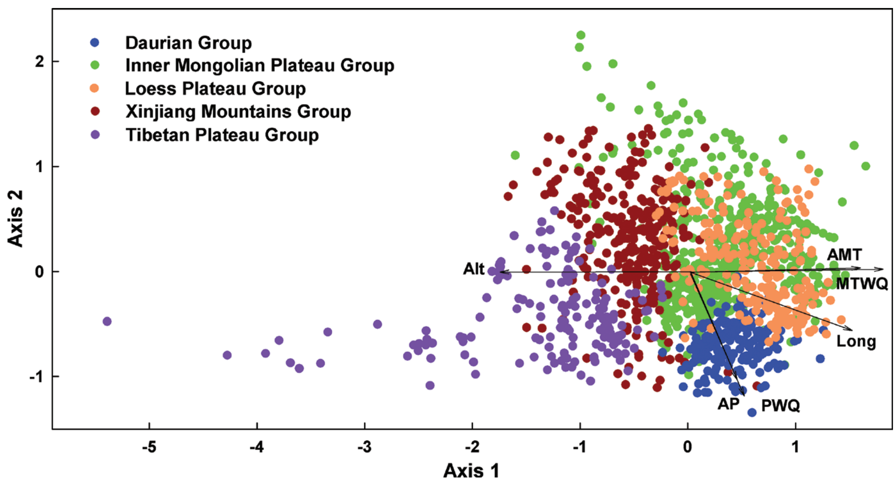

Figure 2. NMDS ordinations of the *Stipa* steppes based on Importance Value data for axes 1 and 2. Plots are highlighted by five biogeographic groups. Stress = 0.21. Site and climatic attributes are overlaid as vectors showing the direction and magnitude of increase for longitude (Long), altitude (Alt), Annual Mean Temperature (AMT), Mean Temperature of Warmest Quarter (MTWQ), Annual Precipitation (AP), and Precipitation of Wettest Quarter (PWQ).

Table 1. Constancy-Importance Value table for five biogeographic groups of *Stipa* steppes in China. The five biogeographic groups are Daurian Group (DG), Inner Mongolian Plateau Group (IMPG), Loess Plateau Group (LPG), Xinjiang Mountains Group (XMG), and Tibetan Plateau Group (TPG). Species are included if they have constancy (Con) ≥ 15% in at least one group. Mean Importance Value (IV) of each species in each group is expressed as percentage. The number in the parentheses is sample size. Indicator species based on Indicator Species Analysis are in boldface type.

Species	DG (188)		IMPG (439)		LPG (231)		XMG (276)		TPG (172)	
	Con	IV	Con	IV	Con	IV	Con	IV	Con	IV
Stipa grandis	**52.1**	**15.4**	1.1	0.1	6.1	0.8	0.4	0.0	–	–
Stipa baicalensis	**53.2**	**10.9**	0.2	0.0	–	–	–	–	–	–
Leymus chinensis	**76.1**	**6.0**	15.0	1.2	16.9	1.4	–	–	–	–
Carex pediformis	**27.1**	**2.1**	2.3	0.1	–	–	2.9	0.2	0.6	0.0
Filifolium sibiricum	**33.5**	**1.7**	0.7	0.0	–	–	–	–	–	–
Poa sect. *Stenopoa*	**34.0**	**1.6**	6.4	0.3	19.1	1.8	1.1	0.1	0.6	0.1
Serratula centauroides	**54.8**	**1.6**	4.6	0.1	1.3	0.0	1.1	0.0	–	–
Achnatherum sibiricum	**32.5**	**1.3**	3.2	0.2	0.4	0.0	1.5	0.1	–	–
Carex korshinskyi	**30.9**	**1.2**	3.9	0.1	0.4	0.0	0.4	0.0	–	–
Cleistogenes chinensis	**23.9**	**1.0**	1.1	0.0	–	–	0.7	0.0	–	–
Bupleurum scorzonerifolium	**37.8**	**0.8**	3.6	0.1	0.9	0.0	–	–	–	–
Lespedeza juncea	**23.9**	**0.7**	–	–	–	–	0.7	0.0	–	–
Thalictrum squarrosum	**28.2**	**0.6**	0.9	0.0	–	–	–	–	–	–
Allium senescens	**17.6**	**0.6**	0.9	0.0	0.4	0.0	2.2	0.1	–	–
Galium verum	**30.9**	**0.6**	0.9	0.0	–	–	5.4	0.1	–	–
Iris tenuifolia	**22.3**	**0.6**	8.9	0.3	4.3	0.2	0.7	0.0	–	–
Cymbaria dahurica	**34.6**	**0.6**	13.9	0.3	2.2	0.1	0.7	0.0	–	–
Allium anisopodium	**21.3**	**0.5**	12.3	0.4	0.9	0.0	1.1	0.0	–	–
Potentilla tanacetifolia	**31.9**	**0.5**	5.5	0.1	2.6	0.0	0.7	0.0	–	–
Sanguisorba officinalis	**19.7**	**0.5**	0.7	0.0	–	–	–	–	–	–
Anemarrhena asphodeloides	**16.0**	**0.4**	2.5	0.1	0.4	0.0	–	–	–	–
Clematis hexapetala	**22.9**	**0.4**	–	–	–	–	–	–	–	–
Pulsatilla turczaninovii	**18.1**	**0.4**	0.5	0.0	–	–	0.7	0.0	–	–
Potentilla verticillaris	**39.9**	**0.4**	6.6	0.1	2.2	0.0	–	–	0.6	0.0
Scutellaria baicalensis	**19.2**	**0.3**	0.2	0.0	0.9	0.0	–	–	–	–
Saposhnikovia divaricata	**25.5**	**0.3**	1.4	0.0	0.9	0.0	–	–	–	–
Scorzonera austriaca	**22.9**	**0.3**	4.3	0.1	1.7	0.1	2.2	0.0	–	–
Astragalus adsurgens	**18.1**	**0.2**	0.2	0.0	1.3	0.1	0.4	0.0	0.6	0.0
Schizonepeta multifida	**15.4**	**0.2**	–	–	–	–	–	–	–	–
Iris dichotoma	**18.6**	**0.1**	0.7	0.0	–	–	–	–	–	–
Viola dissecta	**19.7**	**0.1**	0.2	0.0	1.7	0.0	1.1	0.0	–	–
Agropyron cristatum	38.3	2.1	36.0	2.5	10.0	0.5	21.4	1.7	9.3	1.1
Lespedeza davurica	**50.5**	**2.0**	8.4	0.3	40.3	2.7	0.4	0.0	–	–
Allium tenuissimum	**54.8**	**1.3**	35.1	1.4	11.3	0.6	0.7	0.0	–	–
Koeleria macrantha	**54.8**	**1.2**	16.9	0.7	7.4	0.3	23.9	1.2	4.1	0.3
Allium bidentatum	**50.0**	**1.0**	22.8	0.8	3.0	0.1	1.1	0.0	–	–
Artemisia sacrorum	**20.7**	**1.0**	6.6	0.4	7.8	0.4	5.4	0.3	–	–
Astragalus melilotoides	**19.7**	**0.8**	1.8	0.1	11.7	0.6	–	–	0.6	0.0
Medicago ruthenica	**44.2**	**0.8**	9.8	0.3	6.1	0.2	2.9	0.0	0.6	0.0
Leontopodium leontopodioides	**29.3**	**0.5**	4.1	0.1	0.9	0.0	9.8	0.4	4.7	0.5
Allium ramosum	**18.6**	**0.5**	9.6	0.4	0.9	0.0	2.5	0.1	–	–
Gueldenstaedtia stenophylla	**15.4**	**0.1**	2.1	0.0	10.0	0.2	–	–	–	–
Artemisia frigida	**38.3**	**1.3**	26.2	1.1	15.6	0.7	9.8	0.3	2.3	0.1
Potentilla acaulis	**26.6**	**0.6**	13.2	0.5	1.7	0.0	5.1	0.3	0.6	0.0
Stellera chamaejasme	**24.5**	**0.5**	7.3	0.2	5.6	0.2	2.9	0.1	3.5	0.2
Dysphania aristata	**23.9**	**0.5**	10.9	0.2	5.2	0.1	7.6	0.1	8.1	0.0
Carex duriuscula	28.7	0.9	16.4	0.9	0.9	0.0	0.4	0.0	–	–
Setaria viridis	23.4	0.5	8.0	0.2	18.2	0.3	7.6	0.2	–	–
Stipa tianschanica var. *gobica*	0.5	0.1	**26.7**	**13.6**	2.2	0.5	1.5	0.1	–	–
Stipa sareptana var. *krylovii*	7.5	1.2	**45.8**	**12.3**	11.3	1.3	6.2	0.6	5.2	0.3
Stipa tianschanica var. *klemenzii*	1.1	0.1	**26.2**	**9.3**	6.5	1.3	–	–	–	–
Stipa caucasica subsp. *glareosa*	–	–	**19.6**	**7.6**	–	–	5.4	0.6	16.3	3.9
Allium polyrhizum	2.1	0.0	**25.5**	**2.5**	13.4	0.7	14.1	0.7	1.7	0.2
Haplophyllum dauricum	18.1	0.3	**15.7**	**0.5**	1.3	0.0	–	–	–	–
Astragalus galactites	21.3	0.3	**18.7**	**0.3**	12.6	0.3	1.1	0.0	–	–
Convolvulus ammannii	10.1	0.2	**33.9**	**1.5**	22.5	0.8	3.6	0.1	–	–
Artemisia pubescens	17.0	0.6	**16.0**	**0.7**	10.0	0.5	5.4	0.3	1.7	0.1
Salsola collina	25.5	0.5	27.3	1.5	21.2	0.5	4.4	0.1	–	–
Stipa breviflora	3.7	0.1	6.8	0.5	**76.2**	**25.4**	9.1	1.7	1.2	0.1

Species	DG (188)		IMPG (439)		LPG (231)		XMG (276)		TPG (172)	
	Con	IV	Con	IV	Con	IV	Con	IV	Con	IV
Stipa bungeana	6.4	0.2	3.0	0.1	**57.6**	**22.6**	–	–	–	–
Leymus secalinus	3.2	0.2	7.1	0.6	**21.7**	**1.9**	12.7	1.3	10.5	1.0
Cleistogenes songorica	–	–	20.7	1.1	**19.9**	**1.5**	1.1	0.1	–	–
Polygala tenuifolia	34.0	0.5	15.3	0.4	**28.1**	**1.2**	2.2	0.1	–	–
Astragalus scaberrimus	21.3	0.2	10.7	0.2	**29.4**	**0.5**	0.7	0.0	1.2	0.0
Torularia humilis	1.6	0.0	7.1	0.1	**17.8**	**0.4**	10.1	0.2	8.1	0.2
Ixeridium chinense	29.3	0.3	4.6	0.1	**26.0**	**0.5**	0.4	0.0	–	–
Heteropappus altaicus	46.8	0.9	34.6	0.9	55.8	2.4	27.9	1.2	23.3	0.6
Artemisia scoparia	35.1	1.2	10.5	0.3	44.2	2.9	4.0	0.1	0.6	0.1
Stipa caucasica	–	–	2.1	0.1	–	–	**36.2**	**11.2**	1.2	0.2
Stipa orientalis	–	–	2.3	0.2	1.3	0.1	**25.0**	**7.3**	–	–
Stipa sareptana	–	–	0.2	0.0	–	–	**15.2**	**5.2**	–	–
Seriphidium rhodanthum	–	–	-	-	–	–	**17.8**	**3.5**	–	–
Seriphidium gracilescens	–	–	2.5	0.3	–	–	**18.8**	**2.3**	–	–
Krascheninnikovia ceratoides	1.1	0.0	4.6	0.3	2.6	0.2	**23.2**	**1.7**	2.9	0.1
Carex sp.	–	–	3.2	0.1	1.3	0.1	**26.8**	**1.6**	9.3	0.5
Astragalus sp.	0.5	0.0	2.3	0.0	8.7	0.3	**26.1**	**0.5**	5.8	0.3
Astragalus borodinii	–	–	–	–	–	–	**18.5**	**0.9**	–	–
Polygonum aviculare	0.5	0.0	1.4	0.0	0.4	0.0	**15.9**	**0.5**	0.6	0.0
Festuca ovina	25.5	1.2	6.4	0.3	0.9	0.0	**25.4**	**2.2**	9.9	0.9
Poa sp.	0.5	0.0	2.7	0.1	1.3	0.1	**35.9**	**1.7**	15.1	1.0
Seriphidium sp.	–	–	1.1	0.1	10.8	2.4	**24.6**	**3.4**	2.3	0.1
Kochia prostrata	2.1	0.1	11.4	0.5	0.4	0.0	**17.4**	**0.9**	–	–
Lappula myosotis	5.9	0.1	5.5	0.1	2.6	0.1	**24.6**	**0.5**	1.2	0.0
Chenopodium acuminatum	9.6	0.4	10.0	0.4	6.5	0.1	**19.9**	**0.4**	–	–
Taraxacum mongolicum	9.0	0.0	6.2	0.0	5.6	0.1	**16.3**	**0.2**	2.9	0.0
Potentilla bifurca	31.9	0.4	15.7	0.3	16.5	0.4	14.1	0.3	46.5	2.0
Stipa purpurea	–	–	0.5	0.1	–	–	2.5	0.4	**75.0**	**22.9**
Stipa subsessiliflora var. *basiplumosa*	–	–	–	–	–	–	–	–	**45.4**	**15.1**
Carex moorcroftii	–	–	0.5	0.0	–	–	–	–	**22.7**	**2.3**
Krascheninnikovia compacta	–	–	0.7	0.0	0.4	0.0	1.5	0.1	**20.9**	**1.7**
Astragalus confertus	–	–	–	–	–	–	–	–	**26.2**	**1.4**
Chamaerhodos sabulosa	–	–	0.9	0.1	–	–	1.8	0.0	**19.8**	**1.3**
Oxytropis glacialis	–	–	0.2	0.0	–	–	–	–	**19.8**	**1.2**
Kobresia stolonifera	–	–	–	–	–	–	0.4	0.0	**16.3**	**1.2**
Kobresia robusta	–	–	–	–	–	–	–	–	**18.0**	**1.1**
Astragalus hendersonii	–	–	–	–	–	–	–	–	**23.8**	**1.0**
Kobresia macrantha	–	–	0.2	0.0	0.4	0.0	0.4	0.0	**15.7**	**1.0**
Artemisia demissa	–	–	–	–	–	–	0.4	0.0	**16.9**	**0.5**
Ptilotrichum canescens	6.4	0.1	20.7	0.4	0.9	0.0	0.7	0.0	**33.1**	**1.9**
Oxytropis chiliophylla	–	–	0.7	0.1	–	–	1.8	0.2	**20.9**	**1.3**

Stipa baicalensis steppe alliance

Stipa baicalensis steppe alliance mainly occurs on the Song-Nen Plain, Hulun Buir Plateau, and the eastern Xilingol Plateau (37.27°–50.73°N, 106.12°–125.29°E). The altitude ranges from 133 m to 2244 m, with an average of 578 m. The AMT is 2.1°C and the AP is 390 mm. The main soil types are light chernozems, chernozems, chestnut soils, and meadow soils.

Stipa baicalensis steppe is a meadow steppe and also a transitional type between forests and typical steppe. It is an endemic steppe type restricted to the east of Central Asian subregion. Compared to *Stipa grandis* steppe, *Stipa baicalensis* steppe has a high resistance to cold and requires high water availability. Usually, it has a well developed forb layer (SM5) and high biomass (Suppl. material 2: Table S2). The community cover varies from 21.7% to 89.1%, with an average of 48.7%. The community height varies from 24.4 to 73.5 cm, with an average of 48.6 cm. Aboveground biomass ranges between 80.9 and 972.3 g m^{-2}, with an average of 304.1 g m^{-2}. In total, 302 species were recorded in 94 plots. The community is dominated by *Stipa baicalensis*, which has a mean Importance Value of 20.4%. There are 33 species with a constancy ≥30%, and species with Importance Value ≥1% and indicator species are listed in Table 2. The complete compositional species are listed in SM6. Six associations were identified within this alliance (Suppl. material 3: Tables S3.1, Suppl. material 4: Table S4).

Stipa grandis steppe alliance

Stipa grandis steppe alliance is an endemic type in Central Asia, which is also a representative type of typical steppes in China. Compared to *Stipa baicalensis* steppe, it has a much larger distribution area and its environment is drier and warmer. The center of its distribution is the Mongolian Plateau, and it is also widely distributed in the surrounding areas such as southern Siberia, northern Mongolia, the central Song-Nen Plain, and the northern Loess Plateau (34.56°–49.96°N, 101.33°–124.30°E). The altitude ranges from 136 m to 2819 m, with an average of 1052 m. The AMT is 4.1°C and the AP is 371 mm. The main soil types are chestnut soils and loessial soils.

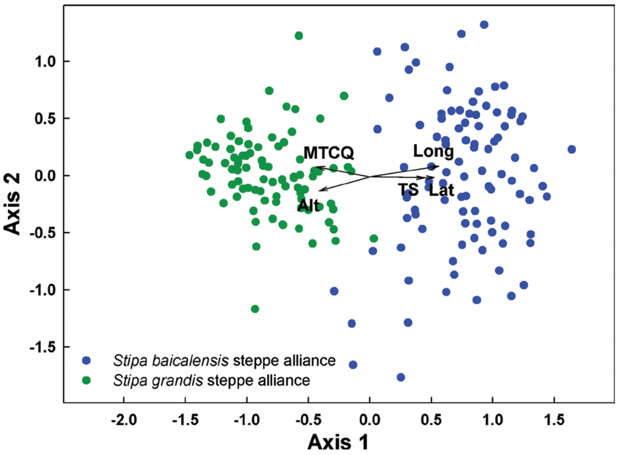

Figure 3. NMDS ordinations of two *Stipa* steppe alliances of the Daurian Group based on Importance Value data for axes 1 and 2. Plots are highlighted by two *Stipa* steppe alliances. Stress=0.20. Site and climatic attributes are overlaid as vectors showing the direction and magnitude of increase for longitude (Long), latitude (Lat), altitude (Alt), Mean Temperature of Coldest Quarter (MTCQ), and Temperature Seasonality (TS).

The community cover varies from 10.0% to 92.4%, with an average of 40.0%. The community height varies from 15.0 to 116.7 cm, with an average of 56.5 cm. Aboveground biomass ranges between 29.2 and 462.1 g m^{-2}, with an average of 192.1 g m^{-2}. In total, 283 species were recorded in 86 plots. The community is dominated by *Stipa grandis*, which has a mean Importance Value of 31.4%. There are 20 species with a constancy ≥30%, and species with Importance Value ≥1% and indicator species are listed in Table 2. Four associations were identified within this alliance (Suppl. material 3: Table S3.2, Suppl. material 4: Table S4).

Classification of the Inner Mongolian Plateau Group

Our clustering protocol classified this group (439 plots × 510 taxa) into four clusters corresponding to the alliance level of the China-VCS, i.e., *Stipa tianschanica* var. *gobica* steppe alliance, *Stipa tianschanica* var. *klemenzii* steppe alliance, *Stipa caucasica* subsp. *glareosa* steppe alliance-I, and *Stipa sareptana* var. *krylovii* steppe alliance (Table 3). NMDS ordination of this group yielded a three-dimensional NMDS solution that accounted for 73.4% of the compositional variation in the data set (Fig. 4). Plots representing the four alliances were clearly grouped into discrete clusters in this ordination. Axis 1 separated plots of *Stipa caucasica* subsp. *glareosa* steppe and *Stipa sareptana* var. *krylovii* steppe alliances. Axis 2 separated plots of *Stipa tianschanica* var. *gobica* steppe alliance from the other three alliances. Axis 3 separated plots of *Stipa tianschanica* var. *klemenzii* steppe alliance from the other three alliances. Biplot overlays for precipitation (AP and PWQ) suggested an associated rainfall gradient with compositional variation on Axis 1. Biplot overlays for temperature suggested an associated temperature gradient with compositional variation on Axes 2 (AMT and MTCQ) and 3 (MTWQ).

Table 2. Constancy-Importance Value table for two *Stipa* steppe alliances in the Daurian Group. Species are included if they have constancy (Con) ≥ 30% in at least one alliance. Mean Importance Value (IV) of each species in each alliance is expressed as percentage. The number in the parentheses is sample size. Indicator species based on Indicator Species Analysis are in boldface type. The two alliances are *Stipa baicalensis* steppe (Baic) and *Stipa grandis* steppe (Gran).

Alliance	Baic (98)		Gran (90)	
Species	Con	IV	Con	IV
Stipa baicalensis	**94.9**	**20.4**	7.8	0.6
Carex pediformis	**48.0**	**3.9**	4.4	0.2
Filifolium sibiricum	**53.1**	**2.6**	12.2	0.6
Cleistogenes chinensis	**37.8**	**1.8**	8.9	0.2
Festuca ovina	**40.8**	**1.7**	8.9	0.6
Allium bidentatum	**67.4**	**1.3**	31.1	0.6
Lespedeza juncea	**37.8**	**1.1**	8.9	0.2
Bupleurum scorzonerifolium	**58.2**	**1.0**	15.6	0.5
Galium verum	**50.0**	**1.0**	10.0	0.2
Thalictrum squarrosum	**42.9**	**0.9**	12.2	0.3
Sanguisorba officinalis	**35.7**	**0.8**	2.2	0.1
Potentilla tanacetifolia	**41.8**	**0.7**	21.1	0.3
Leontopodium leontopodioides	**39.8**	**0.7**	17.8	0.3
Cymbaria dahurica	**42.9**	**0.7**	25.6	0.4
Clematis hexapetala	**36.7**	**0.6**	7.8	0.1
Pulsatilla turczaninovii	**30.6**	**0.6**	4.4	0.1
Potentilla verticillaris	**53.1**	**0.4**	25.6	0.3
Scorzonera austriaca	**33.7**	**0.3**	11.1	0.2
Saposhnikovia divaricata	**36.7**	**0.3**	13.3	0.2
Potentilla bifurca	37.8	0.6	25.6	0.3
Carex duriuscula	36.7	1.1	20.0	0.7
Lespedeza davurica	55.1	2.0	45.6	2.1
Achnatherum sibiricum	40.8	1.4	23.3	1.1
Carex korshinskyi	29.6	1.3	32.2	1.0
Koeleria macrantha	63.3	1.3	45.6	1.1
Medicago ruthenica	48.0	0.7	40.0	0.8
Stellera chamaejasme	30.6	0.6	17.8	0.4
Ixeridium chinense	34.7	0.3	23.3	0.3
Leymus chinensis	80.6	5.3	71.1	6.7
Cleistogenes squarrosa	67.4	5.3	90.0	6.1
Serratula centauroides	57.1	1.4	52.2	1.8
Poa sect. *Stenopoa*	36.7	1.5	31.1	1.8
Artemisia frigida	29.6	1.1	47.8	1.5
Potentilla acaulis	23.5	0.6	30.0	0.7
Heteropappus altaicus	39.8	0.5	54.4	1.3
Stipa grandis	8.2	0.6	**100.0**	**31.4**
Agropyron cristatum	29.6	1.4	**47.8**	**2.8**
Allium tenuissimum	45.9	1.0	64.4	1.6
Astragalus melilotoides	10.2	0.2	**30.0**	**1.5**
Iris tenuifolia	10.2	0.2	**35.6**	**1.0**
Polygala tenuifolia	28.6	0.2	**40.0**	**0.8**
Artemisia scoparia	24.5	0.4	46.7	1.9
Salsola collina	14.3	0.3	37.8	0.7

Stipa tianschanica var. gobica steppe alliance

Stipa tianschanica var. *gobica* steppe alliance mainly occurs in the desert steppe zone and also in the surrounding typical steppe zone and desert zone, e.g., on the Ulan Qab Plateau, Alxa Plateau and the northern Loess Plateau, especially on the rocky slopes of mountains and on the top of hills with stony surfaces (31.57°–43.15°N, 79.71°–115.26°E). Although

Table 3. Constancy-Importance Value table for four *Stipa* steppe alliances in the Inner Mongolian Plateau Group. Species are included if they have constancy (Con) ≥ 30% in at least one alliance. Mean Importance Value (IV) of each species in each alliance is expressed as percentage. The number in the parentheses is sample size. Indicator species based on Indicator Species Analysis are in boldface type. The four alliances are *Stipa tianschanica* var. *gobica* steppe (Gobi), *Stipa tianschanica* var. *klemenzii* steppe (Klem), *Stipa caucasica* subsp. *glareosa* steppe-I (Glar-I), and *Stipa sareptana* var. *krylovii* steppe (Kryl).

Alliance	Gobi (108)		Klem (94)		Glar–I (74)		Kryl (163)	
Species	Con	IV	Con	IV	Con	IV	Con	IV
Stipa tianschanica var. *gobica*	**100.0**	**54.2**	1.1	0.1	6.8	1.0	1.8	0.2
Polygala tenuifolia	**46.3**	**1.2**	7.5	0.3	1.4	0.0	5.5	0.1
Thymus mongolicus	**35.2**	**1.4**	–	–	–	–	8.6	0.5
Allium bidentatum	**34.3**	**1.1**	21.3	0.8	–	–	26.4	1.0
Ptilotrichum canescens	**33.3**	**0.7**	20.2	0.6	16.2	0.3	14.7	0.2
Stipa tianschanica var. *klemenzii*	8.3	0.6	**100.0**	**41.3**	8.1	0.9	3.7	0.4
Cleistogenes songorica	15.7	0.7	**57.5**	**3.6**	17.6	0.8	4.3	0.2
Convolvulus ammannii	24.1	0.6	**56.4**	**3.4**	14.9	0.7	36.2	1.3
Allium tenuissimum	42.6	1.5	**46.8**	**2.0**	10.8	0.5	34.4	1.4
Allium polyrhizum	12.0	0.8	**44.7**	**4.0**	27.0	2.2	22.7	2.9
Astragalus galactites	5.6	0.1	**33.0**	**0.5**	1.4	0.1	27.0	0.4
Stipa caucasica subsp. *glareosa*	5.6	0.5	–	–	**100.0**	**43.6**	3.7	0.2
Stipa sareptana var. *krylovii*	13.9	0.7	19.2	1.8	10.8	1.2	**98.2**	**31.1**
Leymus chinensis	4.6	0.1	7.5	0.4	–	–	**33.1**	**2.8**
Cleistogenes squarrosa	32.4	0.8	37.2	2.0	10.8	0.6	**60.7**	**3.6**
Koeleria macrantha	9.3	0.4	1.1	0.0	5.4	0.2	**36.2**	**1.5**
Agropyron cristatum	21.3	0.8	26.6	2.4	24.3	2.6	**56.4**	**3.8**
Heteropappus altaicus	37.0	0.7	18.1	0.4	12.2	0.7	**52.8**	**1.4**
Artemisia frigida	20.4	0.3	35.1	1.1	4.1	0.2	**35.0**	**2.1**
Salsola collina	14.8	0.5	30.9	2.3	8.1	0.3	42.3	2.2
Potentilla bifurca	0.9	0.0	2.1	0.0	2.7	0.1	39.3	0.7
Carex duriuscula	–	–	9.6	0.5	1.4	0.1	38.0	2.0

it spans a large geographic range, the *Stipa tianschanica* var. *gobica* community usually forms small stands. The altitude ranges from 943 m to 4448 m, with an average of 1599 m. The AMT is 5.6°C and the AP is 284 mm. The main soil types are stony skeletal soils and calcareous lithosols.

The community cover varies from 6.0% to 48.3%, with an average of 22.2%. The community height varies from 4.0 to 42.7 cm, with an average of 23.0 cm. Aboveground biomass ranges between 4.4 and 296.0 g m^{-2}, with an average of 102.4 g m^{-2}. In total, 242 species were recorded in 104 plots. The community is dominated by *Stipa tianschanica* var. *gobica*, which has a mean Importance Value of 54.2%. There are 8 species with a constancy ≥30%, and species with Importance Value ≥1% and indicator species are listed in Table 3. Seven associations were identified within this alliance (Suppl. material 3: Tables S3.3, Suppl. material 4: Table S4).

Stipa tianschanica var. *klemenzii* steppe alliance

Stipa tianschanica var. *klemenzii* steppe alliance is a desert steppe and also an endemic type in Central Asia, mainly occurring on the Ulan Qab Plateau and western Xilingol Plateau (32.42°–50.09°N, 83.34°–117.58°E). The altitude

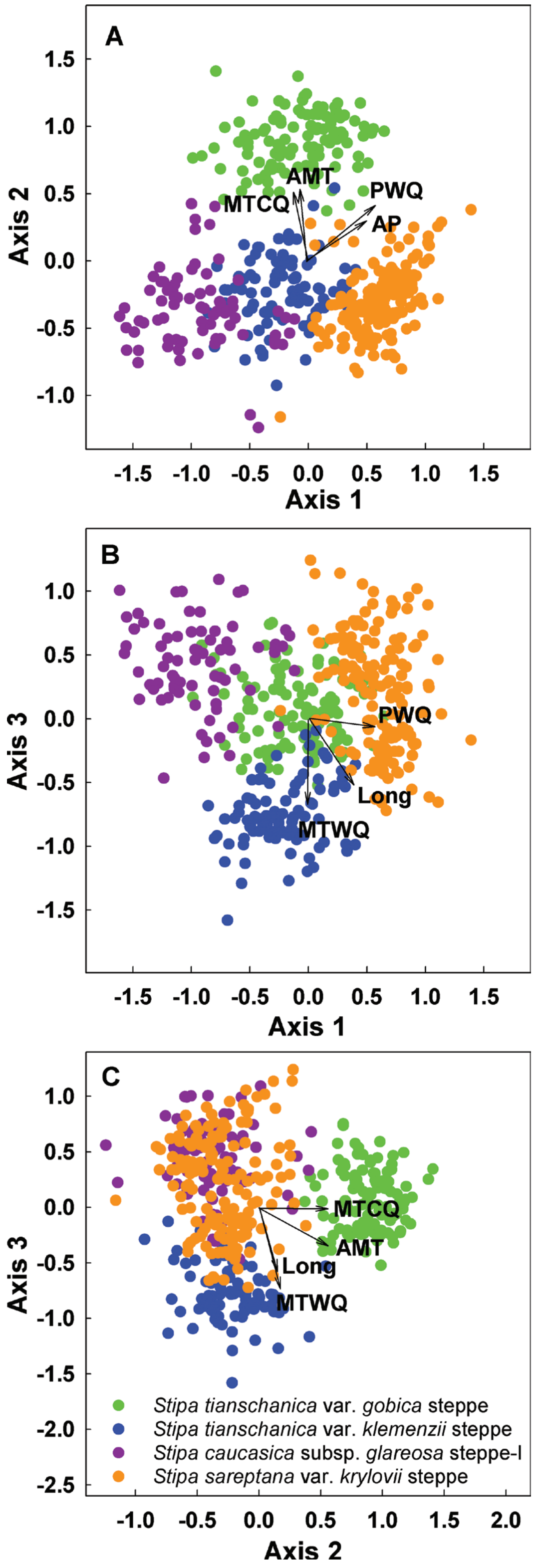

Figure 4. NMDS ordinations of four *Stipa* steppe alliances of the Inner Mongolian Plateau Group based on Importance Value data for axes 1–2(A), 1–3(B) and 2–3(C). Plots are highlighted by four *Stipa* steppe alliances. Stress=0.15. Site and climatic attributes are overlaid as vectors showing the direction and magnitude of increase for longitude (Long), Annual Mean Temperature (AMT), Mean Temperature of Warmest Quarter (MTWQ), Mean Temperature of Coldest Quarter (MTCQ), Annual Precipitation (AP), and Precipitation of Wettest Quarter (PWQ).

ranges from 846 m to 4601 m, with an average of 1443 m. The AMT is 4.7°C and the AP is 193 mm. It is one of the most drought-tolerant *Stipa* steppes in China and requires a sandy surface on brown calcic soils or light chestnut soils.

The community cover varies from 5.5% to 41.7%, with an average of 19.5%. The community height varies from 4.4 to 35.7 cm, with an average of 13.5 cm. Aboveground biomass ranges between 11.6 and 178.1 g m^{-2}, with an average of 61.7 g m^{-2}. In total, 178 species were recorded in 94 plots. The community is dominated by *Stipa tianschanica* var. *klemenzii*, which has a mean Importance Value of 41.3%. There are 9 species with a constancy ≥30%, and species with Importance Value ≥1% and indicator species are listed in Table 3. Seven associations were identified within this alliance (Suppl. material 3: Table S3.4, Suppl. material 4: Table S4).

Stipa caucasica subsp. *glareosa* steppe alliance-I

Stipa caucasica subsp. *glareosa* steppe alliance-I is a desert steppe, mainly distributed in the western Mongolian Plateau and in the proluvial fans of the Beishan, Tianshan, Altai Mountains (31.71°–50.17°N, 75.45°–113.57°E). The altitude ranges from 800 m to 5073 m, with an average of 1948 m. The AMT is 2.1°C and the AP is 136 mm. The main soil types are sandy brown calcic soils, gravelly brown calcic soils, light brown calcic soils, and chestnut soils.

The community cover varies from 4.7% to 59%, with an average of 17.5%. The community height varies from 3.7 to 30.0 cm, with an average of 12.9 cm. Aboveground biomass ranges between 3.3 and 93.3 g m^{-2}, with an average of 45.7 g m^{-2}. In total, 159 species were recorded in 70 plots. The community is dominated by *Stipa caucasica* subsp. *glareosa*, which has a mean Importance Value of 43.6%. Usually, the accompanied species have a low constancy (Table 3). Only five species have a constancy ≥20%, and species with Importance Value ≥1% and indicator species are listed in Table 3 and SM 6. Six associations were identified within this alliance (Suppl. material 3: Table S3.5, Suppl. material 4: Table S4).

Stipa sareptana var. *krylovii* steppe alliance

Stipa sareptana var. *krylovii* steppe alliance is a representative of typical steppe in the Central Asia, mainly occurring on the western Hulun Buir Plateau, Xilingol Plateau, the northern Loess Plateau, the west of Qinghai Lake, on the Tianshan and Qilian Mountains, and the western Mongolian Plateau (35.37°–50.17°N, 80.16°–118.87°E). To the east of its geographic range, *Stipa sareptana* var. *krylovii* steppe overlaps with *Stipa grandis* steppe but prefers more arid conditions. To the west, it can be distributed near the east boundary of desert steppe zone or on the mountains within desert. In the desert steppe zone, it is replaced by *Stipa tianschanica* var. *klemenzii* steppe in mid-temperate region or *Stipa breviflora* steppe in warm-temperate region. The altitude ranges from 549 m to 3467 m, with an average of 1536 m. The AMT is 1.4°C and the AP is 254 mm. The main soil type is chestnut soils.

The community cover varies from 7.4% to 98.2%, with an average of 37.3%. The community height varies from 4.3 to 65.7 cm, with an average of 31.1 cm. Aboveground biomass ranges between 13.2 and 353.1 g m^{-2}, with an average of 109.7 g m^{-2}. In total, 358 species were recorded in 158 plots. The community is dominated by *Stipa sareptana* var. *krylovii*, which has a mean Importance Value of 31.1%. There are 12 species with a constancy ≥30%, and species with Importance Value ≥1% and indicator species are listed in Table 3. Six associations were identified within this alliance (Suppl. material 3: Table S3.6, Suppl. material 4: Table S4).

Classification of the Loess Plateau Group

Our clustering protocol classified this group (231 plots × 303 taxa) into two clusters corresponding to the alliance level of the China-VCS, i.e., *Stipa breviflora* steppe alliance-L and *Stipa bungeana* steppe alliance (Table 4). NMDS ordination of this group yielded a two-dimensional NMDS solution that accounted for 70.0% of the compositional variation in the data set (Fig. 5). Plots representing the two alliances were clearly grouped into discrete clusters along axis 1 in this ordination. Biplot overlays for climates, longitude and altitude suggested a east to west gradient of decreasing temperature (AMT and MTWQ) and rainfall (AP and PWQ), and higher elevation with compositional variation on Axis 1.

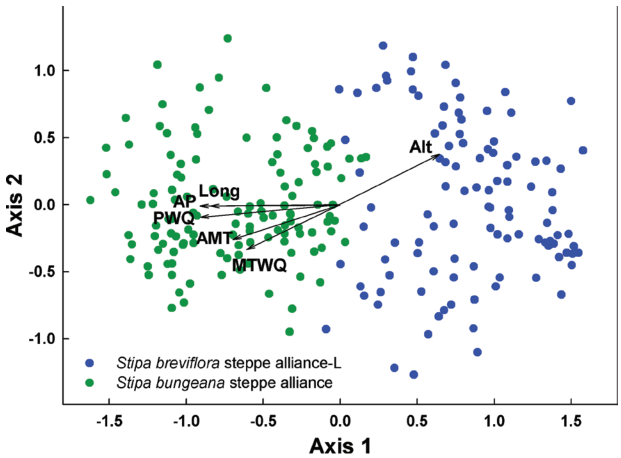

Figure 5. NMDS ordinations of two *Stipa* steppe alliances of the Loess Plateau Group based on Importance Value data for axes 1-2. Plots are highlighted by two *Stipa* steppe alliances. Stress=0.23. Site and climatic attributes are overlaid as vectors showing the direction and magnitude of increase for longitude (Long), altitude (Alt), Annual Mean Temperature (AMT), Mean Temperature of Warmest Quarter (MTWQ), Annual Precipitation (AP), and Precipitation of Wettest Quarter (PWQ).

Stipa breviflora steppe alliance-L

Stipa breviflora steppe alliance-L mainly occurs on the southern slopes of the mountains on the Loess Plateau, on the basin of the eastern Qinghai Province, and on the northern piemonts of Helanshan, Tianshan, Qilian, and Kunlun mountains in the desert region (35.28°–43.84°N, 76.01°–115.36°E). The altitude ranges from 1015 m to 3376 m, with an average of 2250 m. The AMT is 4.5°C and the AP is 229 mm. The main soil types are loessial soils, brown calcic soils and light brown calcic soils.

The community cover varies from 6.7% to 58.3%, with an average of 22.2%. The community height varies from 2.7 to 60.7 cm, with an average of 25.4 cm. Aboveground biomass ranges between 10.9 and 250.4 g m^{-2}, with an average of 74.6 g m^{-2}. In total, 220 species were recorded in 105 plots. The community is dominated by *Stipa breviflora*, which has a mean Importance Value of 43.6%. Usually, the accompanied species have a low constancy. Only three species have a constancy ≥30% and 8 species have a constancy ≥20%, and species with Importance Value ≥1% and indicator species are listed in Table 4. Six associations were identified within this alliance (Suppl. material 3: Table S3.7, Suppl. material 4: Table S4).

Table 4. Constancy-Importance Value table for two *Stipa* steppe alliances in the Loess Plateau Group. Species are included if they have constancy (Con) ≥ 30% in at least one alliance. Mean Importance Value (IV) of each species in each alliance is expressed as percentage. The number in the parentheses is sample size. Indicator species based on Indicator Species Analysis are in boldface type. The two alliances are *Stipa breviflora* steppe-L (Brev-L) and *Stipa bungeana* steppe (Bung).

Alliance	Brev-L (105)		Bung (126)	
Species	Con	IV	Con	IV
Stipa breviflora	**100.0**	**43.6**	56.4	10.2
Cleistogenes songorica	**35.2**	**2.8**	7.1	0.3
Stipa bungeana	6.7	0.4	**100.0**	**41.2**
Lespedeza davurica	11.4	0.6	**64.3**	**4.4**
Heteropappus altaicus	42.9	1.8	**66.7**	**2.9**
Cleistogenes squarrosa	21.0	1.0	**54.8**	**2.0**
Polygala tenuifolia	10.5	0.4	**42.9**	**1.8**
Ixeridium chinense	6.7	0.1	**42.1**	**0.9**
Astragalus scaberrimus	18.1	0.3	**38.9**	**0.6**
Artemisia scoparia	18.1	1.4	65.9	4.2

Stipa bungeana steppe alliance

Stipa bungeana steppe alliance is the most representative plant community of the warm-temperate grasslands, which mainly occurs on the Loess Plateau of China (35.29°–40.90°N, 99.48°–115.54°E). The altitude ranges from 631 m to 3174 m, with an average of 1561 m. The AMT is 7.5°C and the AP is 379 mm. The main soil types are loessial soils and dark loessial soils.

Due to large-scale conversion of grasslands to agricultural lands, *Stipa bungeana* steppe has rapidly declined in distribution and have increasingly become fragmented over the past century. The community cover varies from 10.0% to 56.7%, with an average of 28.3%. The community height varies from 3.0 to 65.3 cm, with an average of 23.9 cm. Aboveground biomass ranges between 14.2 and 235.2 g m^{-2}, with an average of 78.1 g m^{-2}. In total, 200 species were recorded in 126 plots. The community is dominated by *Stipa bungeana*, which has a mean Importance Value of 41.2%. There are 9 species having a constancy ≥30%, and species with Importance Value ≥1% and indicator species are listed in Table 4. Seven associations were identified within this alliance (Suppl. material 3: Table S3.8, Suppl. material 4: Table S4).

Classification of the Xinjiang Mountains Group

Our clustering protocol classified this group (276 plots × 511 taxa) into 13 clusters corresponding to the alliance level of the China-VCS, i.e., *Stipa aliena* steppe alliance, *Stipa breviflora* steppe alliance-X, *Stipa roborowskyi* steppe alliance-X, *Stipa capillata* steppe alliance, *Stipa caucasica* steppe alliance, *Stipa caucasica* subsp. *desertorum* steppe alliance, *Stipa macroglossa* steppe alliance, *Stipa orientalis* steppe alliance, *Stipa przewalskyi* steppe alliance, *Stipa regeliana* steppe alliance, *Stipa sareptana* steppe alliance, *Stipa subsessiliflora* steppe alliance, and *Stipa tianschanica* steppe alliance (Table 5). NMDS ordination of this group yielded a three-dimensional NMDS solution that accounted for 64.3% of the compositional variation in the data set (Fig. 6). Plots representing the 13 alliances were clearly grouped into distinct clusters with some overlap in this ordination. Biplot overlays for longitude (Long) suggested an east-west associated environmental gradient with a compositional variation on Axis 1. Biplot overlays for temperature (MTWQ and TS) and altitude (Alt) suggested a gradient of increasing temperature and temperature seasonality, and lower elevation with a compositional variation on Axis 2.

Stipa aliena steppe alliance

Stipa aliena steppe alliance mainly occurs in the south of Gansu Province and in the meadow steppe zone of southern slope of Qilian Mountain (34.01°–39.05°N, 100.33°–102.39°E). It is distributed at high altitudes with cold climate. The altitude ranges from 2853 m to 3487 m, with an average of 3173 m. The AMT is 1.1°C and the AP is 379 mm. The main soil types are meadow soils and dark felty soils.

The community has high cover and biomasss but low height. The community cover varies from 45.0% to 86.7%, with an average of 64.8%. The community height varies from 10.7 to 26.5 cm, with an average of 18.3 cm. Aboveground biomass ranges between 153.2 and 192.2 g m^{-2}, with an average of 173.6 g m^{-2}. *Stipa aliena* steppe also has high species richness. In total, 99 species were recorded in 6 plots. The community is dominated by *Stipa aliena*, which has a mean Importance Value of 19.1%. There are 61 species having a constancy ≥30%, and species with Importance Value ≥1% and indicator species are listed in Table 5. Due to limited plot data, only one association was identified within this alliance (Suppl. material 4: Table S4).

Stipa breviflora steppe alliance-X

Stipa breviflora steppe alliance-X in this group is different from *Stipa breviflora* steppe alliance-L within the Loess Plateau group. It mainly occurs in the desert steppe zone of

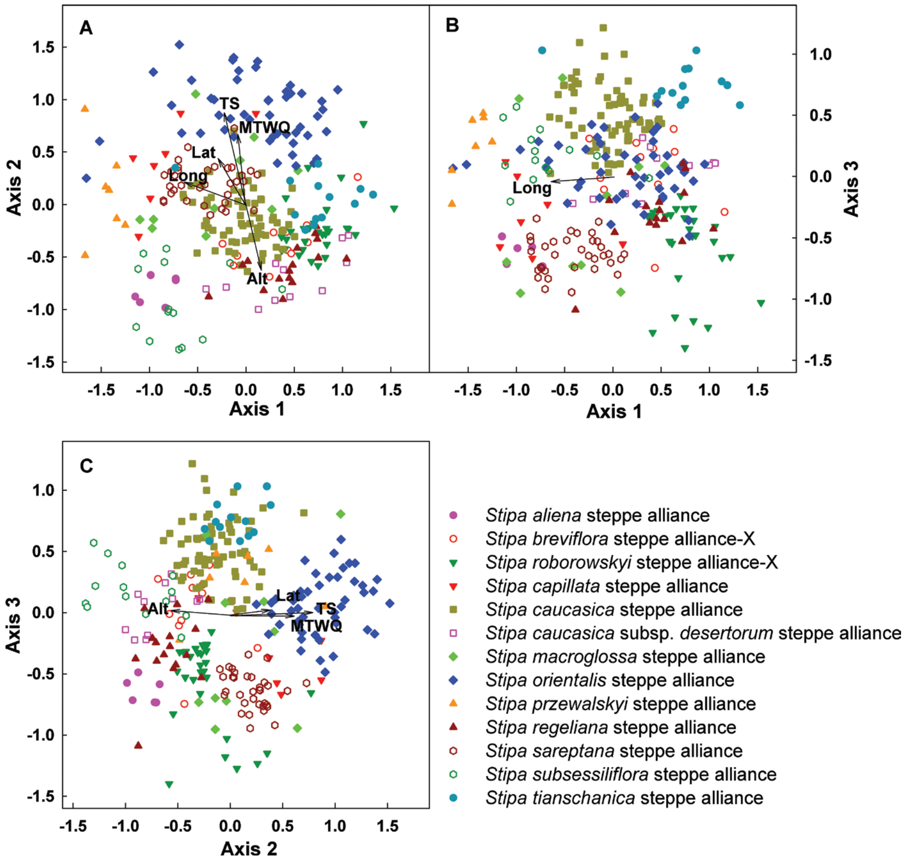

Figure 6. NMDS ordinations of 13 *Stipa* steppe alliances of the Xinjiang Mountains Group based on Importance Value data for axes 1–2(A), 1–3(B) and 2–3(C). Plots are highlighted by 13 *Stipa* steppe alliances. Stress=0.18. Site and climatic attributes are overlaid as vectors showing the direction and magnitude of increase for longitude (Long), latitude (Lat), altitude (Alt), Temperature Seasonality (TS), and Mean Temperature of Warmest Quarter (MTWQ).

the Kunlun Mountain (37.09°–42.72°N, 74.92°–80.35°E). Most of the compositional species are from Middle Asian flora. The altitude ranges from 2198 m to 4091 m, with an average of 2747 m. The AMT is 0.9°C and the AP is 161 mm. The main soil types are chestnut soils and light brown calcic soils.

The community cover varies from 9.0% to 43.1%, with an average of 24.1%. The community height varies from 4.7 to 33.0 cm, with an average of 19.2 cm. Aboveground biomass ranges between 21.6 and 135.7 g m^{-2}, with an average of 71.5 g m^{-2}. In total, 59 species were recorded in 10 plots. The community is dominated by *Stipa breviflora*, which has a mean Importance Value of 20.3%. There are 12 species having a constancy ≥30%, and species with Importance Value ≥1% and indicator species are listed in Table 5. Two associations were identified within this alliance (Suppl. material 3: Table S3.9, Suppl. material 4: Table S4).

Stipa roborowskyi steppe alliance-X

Stipa roborowskyi steppe alliance-X mainly occurs on the Kunlun Mountain (28.18°–37.40°N, 76.90°–87.75°E). The altitude ranges from 2464 m to 4516 m, with an average of 3259 m. The AMT is 1.8°C and the AP is 216 mm. The main soil type are frigid calcic soils and cold calcic soils.

The community cover varies from 5.7% to 41.3%, with an average of 21.8%. The community height varies from 8.2 to 33.2 cm, with an average of 21.9 cm. Aboveground biomass ranges between 27.9 and 163.7 g m^{-2}, with an average of 79.1 g m^{-2}. In total, 89 species were recorded in 30 plots. Most species are from Middle Asian flora. The community is dominated by *Stipa roborowskyi*, which has a mean Importance Value of 45.7%. There are five species having a constancy ≥30%, and species with Importance Value ≥1% are listed in Table 5. *Stipa roborowskyi* is the only diagnostic species. Two assocations were identified within this alliance (Suppl. material 3: Table S3.10, Suppl. material 4: Table S4).

Stipa capillata steppe alliance

Stipa capillata steppe alliance mainly occurs on the proluvial fans and in the lower region of Tianshan Mountain (43.16°–47.37°N, 85.72°–93.42°E). The altitude ranges from 1166 m to 2534 m, with an average of 1697 m. The AMT is 2.1 °C and the AP is 209 mm. The main soil type is chestnut soils.

The community cover varies from 22.7% to 36.3%, with an average of 30.6%. The community height varies from 19.7 to 53.2 cm, with an average of 32.8 cm. Aboveground biomass ranges between 63.6 and 171.2 g m^{-2}, with an average of 121.4 g m^{-2}. In total, 79 species were recorded in 7 plots. Most species are from Middle Asian flora. The community is dominated by *Stipa capillata*, which has a mean Importance Value of 35.4%. There are 14 species having a

Table 5. Constancy-Importance Value table for 13 *Stipa* steppe alliances in the Xinjiang Mountains Group. Species are included if they have constancy (Con) ≥ 30% in at least one alliance. Mean Importance Value (IV) of each species in each alliance is expressed as percentage. The number in the parentheses is sample size. Indicator species are in boldface type. The 13 alliances are *Stipa aliena* steppe (Alie), *Stipa breviflora* steppe-X (Brev-X), *Stipa roborowskyi* steppe-X (Robo-X), *Stipa capillata* steppe (Capt), *Stipa caucasica* steppe (Cauc), *Stipa caucasica* subsp. *desertorum* steppe (Dese), *Stipa macroglossa* steppe (Macr), *Stipa orientalis* steppe (Orie), *Stipa przewalskyi* steppe (Prze), *Stipa regeliana* steppe (Rege), *Stipa sareptana* steppe (Sare), *Stipa subsessiliflora* steppe (Subs), and *Stipa tianschanica* steppe (Tian).

Alliance	Alie (6)		Brev–X (10)		Robo–X (30)		Capt (7)		Cauc (69)		Dese (11)		Macr (10)		Orie (48)		Prze (7)		Rege (16)		Sare (34)		Subs (14)		Tian (13)	
Species	Con	IV	Con	IV	Con	IV	Con	IV	Con	IV	Con	IV	Con	IV	Con	IV	Con	IV	Con	IV	Con	IV	Con	IV	Con	IV
Stipa aliena	**100.0**	**19.1**	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Poa sp.	**100.0**	**3.5**	36.4	1.9	26.7	1.8	57.1	1.5	34.8	1.9	54.6	2.9	60.0	2.2	25.0	1.0	28.6	0.9	50.0	2.7	38.2	1.1	35.7	3.6	7.7	0.2
Leontopodium leontopodioides	**83.3**	**5.5**	9.1	0.6	10.0	0.4	–	–	10.1	0.4	–	–	10.0	0.0	–	–	42.9	0.7	25.0	0.8	2.9	0.0	14.3	0.5	–	–
Stellera chamaejasme	**83.3**	**1.5**	–	–	3.3	0.0	–	–	–	–	–	–	–	–	–	–	28.6	1.1	–	–	–	–	–	–	–	–
Taraxacum sp.	**83.3**	**0.5**	27.3	0.1	3.3	0.0	28.6	0.1	18.8	0.4	–	–	10.0	0.0	6.3	0.0	42.9	0.2	18.8	0.2	20.6	0.2	21.4	0.2	7.7	0.0
Koeleria macrantha	**66.7**	**3.9**	36.4	1.6	6.7	0.3	57.1	5.4	29.0	1.5	–	–	20.0	0.8	12.5	0.5	28.6	1.0	12.5	0.2	52.9	2.8	14.3	0.7	–	–
Saussurea sp.	**66.7**	**0.9**	–	–	3.3	0.0	–	–	23.2	0.5	–	–	–	–	–	–	42.9	0.3	–	–	5.9	0.1	21.4	0.6	15.4	0.8
Anaphalis lactea	**50.0**	**3.9**	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Elymus nutans	**50.0**	**2.8**	–	–	–	–	–	–	–	–	18.2	2.7	–	–	–	–	–	–	12.5	1.2	–	–	–	–	–	–
Potentilla argentea	**50.0**	**1.6**	9.1	0.1	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	2.9	0.0	–	–	–	–
Festuca rubra	**50.0**	**1.6**	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Eleocharis pauciflora	**50.0**	**1.6**	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Bupleurum chinense	**50.0**	**1.2**	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Medicago ruthenica	**50.0**	**0.9**	–	–	–	–	–	–	–	–	–	–	–	–	–	–	57.1	0.7	–	–	2.9	0.0	–	–	–	–
Pedicularis chinensis	**50.0**	**0.8**	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Kobresia sp.	**33.3**	**4.5**	–	–	–	–	–	–	1.5	0.0	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Polygonum viviparum	**33.3**	**2.3**	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Carex caespitosa	**33.3**	**1.8**	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Bupleurum sp.	**33.3**	**1.2**	9.1	0.3	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Anemone narcissiflora var. *sibirica*	**33.3**	**1.0**	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Aster flaccidus	**33.3**	**0.9**	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	2.9	0.0	–	–	–	–
Androsace umbellata	**33.3**	**0.8**	–	–	3.3	0.0	–	–	7.3	0.1	–	–	–	–	–	–	–	–	6.3	0.1	–	–	–	–	–	–
Adenophora stenanthina	**33.3**	**0.7**	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Polygonum alpinum	**33.3**	**0.7**	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	2.9	0.1	–	–	–	–
Morina chinensis	**33.3**	**0.6**	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Oxytropis latibracteata	**33.3**	**0.6**	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Trollius farreri	**33.3**	**0.6**	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Ligularia mongolica	**33.3**	**0.5**	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Thalictrum alpinum	**33.3**	**0.5**	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	6.3	0.1	–	–	–	–	–	–
Tephroseris turczaninowii	**33.3**	**0.4**	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Geranium sibiricum	**33.3**	**0.3**	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Pedicularis sp.	**33.3**	**0.3**	9.1	0.0	–	–	–	–	2.9	0.0	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Veronica didyma	**33.3**	**0.3**	–	–	–	–	–	–	–	–	–	–	–	–	2.1	0.0	–	–	–	–	2.9	0.0	–	–	–	–
Lancea tibetica	**33.3**	**0.3**	–	–	3.3	0.0	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Aconitum gymnandrum	**33.3**	**0.2**	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Anemone cathayensis	**33.3**	**0.2**	–	–	–	–	–	–	–	–	–	–	10.0	0.2	–	–	–	–	–	–	–	–	–	–	–	–
Tibetia himalaica	**33.3**	**0.2**	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–

Alliance	Alie (6)		Brev–X (10)		Robo–X (30)		Capt (7)		Cauc (69)		Dese (11)		Macr (10)		Orie (48)		Prze (7)		Rege (16)		Sare (34)		Subs (14)		Tian (13)	
Species	**Con**	**IV**	**Con**	**IV**	**Con**	**IV**	**Con**	**IV**	**Con**	**IV**	**Con**	**IV**	**Con**	**IV**	**Con**	**IV**	**Con**	**IV**	**Con**	**IV**	**Con**	**IV**	**Con**	**IV**	**Con**	**IV**
Gentiana straminea	**33.3**	**0.1**	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Lamium amplexicaule	**33.3**	**0.1**	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Viola verecunda	**33.3**	**0.1**	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Thermopsis lanceolata	**33.3**	**1.0**	–	–	–	–	–	–	–	–	–	–	–	–	–	–	42.9	0.4	–	–	–	–	–	–	–	–
Artemisia pubescens	33.3	1.4	–	–	–	–	14.3	0.3	–	–	–	–	10.0	0.4	6.3	0.3	–	–	18.8	0.7	14.7	1.6	–	–	–	–
Roegneria kamoji	33.3	1.3	–	–	13.3	0.9	–	–	2.9	0.0	–	–	10.0	0.5	4.2	0.3	–	–	6.3	0.6	–	–	–	–	7.7	0.9
Silene conoidea	**33.3**	**0.7**	–	–	–	–	14.3	0.1	–	–	–	–	–	–	2.1	0.0	28.6	0.2	6.3	0.1	–	–	–	–	–	–
Potentilla chinensis	**33.3**	**0.6**	9.1	0.1	–	–	–	–	2.9	0.1	–	–	–	–	4.2	0.0	14.3	0.1	–	–	8.8	0.0	–	–	7.7	0.5
Thalictrum minus	**33.3**	**0.5**	–	–	–	–	–	–	–	–	–	–	–	–	–	–	14.3	0.3	–	–	2.9	0.0	–	–	–	–
Allium senescens	**33.3**	**0.3**	9.1	0.0	–	–	14.3	0.3	1.5	0.2	–	–	–	–	–	–	14.3	0.1	–	–	–	–	–	–	–	–
Halenia corniculata	**33.3**	**0.3**	–	–	–	–	–	–	–	–	–	–	–	–	–	–	14.3	0.0	–	–	–	–	–	–	–	–
Dracocephalum tanguticum	**33.3**	**0.3**	–	–	–	–	–	–	–	–	–	–	–	–	–	–	14.3	0.2	–	–	–	–	–	–	–	–
Erigeron acer	33.3	0.2	–	–	–	–	14.3	0.2	1.5	0.1	–	–	10.0	0.1	–	–	–	–	6.3	0.1	11.8	0.1	–	–	–	–
Astragalus sp.	66.7	1.4	–	–	63.3	1.7	14.3	0.2	–	–	18.2	0.7	20.0	0.4	25.0	0.3	14.3	0.0	56.3	1.1	47.1	0.6	35.7	1.2	7.7	0.1
Stipa breviflora	–	–	**72.7**	**20.0**	40.0	7.1	–	–	–	–	–	–	–	–	6.3	0.6	–	–	12.5	0.9	–	–	–	–	–	–
Astragalus tibetanus	–	–	**81.8**	**3.7**	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Seriphidium sp.	–	–	**100.0**	**16.2**	–	–	14.3	0.5	–	–	–	–	–	–	45.8	6.5	–	–	–	–	61.8	8.8	14.3	2.6	92.3	8.5
Artemisia dracunculus	–	–	**36.4**	**1.8**	–	–	14.3	0.2	4.4	0.2	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Elymus dahuricus	–	–	**36.4**	**4.1**	3.3	0.4	–	–	–	–	–	–	–	–	–	–	28.6	1.0	6.3	0.0	–	–	7.1	0.1	–	–
Stipa roborowskyi	–	–	–	–	**100.0**	**45.7**	–	–	–	–	–	–	–	–	4.2	0.3	–	–	18.8	2.0	–	–	–	–	–	–
Allium sp.	16.7	0.2	18.2	0.5	30.0	1.5	–	–	11.6	0.4	–	–	–	–	2.1	0.1	–	–	6.3	0.2	2.9	0.1	7.1	0.3	15.4	0.4
Stipa capillata	–	–	9.1	0.3	–	–	**85.7**	**35.4**	2.9	0.1	–	–	–	–	4.2	0.3	–	–	–	–	–	–	–	–	–	–
Artemisia rutifolia	–	–	–	–	–	–	**71.4**	**3.1**	11.6	0.6	–	–	40.0	2.4	29.2	2.9	–	–	–	–	5.9	0.1	–	–	15.4	1.2
Kochia prostrata	–	–	–	–	–	–	**57.1**	**4.8**	17.4	0.5	–	–	10.0	0.1	29.2	1.7	–	–	–	–	50.0	2.5	–	–	–	–
Allium subtilissimum	–	–	–	–	–	–	**42.9**	**0.7**	20.3	0.5	–	–	10.0	0.3	16.7	0.4	–	–	–	–	14.7	0.2	7.1	0.1	–	–
Convolvulus ammannii	–	–	–	–	–	–	**42.9**	**0.7**	5.8	0.2	–	–	–	–	6.3	0.3	–	–	–	–	–	–	–	–	–	–
Potentilla sericea	–	–	–	–	–	–	**42.9**	**0.6**	10.1	0.3	18.2	1.1	–	–	2.1	0.0	–	–	18.8	0.2	2.9	0.0	14.3	0.1	–	–
Orostachys spinosus	–	–	–	–	–	–	**42.9**	**0.5**	–	–	–	–	10.0	0.0	12.5	0.3	–	–	–	–	8.8	0.2	–	–	–	–
Androsace maxima	–	–	–	–	–	–	**42.9**	**0.3**	1.5	0.0	–	–	–	–	20.8	0.2	–	–	–	–	23.5	0.1	–	–	–	–
Goniolimon speciosum	–	–	–	–	–	–	**42.9**	**0.1**	5.8	0.0	–	–	–	–	–	–	–	–	–	–	8.8	0.1	–	–	–	–
Dysphania aristata	33.3	0.1	–	–	13.3	0.2	28.6	0.1	10.1	0.3	–	–	10.0	0.4	10.4	0.1	–	–	–	–	–	–	–	–	–	–
Stipa caucasica	–	–	72.7	3.0	–	–	–	–	**100.0**	**41.5**	18.2	2.3	40.0	1.4	8.3	0.4	–	–	12.5	0.6	2.9	0.0	7.1	0.8	69.2	8.5
Seriphidium gracilescens	–	–	–	–	–	–	–	–	**75.4**	**9.1**	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Astragalus borodinii	–	–	–	–	–	–	–	–	**73.9**	**3.4**	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Stipa caucasica subsp. *desertorum*	–	–	–	–	–	–	–	–	–	–	**100.0**	**36.8**	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Seriphidium rhodanthum	–	–	–	–	76.7	17.3	–	–	–	–	**100.0**	**16.4**	–	–	–	–	–	–	93.8	17.2	–	–	–	–	–	–
Oxytropis stracheyana	–	–	–	–	16.7	1.2	–	–	2.9	0.4	**63.6**	**8.2**	–	–	6.3	0.5	–	–	–	–	–	–	–	–	–	–
Krascheninnikovia ceratoides	–	–	45.5	2.0	6.7	0.4	–	–	33.3	2.6	**63.6**	**3.7**	–	–	27.1	2.6	–	–	25.0	2.3	–	–	14.3	0.5	61.5	3.2
Torularia humilis	33.3	0.2	18.2	0.4	16.7	0.2	–	–	1.5	0.1	**45.5**	**2.2**	–	–	2.1	0.0	14.3	0.1	50.0	1.2	–	–	21.4	0.3	–	–
Potentilla bifurca	50.0	0.6	18.2	0.4	10.0	0.1	28.6	0.3	14.5	0.4	36.4	2.1	–	–	2.1	0.1	42.9	0.9	31.3	0.4	14.7	0.3	7.1	0.1	–	–
Stipa macroglossa	–	–	–	–	–	–	–	–	7.3	0.3	–	–	**90.0**	**38.2**	–	–	–	–	–	–	–	–	–	–	–	–
Seriphidium terrae–albae	–	–	–	–	–	–	–	–	–	–	–	–	**60.0**	**7.2**	–	–	–	–	–	–	–	–	–	–	–	–
Ziziphora bungeana	–	–	–	–	–	–	–	–	–	–	–	–	**30.0**	**1.0**	4.2	0.3	–	–	–	–	–	–	–	–	–	–

Alliance	Alie (6)		Brev–X (10)		Robo–X (30)		Capt (7)		Cauc (69)		Dese (11)		Macr (10)		Orie (48)		Prze (7)		Rege (16)		Sare (34)		Subs (14)		Tian (13)	
Species	Con	IV	Con	IV	Con	IV	Con	IV	Con	IV	Con	IV	Con	IV	Con	IV	Con	IV	Con	IV	Con	IV	Con	IV	Con	IV
Spiraea hypericifolia	–	–	–	–	–	–	28.6	0.7	1.5	0.0	–	–	**40.0**	**1.4**	–	–	–	–	–	–	20.6	0.6	–	–	–	–
Setaria viridis	–	–	–	–	–	–	–	–	7.3	0.3	–	–	30.0	1.3	4.2	0.1	–	–	–	–	32.4	0.7	–	–	–	–
Polygonum polycnemoides	–	–	–	–	–	–	–	–	7.3	0.2	–	–	30.0	0.4	6.3	0.2	–	–	–	–	23.5	0.3	–	–	–	–
Stipa orientalis	–	–	–	–	3.3	0.2	14.3	0.5	15.9	0.7	–	–	30.0	0.9	**95.8**	**40.1**	–	–	–	–	11.8	0.4	–	–	23.1	1.4
Stipa przewalskyi	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	**100.0**	**41.4**	–	–	–	–	–	–	–	–
Carex pediformis	16.7	1.0	–	–	–	–	–	–	–	–	–	–	–	–	4.2	0.2	**57.1**	**6.9**	–	–	2.9	0.1	–	–	–	–
Poa sect. *Stenopoa*	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	**42.9**	**3.2**	–	–	–	–	–	–	–	–
Polygala tenuifolia	–	–	–	–	–	–	–	–	–	–	–	–	–	–	6.3	0.2	**42.9**	**0.5**	–	–	–	–	–	–	–	–
Leymus secalinus	–	–	–	–	10.0	0.3	28.6	0.9	7.3	1.3	18.2	1.9	10.0	1.2	6.3	0.4	**71.4**	**8.4**	6.3	0.3	20.6	0.6	42.9	8.1	–	–
Artemisia sacrorum	50.0	0.7	–	–	–	–	–	–	–	–	–	–	30.0	0.9	4.2	0.3	**85.7**	**7.4**	–	–	2.9	0.2	–	–	–	–
Heteropappus altaicus	–	–	36.4	1.2	20.0	0.9	57.1	3.6	23.2	0.9	–	–	20.0	0.6	41.7	2.8	**85.7**	**1.8**	25.0	0.6	35.3	0.7	21.4	0.5	–	–
Galium verum	33.3	0.6	–	–	–	–	14.3	0.8	–	–	–	–	20.0	0.2	4.2	0.1	42.9	0.7	6.3	0.0	11.8	0.2	–	–	–	–
Stipa regeliana	–	–	–	–	13.3	1.3	–	–	2.9	0.7	–	–	–	–	–	–	–	–	**100.0**	**42.2**	–	–	–	–	–	–
Stipa purpurea	33.3	0.6	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	**31.3**	**6.1**	–	–	–	–	–	–
Stipa sareptana	–	–	–	–	–	–	14.3	2.7	5.8	0.2	–	–	10.0	1.1	4.2	0.1	–	–	–	–	**100.0**	**40.7**	–	–	–	–
Festuca ovina	33.3	0.7	–	–	3.3	0.1	71.4	9.3	18.8	1.2	–	–	60.0	3.5	18.8	0.9	–	–	18.8	1.1	**85.3**	**10.4**	14.3	0.7	–	–
Carex sp.	83.3	3.2	27.3	0.4	–	–	71.4	2.4	23.2	2.1	18.2	3.3	60.0	4.2	8.3	0.3	–	–	–	–	**82.4**	**4.1**	35.7	2.1	–	–
Polygonum aviculare	–	–	–	–	3.3	0.0	14.3	0.1	11.6	0.3	–	–	20.0	0.2	16.7	0.6	–	–	–	–	**70.6**	**2.4**	–	–	–	–
Chenopodium acuminatum	–	–	9.1	0.1	–	–	–	–	24.6	0.5	–	–	10.0	0.2	35.4	1.1	–	–	–	–	**52.9**	**0.9**	7.1	0.0	–	–
Filago arvensis	–	–	–	–	–	–	–	–	1.5	0.0	–	–	–	–	4.2	0.0	–	–	–	–	**44.1**	**0.7**	–	–	–	–
Alyssum desertorum	–	–	–	–	–	–	–	–	5.8	0.1	–	–	10.0	0.1	8.3	0.1	–	–	–	–	**35.3**	**0.5**	–	–	–	–
Lappula myosotis	–	–	18.2	0.3	–	–	14.3	0.0	33.3	0.8	–	–	20.0	0.2	27.1	0.4	28.6	0.2	6.3	0.2	55.9	1.1	28.6	0.8	7.7	0.1
Stipa subsessiliflora	–	–	9.1	2.8	–	–	–	–	–	–	54.6	10.7	–	–	–	–	–	–	–	–	–	–	**100.0**	**56.8**	–	–
Draba nemorosa	–	–	–	–	–	–	14.3	0.0	4.4	0.0	–	–	–	–	6.3	0.1	–	–	–	–	2.9	0.0	**50.0**	**1.0**	–	–
Agropyron cristatum	–	–	36.4	2.7	3.3	0.1	28.6	2.6	31.9	3.4	–	–	–	–	20.8	1.2	42.9	1.1	–	–	32.4	1.0	35.7	5.7	7.7	0.8
Oxytropis sp.	33.3	1.2	36.4	0.6	–	–	–	–	20.3	1.0	18.2	1.0	–	–	6.3	0.1	–	–	6.3	0.1	8.8	0.3	35.7	1.1	15.4	0.7
Stipa tianschanica	–	–	–	–	–	–	–	–	4.4	0.2	–	–	–	–	–	–	–	–	–	–	–	–	–	–	**100.0**	**36.7**
Lagochilus sp.	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	**61.5**	**2.6**
Asterothamnus fruticosus	–	–	–	–	–	–	–	–	1.5	0.1	–	–	–	–	–	–	–	–	–	–	–	–	–	–	**46.2**	**1.5**
Convolvulus fruticosus	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	**38.5**	**1.4**
Ephedra glauca	–	–	–	–	–	–	–	–	5.8	0.2	–	–	–	–	–	–	–	–	–	–	–	–	–	–	**30.8**	**1.8**
Olgaea lanipes	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	**30.8**	**1.5**
Allium polyrhizum	–	–	9.1	0.2	13.3	0.9	14.3	0.4	18.8	0.9	–	–	–	–	12.5	0.7	–	–	25.0	1.0	–	–	–	–	**76.9**	**3.0**

constancy ≥30%, and species with Importance Value ≥1% and indicator species are listed in Table 5. Due to the limited plot data, only one assocation was identified within this alliance (Suppl. material 4: Table S4).

Stipa caucasica steppe alliance

Stipa caucasica steppe alliance is a desert steppe widely distributed in Xinjiang Province, mainly on the slopes of Tianshan Mountain (36.85°–47.24°N, 74.65°–94.83°E). The altitude ranges from 1307 m to 4434 m, with an average of 2423 m. The AMT is 1.5°C and the AP is 170 mm. The main soil types are chestnut soils, cold calcic soils and light brown calcic soils, and the soil surface is largely covered by gravel and screes.

The community cover varies from 4.0% to 50.1%, with an average of 20.0%. The community height varies from 4.0 to 23.5 cm, with an average of 12.2 cm. Aboveground biomass ranges between 13.7 and 238.8 g m^{-2}, with an average of 80.9 g m^{-2}. In total, 183 species were recorded in 65 plots. Most species are from Middle Asian flora. The community is dominated by *Stipa caucasica*, which has a mean Importance Value of 41.5%. There are 7 species having a constancy ≥30%, and species with Importance Value ≥1% and indicator species are listed in Table 5. Five associations were identified within this alliance (Suppl. material 3: Table S3.11, Suppl. material 4: Table S4).

Stipa caucasica subsp. _desertorum_ steppe alliance

Stipa caucasica subsp. *desertorum* steppe alliance occurs on the Pamir Plateau of Xinjiang Province (36.89°–38.27°N, 74.91°–75.54°E). The altitude ranges from 3924 m to 4226 m, with an average of 4090 m. The AMT is -5.2°C and the AP is 74 mm. The main soil types are cold calcic soils and brown calcic soil.

This vegetation is sparse and short due to the harsh environments. The community cover varies from 4.7% to 25%, with an average of 13.1%. The community height varies from 6.0 to 12.5 cm, with an average of 8.3 cm. Aboveground biomass ranges between 10.4 and 74.6 g m^{-2}, with an average of 36.0 g m^{-2}. In total, 21 species were recorded in 11 plots. The community is dominated by *Stipa caucasica* subsp. *desertorum*, which has a mean Importance Value of 36.8%. There are 8 species having a constancy ≥ 30%, and species with Importance Value ≥1% and indicator species are listed in Table 5. Due to the limited data, only one association was identified (Suppl. material 4: Table S4).

Stipa macroglossa steppe alliance

The center of the *Stipa macroglossa* steppe alliance distribution is in Middle Asia. Xinjiang is its eastern boundary and it is limited to the steep slopes of the Tianshan and Altai Mountains (43.25°–48.18°N, 81.35°–93.83°E). The altitude ranges from 1055 m to 2000 m, with an average of 1523 m. The AMT is 3.8 °C and the AP is 221 mm. The main soil type is chestnut soils, with a high cover of rock outcrops.

The community cover varies from 15% to 40.7%, with an average of 29.6%. The community height varies from 25.0 to 56.1 cm, with an average of 33.8 cm. Aboveground biomass ranges between 71.5 and 350.2 g m^{-2}, with an average of 177.7 g m^{-2}. In total, 71 species were recorded in 10 plots. Most species are from Middle Asian flora. The community is dominated by *Stipa macroglossa*, which has a mean Importance Value of 38.2%. There are 13 species having a constancy ≥30%, and species with Importance Value ≥1% and indicator species are listed in Table 5. One association and two communities were identified within this alliance (Suppl. material 3: Table S3.12, Suppl. material 4: Table S4).

Stipa orientalis steppe alliance

Stipa orientalis steppe alliance is a desert steppe developed on rocky mountains, mainly occurring on the Altai and Tianshan Mountains, in the Ngari district of the Tibetan Plateau, and in western Mongolia (30.21°–50.10°N, 79.29°–102.96°E). It is considered as a geographic replacement alliance of *Stipa tianschanica* var. *gobica* steppe in the east. The altitude ranges from 974 m to 4581 m, with an average of 1869 m. The AMT is 1.9°C and the AP is 197 mm. The main soil types are chestnut soils and light brown calcic soils, and the soil surface is largely covered by gravel.

The community cover varies from 5% to 44.7%, with an average of 18.9%. The community height varies from 4.0 to 43.8 cm, with an average of 17.3 cm. Aboveground biomass ranges between 19.1 and 199.9 g m^{-2}, with an average of 77.2 g m^{-2}. In total, 214 species were recorded in 46 plots. The community is dominated by *Stipa orientalis*, which has a mean Importance Value of 40.1%. Only four species have a constancy ≥30%, and species with Importance Value ≥1% are listed in Table 5. *Stipa orientalis* is the only diagnostic species. Four associations and three communities were identified within this alliance (Suppl. material 3: Table S3.13, Suppl. material 4: Table S4).

Stipa przewalskyi steppe alliance

Stipa przewalskyi steppe alliance mainly occurs from the northern slope of Qilian Mountain to the east of Qinghai Province (36.12°–40.60°N, 101.99°–110.46°E). The altitude ranges from 1156 m to 2778 m, with an average of 2235 m. The AMT is 4.6 °C and the AP is 317 mm. The main soil type is chestnut soils.

The community usually has high cover, height, biomass, and species richness. The community cover varies from 31.3% to 71.3%, with an average of 47.9%. The community height varies from 40.3 to 73.0 cm, with an average of 57.0 cm. Aboveground biomass ranges between 94.3 and 289.8 g m^{-2}, with an average of 178.9 g m^{-2}. In total, 83 species were recorded in 7 plots. Most species are from Central Asian flora. The community is dominated by *Stipa przewalskyi*, which has a mean Importance Value of 41.2%. There are 15 species having a constancy ≥30%, and species with Importance Value ≥1% and indicator species are listed in Table 5. Due to the limited data, only one association was identified within this alliance (Suppl. material 4: Table S4).

Stipa regeliana steppe alliance

Stipa regeliana steppe alliance mainly occurs on the Kunlun Mountain and in the Yurduz Basin of Tianshan Mountain (36.19°–42.72°N, 75.97°–83.70°E). It is sometimes mixed with *Stipa roborowskyi* and *Stipa purpurea* steppes. The altitude ranges from 2592 m to 3508 m, with an average of 3091 m. The AMT is 0.5°C and the AP is 113 mm. The main soil type are brown calcic soils and cold calcic soils.

The community cover varies from 8% to 28.4%, with an average of 17.4%. The community height varies from 5.2 to 31.0 cm, with an average of 20.7 cm. Aboveground biomass ranges between 23.1 and 117.6 g m^{-2}, with an average of 55.4 g m^{-2}. In total, 46 species were recorded in 15 plots. The community is dominated by *Stipa regeliana*, which has a mean Importance Value of 42.2%. There are 7 species having a constancy ≥30%, and species with Importance Value ≥1% and indicator species are listed in Table 5. Two associations were identified within this alliance (Suppl. material 3: Table S3.14, Suppl. material 4: Table S4).

Stipa sareptana steppe alliance

Stipa sareptana steppe alliance is a typical steppe commonly occuring in Xinjiang (42.89°–48.26°N, 80.89°–90.78°E). It is often mixed with *Stipa capillata* steppe. The altitude ranges from 861 m to 2334 m, with an average of 1327 m. The AMT is 4.1°C and the AP is 233 mm. The main soil types are chestnut soils and brown calcic soils.

The community cover varies from 14.0% to 89.7%, with an average of 37.6%. The community height varies from 23.5 to 132.7 cm, with an average of 47.6 cm. Aboveground biomass ranges between 58.9 and 545.0 g m^{-2}, with an average of 185.6 g m^{-2}. In total, 149 species were recorded in 33 plots. Most species are from Middle Asian flora. The community is dominated by *Stipa sareptana*, which has a mean Importance Value of 40.7%. There are 16 species having a constancy ≥30%, and species with Importance Value ≥1% and indicator species are listed in Table 5. Three associations were identified within this alliance (Suppl. material 3: Table S3.15, Suppl. material 4: Table S4).

Stipa subsessiliflora steppe alliance

Stipa subsessiliflora steppe alliance mainly occurs in the Yurduz Basin and in the mountainous areas of the desert zone (37.02°–43.12°N, 74.90°–98.39°E). The altitude ranges from 2471 m to 4114 m, with an average of 3462 m. The AMT is -2.2°C and the AP is 139 mm. The main soil types are cold calcic soils, light cold calcic soils and frigid calcic soils, and the topsoil is slightly salinized.

The community cover varies from 11.3% to 32.7%, with an average of 18.1%. The community height varies from 5.8 to 24.0 cm, with an average of 14.1 cm. Aboveground biomass ranges between 12.2 and 106.8 g m^{-2}, with an average of 57.6 g m^{-2}. In total, 50 species were recorded in 14 plots. Many species are endemic to the Tibetan Plateau or belong to Middle Asian flora. The community is dominated by *Stipa subsessiliflora*, which has a mean Importance Value of 56.8%. There are 8 species having a constancy ≥30%, and species with Importance Value ≥1% and indicator species are listed in Table 5. Two associations and two communities were identified within this alliance (Suppl. material 3: Table S3.16, Suppl. material 4: Table S4).

Stipa tianschanica steppe alliance

Stipa tianschanica steppe alliance is a common desert steppe in the mountainous areas of the desert zone, mainly occuring on the stony slopes of the Tianshan and Qilian Mountains (39.52°–43.16°N, 74.65°–87.58°E). It spans a large longitudinal range but does not develop extensive stands. The altitude ranges from 2057 m to 2953 m, with an average of 2440 m. The AMT is 3.1°C and the AP is 138 mm. The main soil types are chestnut soils, brown calcic soils and cold calcic soils.

The community cover varies from 6.3% to 23.3%, with an average of 12.4%. The community height varies from 11.3 to 27.5 cm, with an average of 18.7 cm. Aboveground biomass ranges between 30.4 and 78.1 g m^{-2}, with an average of 44.7 g m^{-2}. In total, 43 species were recorded in 12 plots. The community is dominated by *Stipa tianschanica*, which has a mean Importance Value of 36.7%. There are 11 species having a constancy ≥30%, and species with Importance Value ≥1% and indicator species are listed in Table 5. Two associations and one community were identified within this alliance (Suppl. material 3: Table S3.17, Suppl. material 4: Table S4).

Classification of the Tibetan Plateau Group

Our clustering protocol classified this group (172 plots × 251 taxa) into five clusters corresponding to the alliance level of the China-VCS, i.e., *Stipa purpurea* steppe alliance, *Stipa subsessiliflora* var. *basiplumosa* steppe alliance, *Stipa roborowskyi* steppe alliance-T, *Stipa caucasica* subsp. *glareosa* steppe alliance-T, and *Stipa capillacea* steppe alliance (Table 6). NMDS ordination of this group yielded a three-dimensional NMDS solution that accounted for 65.8% of the compositional variation in the data set (Fig. 7). Plots representing the five alliances were clearly grouped into discrete clusters with a little overlap in this ordination. Axis 1 separated plots of *Stipa subsessiliflora* var. *basiplumosa* steppe alliance and *Stipa caucasica* subsp. *glareosa* steppe alliance-T from the other three alliances. Axis 2 separated plots of *Stipa capillacea* steppe alliance and *Stipa roborowskyi* steppe alliance-T from the other three alliances. Axis 3 separated plots of *Stipa subsessiliflora* var. *basiplumosa* steppe and *Stipa caucasica* subsp. *glareosa* steppe alliances. Biplot overlays for temperature (MTWQ), altitude (Alt) and longitude (Long) suggested an east-west associated environmental gradient of decreasing temperature and higher elevation with a compositional variation on Axis 1. Biplot overlays for precipitation (AP and PWQ) suggested an associated gradient of increasing rainfall with a compositional variation on Axis 3.

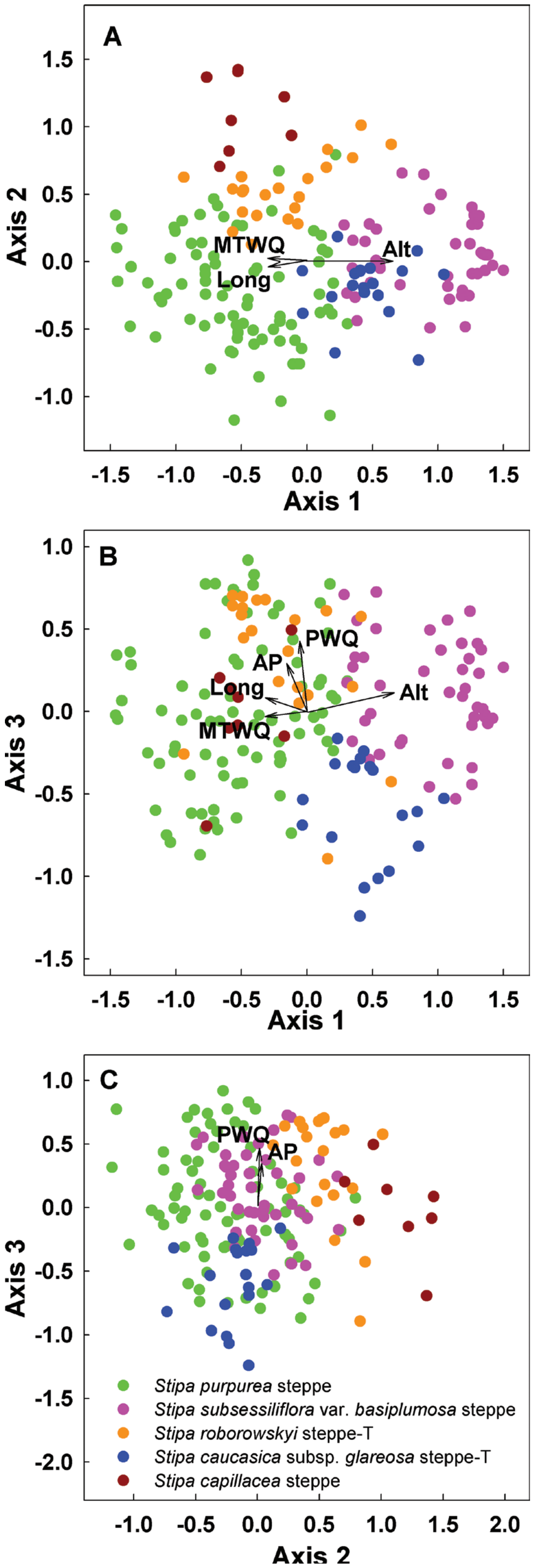

Figure 7. NMDS ordinations of five *Stipa* steppe alliances of the Tibetan Plateau Group based on Importance Value data for axes 1-2(A), 1-3(B) and 2-3(C). Plots are highlighted by five *Stipa* steppe alliances. Stress=0.18. Site and climatic attributes are overlaid as vectors showing the direction and magnitude of increase for longitude (Long), altitude (Alt), Mean Temperature of Warmest Quarter (MTWQ), Annual Precipitation (AP), and Precipitation of Wettest Quarter (PWQ).

Stipa purpurea steppe alliance

Stipa purpurea steppe alliance is widely distributed on the Tibetan Plateau and its surrounding high mountains (30.61°–42.98°N, 74.91°–101.78°E). The distribution range occupies more than 15% of the Tibetan Plateau. It is a typical alpine steppe and the environment is arid, cold and windy. The altitude ranges from 2477 m to 5207 m, with an average of 4302 m. The AMT is -2.1°C and the AP is 208 mm. The main soil types are frigid calcic soils, cold calcic soils and light frigid calcic soils.

The community cover varies from 9.0% to 75.0%, with an average of 29.1%. The community height varies from 3.3 to 41 cm, with an average of 18.7 cm. Aboveground biomass ranges between 17.3 and 253.7 g m^{-2}, with an average of 77.4 g m^{-2}. In total, 208 species were recorded in 78 plots and most species in this alliance are endemic to the Tibetan Plateau. The community is dominated by *Stipa purpurea*, which has a mean Importance Value of 36.9%. The accompanied species usually have a low constancy. Only four species have a constancy ≥30%, and species with Importance Value ≥1% are listed in Table 6. Typical diagnostic species is *Stipa purpurea*. Six associations were identified within this alliance (Suppl. materials 3, 4: Tables S3.18, S4).

Stipa subsessiliflora var. *basiplumosa* steppe alliance

Stipa subsessiliflora var. *basiplumosa* steppe alliance is an endemic vegetation alliance restricted to the Tibetan Plateau, distributed mainly on the outskirts of lake basins and the central sections of proluvial fans of mountains (30.89°–34.26°N, 81.37°–90.44°E). The environment of *Stipa subsessiliflora* var. *basiplumosa* steppe is the coldest at the highest altitude range, and the soil surface is more stony and more arid than that of *Stipa purpurea* steppe alliance. The altitude ranges from 4509 m to 5224 m, with an average of 4873 m. The AMT is -3.9°C and the AP is 156 mm. The main soil type is frigid calcic soils.

The vegetation is sparse and low due to the harsh environment. The community cover varies from 4.1% to 54.1%, with an average of 21.8%. The community height varies from 4 to 26 cm, with an average of 13.0 cm. Aboveground biomass ranges between 9.8 and 66.9 g m^{-2}, with an average of 31.9 g m^{-2}. Species richness is very low. In total, 74 species were recorded in 44 plots. The community is dominated by *Stipa subsessiliflora* var. *basiplumosa*, which has a mean Importance Value of 46.6%. The accompanied species usually have a low constancy. Only six species have a constancy ≥30%, and species with Importance Value ≥1% and indicator species are listed in Table 6. Four associations and two communities were identified within this alliance (Suppl. material 3: Table S3.19, Suppl. material 4: Table S4).

Stipa roborowskyi steppe alliance-T

Stipa roborowskyi steppe alliance-T mainly occurs in the districts of Ngari, Nagqu and Shigatse of the Tibetan Plateau (28.64°–39.47°N, 79.04°–97.68°E). Its distribution range overlaps somewhat with that of *Stipa purpurea* steppe but is much smaller. The altitude ranges from 3289 m to 4911 m, with an average of 4595 m. The AMT

Table 6. Constancy-Importance Value table for five *Stipa* steppe alliances in the Tibetan Plateau Group. Species are included if they have constancy (Con) ≥ 30% in at least one alliance. Mean Importance Value (IV) of each species in each alliance is expressed as percentage. The number in the parentheses is sample size. Indicator species are in boldface type. The five alliances are *Stipa purpurea* steppe (Purp), *Stipa subsessiliflora* var. *basiplumosa* steppe (Basi), *Stipa roborowskyi* steppe-T (Robo-T), *Stipa caucasica* subsp. *glareosa* steppe-T (Glar-T), and *Stipa capillacea* steppe (Capl).

Alliance	Purp (80)		Basi (44)		Robo–T (44)		Glar–T (19)		Capl (8)	
Species	Con	IV	Con	IV	Con	IV	Con	IV	Con	IV
Stipa purpurea	**98.8**	**36.9**	34.1	6.0	90.5	20.6	57.9	13.6	62.5	3.5
Stipa subsessiliflora var. *basiplumosa*	16.3	2.3	**100.0**	**46.7**	47.6	5.4	52.6	12.8	12.5	0.6
Krascheninnikovia compacta	7.5	0.3	**59.1**	**5.8**	–	–	21.1	1.0	–	–
Oxytropis glacialis	12.5	0.6	36.4	2.5	4.8	0.1	31.6	2.1	12.5	0.2
Carex moorcroftii	17.5	1.3	34.1	5.1	28.6	1.5	15.8	1.7	12.5	0.5
Stipa roborowskyi	1.3	0.0	–	–	**100.0**	**34.1**	5.3	0.4	25.0	1.9
Oxytropis microphylla	3.8	0.2	–	–	**57.1**	**2.6**	–	–	12.5	0.2
Swertia hispidicalyx	10.0	0.2	4.6	0.1	**57.1**	**1.5**	–	–	37.5	1.4
Kobresia stolonifera	11.3	0.7	13.6	1.8	**52.4**	**2.0**	10.5	1.0	–	–
Rhodiola tibetica	–	–	6.8	0.1	**38.1**	**1.2**	–	–	12.5	0.0
Astragalus hendersonii	21.3	1.0	18.2	1.1	47.6	0.8	21.1	0.9	25.0	0.3
Heteropappus altaicus	30.0	0.9	6.8	0.2	42.9	0.7	5.3	0.3	37.5	0.6
Stipa caucasica subsp. *glareosa*	2.5	0.2	13.6	2.1	4.8	0.3	**100.0**	**29.3**	–	–
Oxytropis chiliophylla	15.0	1.0	13.6	0.3	9.5	0.3	**84.2**	**6.4**	–	–
Carex montis-everestii	10.0	0.6	13.6	1.7	–	–	**36.8**	**3.8**	–	–
Chamaerhodos sabulosa	13.8	0.7	9.1	0.4	14.3	0.3	73.7	7.3	25.0	0.3
Ptilotrichum canescens	16.3	0.5	50.0	3.6	23.8	0.3	89.5	6.1	–	–
Potentilla bifurca	58.8	2.1	15.9	1.5	47.6	1.9	57.9	2.3	62.5	3.2
Astragalus confertus	32.5	2.0	6.8	0.4	19.1	0.5	36.8	1.5	62.5	2.2
Stipa capillacea	2.5	0.2	–	–	14.3	0.5	–	–	**100.0**	**45.3**
Carex sp.	8.8	0.5	2.3	0.1	19.1	1.0	–	–	**50.0**	**3.3**
Dimorphostemon glandulosus	8.8	0.1	4.6	0.1	–	–	–	–	**50.0**	**0.5**
Potentilla saundersiana	2.5	0.0	–	–	–	–	–	–	**50.0**	**2.6**
Poa litwinowiana	16.3	1.2	–	–	33.3	1.3	–	–	**75.0**	**5.2**
Artemisia demissa	15.0	0.6	4.6	0.1	47.6	0.9	–	–	**62.5**	**2.0**
Boraginaceae	1.3	0.1	–	–	33.3	0.4	–	–	**62.5**	**0.9**
Kobresia macrantha	13.8	0.8	4.6	0.3	47.6	2.4	–	–	**50.0**	**3.9**
Astragalus tribulifolius	8.8	0.3	2.3	0.0	38.1	1.0	10.5	1.6	**50.0**	**1.0**
Gentiana scabra	–	–	–	–	14.3	0.1	–	–	**37.5**	**0.3**
Sibbaldia adpressa	18.8	0.4	–	–	23.8	0.3	–	–	**37.5**	**0.5**
Kobresia humilis	7.5	0.6	–	–	–	–	–	–	**37.5**	**2.5**
Rhodiola smithii	11.3	0.2	–	–	4.8	0.2	–	–	**37.5**	**0.5**

is -2.1°C and the AP is 388 mm. The main soil type is frigid calcic soils.

The community cover varies from 16.3% to 41.7%, with an average of 23.9%. The community height varies from 8 to 36 cm, with an average of 20.1 cm. Aboveground biomass ranges between 27.1 and 102.8 g m^{-2}, with an average of 51.0 g m^{-2}. In total, 89 species were recorded in 21 plots. Most species in this alliance are endemic to the Tibetan Plateau. The community is dominated by *Stipa roborowskyi*, which has a mean Importance Value of 34.1%. There are 15 species having a constancy ≥30%, and species with Importance Value ≥1% and indicator species are listed in Table 6. Two associations and one community were identified within this alliance (Suppl. material 3: Tables S3.20, Suppl. material 4: Table S4).

Stipa caucasica subsp. *glareosa* steppe alliance-T

Stipa caucasica subsp. *glareosa* has an extremely strong drought and cold tolerance. Besides usually forming a desert steppe in temperate zone, it can also be the dominant species in the alpine steppe of the Tibetan Plateau where it forms alpine *Stipa caucasica* subsp. *glareosa* steppe alliance-T, in which most accompanying species are endemic to the Tibetan Plateau. *Stipa caucasica* subsp. *glareosa* steppe alliance-T mainly occurs in the Ngari district of the Tibetan Plateau, occupying the most arid habitats (31.51°–33.67°N, 80.01°–87.97°E). The altitude ranges from 4477 m to 4891 m, with an average of 4663 m. The AMT is -2.9°C and the AP is 140 mm. The main soil type is frigid calcic soils.

The community cover varies from 4% to 38%, with an average of 19.4%. The community height varies from 5.3 to 26 cm, with an average of 9.5 cm. In total, 31 species were recorded in 19 plots. The community is dominated by *Stipa caucasica* subsp. *glareosa*, which has a mean Importance Value of 29.3%. There are 10 species having a constancy ≥30%, and species with Importance Value ≥1% and indicator species are listed in Table 6. Three associations were identified within this alliance (Suppl. material 3: Table S3.21, Suppl. material 4: TableS4).

Stipa capillacea steppe alliance

Stipa capillacea steppe is also an endemic steppe restricted to the Tibetan Plateau. It mainly occurs in the districts of Ngari, Nagqu and Shigatse of the Tibetan Plateau (29.29°–31.33°N, 82.19°–91.07°E). Compared to other alliances, it is an alpine meadow steppe and prefers warmer and wetter climates. The altitude ranges from 4286 m to 4941 m, with an average of 4628 m. The AMT is -1.3°C and the AP is 258 mm. The main soil type is frigid calcic soils.

The community cover varies from 18.2% to 66.3%, with an average of 39.7%. The community height varies from 9 to 35.7 cm, with an average of 24.4 cm. Aboveground biomass ranges between 31.6 and 225.5 g m^{-2}, with an average of 113.3 g m^{-2}. In total, 62 species were recorded in 8 plots. Most species in this alliance are endemic to the Tibetan Plateau. The community is dominated by *Stipa capillacea*, which has a mean Importance Value of 45.3%. There are 18 species having a constancy ≥30%, and species with Importance Value ≥1% and indicator species are listed in Table 6. Due to the limited data, only one association was identified (Suppl. material 4: Table S4).

Discussion

Refining the classification of *Stipa* steppes into alliances and associations

The optimal use of available plot data from varied existing resources is very important for facilitating further development of the China-VCS. To the best of our knowedge, this is the first systematical and comprehensive classification for *Stipa* steppes in China using a standard quantitative method. Based on 1337 plots, we defined five biogeographic groups, 26 alliances and 91 associations and 12 communities (Suppl. material 4: Table S4).

In the latest China-VCS, Tussock Steppe was classified into four Vegetation Subformations. This was mainly based on the ecological conditions and geographical distribution, especially water availability, soil property and temperature, and has not been examined using plot data. *Stipa* steppes are the most important and dominant types in the Tussock Steppe. In our study, we tried to use the plot data of *Stipa* steppes to verify the four vegetation subformations. Our classification firstly yielded five biogeographic groups, that did not completely agree with the four Vegetation Subformations. Only the Tibetan Plateau Group corresponds well to the Tussock Alpine Steppe (Table 7). Among the four vegetation subformations, Tussock Desert Steppe occurs in arid environments, and the vegetation is dwarfed and sparse, with low species richness and productivity. Tussock Meadow Steppe occurs in the habitats with good water availability, and the vegetation usually shows high community height, cover, productivity, and species richness. Tussock Typical Steppe has the environmental features and community characteristics intermediate to the two aforementioned steppe communities. Tussock Alpine Steppe occurs on alpine habitats with cold climate, and the vegetation is dwarf, and it is rich in cushion plants. The same vegetation subformations usually have similiar community physiognomy and structure but species composition does not always have high similiarity. For example, both *Stipa tianschanica* var. *gobica* steppe on the Mongolian Plateau and *Stipa caucasica* steppe on the Xinjiang mountains belong to Tussock Desert Steppe and have similiar habitats and community physiognomy and structure (Suppl. material 2: Table S2), but the dominant

Table 7. The crosswalk table for the five Biogeographic Groups of this study, Vegetation Subformation of China-VCS, and Divsion of IVC.

Biogeographic Groups	Alliance	Vegetation Subformation of China-VCS	Division of IVC	Formation of IVC
Daurian Group	*Stipa baicalensis* steppe	Tussock Meadow Steppe	Eastern Eurasian Grassland and Shrubland	Temperate Grassland, Meadow and Shrubland
	Stipa grandis steppe	Tussock Typical Steppe		
Inner Mongolian Plateau Group	*Stipa sareptana* var. *krylovii* steppe	Tussock Typical Steppe	Eastern Eurasian Cool Semi-Desert Scrub & Grassland	Cool Semi-Desert Scrub & Grassland
	Stipa tianschanica var. *gobica* steppe	Tussock Desert Steppe		
	Stipa tianschanica var. *klemenzii* steppe	Tussock Desert Steppe		
	Stipa caucasica subsp. *glareosa* steppe-I	Tussock Desert Steppe		
Loess Plateau Group	*Stipa breviflora* steppe-L	Tussock Desert Steppe		
	Stipa bungeana steppe	Tussock Typical Steppe		
Xinjiang Mountains Group	*Stipa orientalis* steppe	Tussock Desert Steppe		
	Stipa breviflora steppe-X	Tussock Desert Steppe		
	Stipa tianschanica steppe	Tussock Desert Steppe		
	Stipa caucasica steppe	Tussock Desert Steppe		
	Stipa sareptana steppe	Tussock Typical Steppe		
	Stipa macroglossa steppe	Tussock Typical Steppe		
	Stipa capillata steppe	Tussock Typical Steppe		
	Stipa przewalskyi steppe	Tussock Typical Steppe		
	Stipa regeliana steppe	Tussock Alpine Steppe	Central Asian Alpine Scrub, Herbaceous Meadows and Grasslands	Alpine Forb Meadow & Grassland
	Stipa caucasica subsp. *desertorum* steppe	Tussock Alpine Steppe		
	Stipa subsessiliflora steppe	Tussock Alpine Steppe		
	Stipa aliena steppe	Tussock Alpine Steppe		
	Stipa roborowskyi steppe-X	Tussock Alpine Steppe		
Tibetan Plateau Group	*Stipa purpurea* steppe	Tussock Alpine Steppe		
	Stipa subsessiliflora var. *basiplumosa* steppe	Tussock Alpine Steppe		
	Stipa roborowskyi steppe-T	Tussock Alpine Steppe		
	Stipa caucasica subsp. *glareosa* steppe-T	Tussock Alpine Steppe		
	Stipa capillacea steppe	Tussock Alpine Steppe		

The Division and Formation of IVC refer to Dixon et al. (2014).

and accompanying species are very different due to different regional floristic elements.

The five biogeographic groups of our plot-based classification reflected more similarity in species composition than in environment. For example, in the Daurian Group, the *Stipa baicalensis* steppe and *Stipa grandis* steppe alliances have a big overlap in distribution and share many common species, especially on the Song-Nen Plain, and sometimes form mosaic vegetation patches. However, the *Stipa baicalensis* steppe usually occurs in the depression areas and lower slope of hills with favorable water availability and has high species richness and productivity, belonging to Tussock Meadow Steppe. While, the *Stipa grandis* steppe is commonly distributed on the top of hills or on the ridge of sandy soils. Its distribution area is larger and the environment is drier and warmer relative to the *Stipa baicalensis* steppe. It was assigned to Tussock Typical Steppe in China-VCS. The *Stipa* steppe alliances in the Xinjiang Mountains region have many common species, in particularly the *Seriphidium*, *Poa*, *Carex*, *Malcolmia*, and *Veronica* species from Middle Asian flora, and show relatively high similarity in species composition. However, there are complex and diverse terrains and climates across the large geographic range, which developed different vegetation subformations. The *Stipa orientalis* steppe, *Stipa breviflora* steppe-X, *Stipa tianschanica* steppe, and *Stipa caucasica* steppe mainly occur on sunny slopes or on proluvial fans with arid conditions, that belong to Tussock Desert Steppe. The *Stipa sareptana* steppe, *Stipa capillata* steppe, *Stipa macroglossa* steppe, and *Stipa przewalskyi* steppe mainly occcur in depressions or on shady slopes with better water availability, and are classified as Tussock Typical Steppe. The *Stipa regeliana* steppe, *Stipa caucasica* subsp. *desertorum* steppe, *Stipa subsessiliflora* steppe, *Stipa aliena* steppe, and *Stipa roborowskyi* steppe-X on the high mountains of the outer edge of Tibetan Plateau with alpine environments are considered as Tussock Alpine Steppe. These findings suggest that besides ecological conditions, regional floristic elements and species composition should be taken into consideration in the Chinese vegetation classification, especially when doing vegetation classification above the alliance level at a large geographic scale.

Our quantitative classification defined 26 *Stipa* steppe alliances, supporting and verifing the validity of most *Stipa*-dominated alliances (19 out of 22) in the current vegetation classfication scheme of China (ECVC, 1980; ECVMCCAS, 2007; Guo et al. 2018; Guo et al. 2020). Only three alliances (*Stipa kirghisorum*, *Stipa penicillata* and *Stipa arabica* steppe alliances) were not verified due to the limited data. We also defined and proposed four new alliances, e.g., *Stipa tianschanica* steppe alliance, *Stipa caucasica* subsp. *desertorum* steppe alliance, *Stipa regeliana* steppe alliance, and *Stipa macroglossa* steppe alliance. In addition, three *Stipa* species-dominated alliances (*Stipa caucasica* subsp. *glareosa* steppe, *Stipa roborowskyi* steppe and *Stipa breviflora* steppe) in the previous classification system were further divided into two regional alliances, respectively, due to large variation in speicies composition in different biogeographic regions. For example, *Stipa caucasica* subsp. *glareosa*-dominated communities were previously defined as *Stipa caucasica* subsp. *glareosa* steppe alliance within the vegetation subformation of Tussock Desert Steppe in the China-VCS (ECVC 1980). However, *Stipa caucasica* subsp. *glareosa* is distributed widely, being an important dominant species from the western Mongolian Plateau to the Tibetan Plateau. Except for *Stipa caucasica* subsp. *glareosa*, there is a wide variety of species composition changes between different habitats across such a large geographic range. Our study classified these *Stipa caucasica* subsp. *glareosa*-dominated communities into two *Stipa caucasica* subsp. *glareosa* steppe alliances, i.e., *Stipa caucasica* subsp. *glareosa* steppe alliance-I within the Inner Mongolian Plateau Group (indicated by *Stipa caucasica* subsp. *glareosa*, *Anabasis brevifolia*, *Ajania fruticulosa*, and *Krascheninnikovia ceratoides*) and *Stipa caucasica* subsp. *glareosa* steppe alliance-T within the Tibetan Plateau Group (indicated by *Stipa caucasica* subsp. *glareosa*, *Oxytropis chiliophylla*, and *Carex montis-everestii*).

At the association level, this study also got a more comprehensive and coherent classification than previous studies, in relation to environmental factors, such as soil, temperature, water availability, and disturbance. For example, we had previously identified four associations within the *Stipa tianschanica* var. *klemenzii* steppe alliance based on biomass data set (49 plots × 85 taxa) (Liu et al. 2019). Using the Importance Value data set (94 plots × 178 taxa) in the current study, we not only verified the four associations but also defined three new typical association types (Table 7), more precisely and rigorously defining associations in relation to different envrionmental factors and identifying stronger indicator species. The *Stipa caucasica* subsp. *glareosa* steppe alliance-I was classified into six associations reflecting different environmental factors, such as sandy soils, drought, stony habitats, and salinization. In the *Stipa sareptana* var. *krylovii* steppe alliance, the degraded association type (*Stipa sareptana* var. *krylovii* – *Artemisia frigida* steppe) previously identified (Liu et al. 2019) was divided into two association types reflecting different grazing intensities. *Stipa sareptana* var. *krylovii* – *Artemisia frigida* steppe association reflected long-time moderate grazing disturbance, while *Stipa sareptana* var. *krylovii* + *Potentilla acaulis* steppe association indicated long-time severe grazing disturbance. The previously reported *Krascheninnikovia compacta* – *Stipa subsessiliflora* alpine desert steppe in the Tibetan Plateau (Miehe et al. 2011) is also verified by our classification as the association of *Stipa subsessiliflora* var. *basiplumosa* – *Krascheninnikovia compacta* steppe.

The compatibilty of China-VCS with other international approaches

To a certain extent, our association classification reflects some similiar associations based on the Braun-Blanquet approach in the relevant regions of Mongolia. The association of *Stipa krylovii*+*Cleistogenes squarrosa* is the most typical association type within the *Stipa sareptana* var. *krylovii* steppe alliance. Due to human disturbance, *Cleistogenes squarrosa and Carex duriuscula* show higher constancy and dominance than *Cymbaria dahurica* in this association. which could be a degraded variant of the Cymbario dahuricae-Stipetum krylovii HILBIG (1987) 1990 that is the characteristic steppe community of the steppe zone in Mongolia (Hilbig 1987, 1990, 1995, 2000, 2009). The association of *Stipa sareptana* var. *krylovii* + *Artemisia frigida* steppe is similar to the Hedysaro pumili-Stipetum krylovii Hilbig (1987) 1990 corr. 1995 distributed in the southern and western Mongolia (Hilbig 2000; von Wehrden et al. 2009; Zemmrich et al. 2010), with the same indicator species, *Agropyron cristatum* and *Artemisia frigida*. The typical association of *Stipa caucasica* subsp. *glareosa* – *Anabasis brevifolia* steppe in the desert region is similiar to the association of Stipo glareosae-Anabasetum brevifoliae HILBIG (1987) 1990 extensively occuring in the southern Mongolia semi-desert (Hilbig 1995, 2000; Wesche et al. 2005; von Wehrden et al. 2009; Zemmrich et al. 2010). The *Stipa grandis-Lespedeza davurica* association and *Stipa grandis+Leymus chinensis* association could be considered as variants of the Poo attenuatae-Stipetum grandis KASHAPOV et al.1987 emend. (Hilbig 1995) since *Poa* sect. *Stenopoa* and *Carex korshinskyi* are important indicator species.

How to improve the compatibility of China-VCS with other international standards is one of the greatest challenges in developing the China-VCS (Song 2011; Guo et al. 2018, 2020; Liu et al. 2019). Compared with the EcoVeg approach of the International Vegetation Classification (Faber-Langendoen et al. 2014, 2018, 2020), the China-VCS and EcoVeg approaches have many similarities. Based on 1337 plots across the whole distribution range of *Stipa* steppes in China, the resulted five biogeographic groups roughly correspond to three Divisions of International Vegetation Classfication (Table 7; Dixon et al. 2014). The five biogeographic groups could be considered as regional Alliance Group level of China-VCS. Based on the diagnostic species and their contancies (>25%) (Table 1) and the regional differences of ecological conditions, the five biogeographic groups could be equal to Macrogroup or Group levels of IVC (Faber-Langendoen et al. 2020). For example, the Xinjiang Mountains Group can be considered as a macrogroup of IVC and then could be divided into three groups along altitudinal gradient of climates, while the other four biogeogrpahic groups are equal to four groups of IVC. The association and alliance levels of the China-VCS are somewhat similar to the association and alliance levels of EcoVeg (Liu et al. 2019; Faber-Langendoen et al. 2020). In the China-VCS, the alliance is defined as ‘the assemblage of the plant communities with the same dominant species in the dominant stratum within one Vegetation Formation or Vegetation Subformation’ (Guo et al. 2018), while the higher level classification is based on the dominant growth form and community physiognomy. In IVC alliances, ‘the emphasis of having at least one diagnostic species in the dominant stratum provides a link to the higher-level physiognomic classification units’ (Jennings et al. 2009). Diagnostic species in the EcoVeg approach may or may not be dominant. The emphasis on dominance in EcoVeg is greater at the alliance level than at the association level. We used a set of strong diagnostic species to define biogeographic groups, and furthermore, used dominant species in the dominant stratum and diagnostic species from multiple strata to define alliances and associations, improving compatibility with the IVC (Liu et al. 2019).

In summary, based on 1337 plots, we did a systematical and comprehensive classification for *Stipa* steppes in China, defining five biogeographic groups, 26 alliances, 91 associations and 12 communites. The *Stipa*-dominated alliances in the framework of current China-VCS were verified. The four vegetation subformations of Tussock Steppe were not completely supported by the five biogeographic groups, due to different classification criteria. Our classification used a set of dominant species and diagnostic species to define biogeographic groups, alliances and associations, ensuring compatibility with the IVC.

Data availability

All data are in VegChina (http://vegetation.ibcas.ac.cn/vegchina/#/index).

Author contributions

K.G. and C.L. planned the research, all the authors conducted the field sampling, C.L. and X.Q. performed the statistical analyses and led the writing, all authors critically revised the manuscript.

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References

Chen LZ, Sun H, Guo K (2014) Flora and Vegetation Geography of China. Science Press, Beijing.

De Cáceres M, Chytrý M, Agrillo E, Attorre F, Botta-Dukát Z, Capelo J, Czúcz B, Dengler J, Ewald J, … Wiser S (2015) A comparative framework for broad-scale plot-based vegetation classification. Applied Vegetation Science 18: 543–560. https://doi.org/10.1111/avsc.12179

De Cáceres M, Font X, Oliva F (2010) The management of numerical vegetation classification with fuzzy clustering methods. Journal of Vegetation Science 21: 1138–1151. https://doi.org/10.1111/j.1654-1103.2010.01211.x

De Cáceres M, Franklin SB, Hunter JT, Landucci F, Dengler J, Roberts D W (2018) Global overview of plot-based vegetation classification approaches. Phytocoenologia 48: 101–112. https://doi.org/10.1127/phyto/2018/0256

Dixon AP, Faber-Langendoen D, Josse C, Morrison J, Loucks CJ (2014) Distribution mapping of world grassland types. Journal of Biogeography 41: 2003–2019. https://doi.org/10.1111/jbi.12381

Dufrêne M, Legendre P (1997) Species assemblages and indicator species: the need for a flexible asymmetrical approach. Ecological Monographs 67: 345–366. https://doi.org/10.2307/2963459

ECFC [The editorial committee of Flora of China] (1994–2013) Flora of China. Science Press, Beijing; Missouri Botanical Garden, St. Louis.

ECFRPS [The editorial committee of Flora Reipublicae Popularis Sinicae] (1959–2004) Flora reipublicae popularis sinicae. Science Press, Beijing.

ECVC [The editorial committee of vegetation of China] (1980) Vegetation of China. Science Press, Beijing.

ECVMC-CAS [The Editorial Committee of Vegetation Map of China, Chinese Academy of Sciences] (2007) Vegetation of China and Its'Geographic Pattern: Illustration of the Vegetation Map of the People's Republic of China 1:1000000. Geological Publishing House, Beijing.

Ermakov N, Chytrý M, Valachovič M (2006) Vegetation of the rock outcrops and screes in the forest-steppe and steppe belts of the Altai and Western Sayan Mts., southern Siberia. Phytocoenologia 36: 509–545. https://doi.org/10.1127/0340-269X/2006/0036-0509

Faber-Langendoen D, Baldwin K, Peet RK, Meidinger D, Muldavin E Keeler-Wolf T, Josse C (2018) The EcoVeg approach in the Americas: U.S., Canadian and International Vegetation Classifications. Phytocoenologia 48: 215–237. https://doi.org/10.1127/phyto/2017/0165

Faber-Langendoen D, Keeler-Wolf T, Meidinger D, Tart D, Hoagland B, Josse C, Navarro G, Ponomarenko S, Saucier J, … Comer, P (2014) EcoVeg: a new approach to vegetation description and classification. Ecological Monographs 84: 533–561. https://doi.org/10.1890/13-2334.1

Faber-Langendoen D, Navarro G, Willner W, Keith DA, Liu CC, Guo K, Meidinger D (2020) Perspectives on Terrestrial Biomes: The International Vegetation Classification. In: Goldstein MI, DellaSala DA (Eds) Encyclopedia of the World's Biomes, Vol. 1. Elsevier, 1–15. https://doi.org/10.1016/B978-0-12-409548-9.12417-0

Fang JY, Guo K, Wang GH, Tang ZY, Xie ZQ, Shen ZH, Wang RQ, Qiang S, Liang CZ, … Yu D (2020) Vegetation classification system and classification of vegetation types used for the compilation of vegetation of China. Chinese Journal of Plant Ecology 44: 96–110. [In Chinese] https://doi.org/10.17521/cjpe.2019.0259

Franklin J, Andrade R, Daniels ML, Fairbairn P, Fandino MC, Gillespie TW, González G, Gonzalez O, Imbert D, … Vennetier M (2018) Geographical ecology of dry forest tree communities in the West Indies. Journal of Biogeography 45: 1168–1181. https://doi.org/10.1111/jbi.13198

Franklin J, Ripplinger J, Freid EH, Marcano-Vega, H, Steadman DW (2015) Regional variation in Caribbean dry forest tree species composition. Plant Ecology 216: 873–886. https://doi.org/10.1007/s11258-015-0474-8

Franklin SB, Hunter JT, De Cáceres M, Dengler J, Landucci F, Krestov P (2016) Introducing the IAVS Vegetation Classification Working Group. Phytocoenologia 46: 5–8. https://doi.org/10.1127/phyto/2016/0116

Guo K, Fang JY, Wang GH, Tang ZY, Xie ZQ, Shen ZH, Wang RQ, Qiang S, Liang CZ, … Yu D (2020) A revised scheme of vegetation classification system of China. Chinese Journal of Plant Ecology 44: 111–127. [In Chinese] https://doi.org/10.17521/cjpe.2019.0271

Guo K, Liu CC, Xie ZQ, Li FY, Franklin SB, Lu ZJ, Ma KP (2018) China Vegetation Classification: concept, approach and applications. Phytocoenologia 48: 113–120. https://doi.org/10.1127/phyto/2017/0166

Hamasha HR, von Hagen KB, Roser M (2012) *Stipa* (Poaceae) and allies in the Old World: molecular phylogenetics realigns genus circumscription and gives evidence on the origin of American and Australian lineages. Plant Systematics and Evolution 298: 351–367. https://doi.org/10.1007/s00606-011-0549-5

Hijmans RJ, Cameron SE, Parra JL, Jones PG, Jarvis A (2005) Very high resolution interpolated climate surfaces for global land areas. International Journal of Climatology 25: 1965–1978. https://doi.org/10.1002/joc.1276

Hilbig W (1987) Pflanzengesellschaften der Mongolischen Volksrepublik. Univ. Halle-Wittenberg, Diss. B, Textband 239 S., Tab.band 202 S.

Hilbig W (1995) The vegetation of Mongolia. SPB Academic Publishing, Amsterdam 107(1–2): 147–148.

Hilbig W (1990) Neu beschriebene Pflanzengesellschaften aus der Mongolischen Volksrepublik. Feddes Repertorium 101: 189–206. https://doi.org/10.1002/fedr.19901010313

Hilbig W (2000) Kommentierte Übersicht über die Pflanzengesellschaften und ihre höheren Syntaxa in der Mongolei. Feddes Repertorium 111: 75–120. https://doi.org/10.1002/fedr.20001110108

Hilbig W (2009) Validierung von Subassoziationen mongolischer Pflanzengesellschaften. Feddes Repertorium 120: 91–122. https://doi.org/10.1002/fedr.200811196

IMNSEG-CAS [Inner Mongolia and Ningxia Scientific Expedition Group, Chinese Academic of Sciences] (1985) Vegetation of Inner Mongolia. Science Press, Beijing.

Jennings MD, Faber-Langendoen D, Loucks OL, Peet RK, Roberts D (2009) Standards for Associations and Alliances of the U.S. National Vegetation Classification. Ecological Monographs 79: 173–199. https://doi.org/10.1890/07-1804.1

Lavrenko EM, Karamysheva ZV (1993) Steppes of the former Soviet Union and Mongolia. In: Coupland RT (Ed.) Ecosystems of the world 8B – Natural grasslands. Elsevier, Amsterdam.

Li FY, Jäschke Y, Guo K, Wesche K (2020) Grasslands of China. In: Goldstein MI, DellaSala DA (Eds) Encyclopedia of the World's Biomes, Vol. 3. Elsevier, 773–784. https://doi.org/10.1016/B978-0-12-409548-9.12120-7

Liu CC, Wentworth TR, Qiao XG, Guo K, Hou DJ (2019) Vegetation classification at the association level under the China Vegetation Classification System: an example of six *Stipa* steppe formations in China. Journal of Plant Ecology 12: 1009–1024. https://doi.org/10.1093/jpe/rtz028

Lu SZ, Qiao XG, Zhao LQ, Wang Z, Gao CG, Wang J, Guo K (2020) Basic characteristics of *Stipa sareptana* var. *krylovii* communities in China. Chinese Journal of Plant Ecology 44: 1087–1094. [in Chinese] https://doi.org/10.17521/cjpe.2020.0072

McCune B, Grace J (2002) Analysis of Ecological Communities. MjM Software, Gleneden Beach, Oregon, 284 pp.

Miehe G, Bach K, Miehe S, Kluge J, Yongping Y, Duo L, Co S, Wesche K (2011) Alpine steppe plant communities of the Tibetan highlands. Applied Vegetation Science 14: 547–560. https://doi.org/10.1111/j.1654-109X.2011.01147.x

Peck JE (2016) Multivariate Analysis for Community Ecologists: Step-by-Step, 2nd Edn. MjM Software Design, Gleneden Beach, Oregon.

Qiao XG (2019) Community characteristics of Stipa steppes in China. Ph.D. thesis, University of Chinese Academy of Sciences, Beijing.

Qiao XG, Guo K, Zhao LQ, Liu CC, Zhao HW, Hou DJ, Gao CG (2017a) Distribution, community characteristics and classification of *Stipa tianschanica* var. *klemenzii steppe* in China. Chinese Journal of Plant Ecology 41: 231–237. [in Chinese] https://doi.org/10.17521/cjpe.2016.0053

Qiao XG, Guo K, Zhao LQ, Wang Z, Liu CC (2020) Community characteristics of *Stipa bungeana* alliance in China. Chinese Journal of Plant Ecology 44: 986–994. [in Chinese] https://doi.org/10.17521/cjpe.2020.0150

Qiao XG, Guo K, Zhao LQ, Yang Y, Zhao HW (2017b) Distribution, community characteristics and classification of *Stipa basiplumosa* steppe on Tibetan Plateau. Geographical Research 36: 2432–2440. [in Chinese]

Roberts DW (2016) Optpart: Optimal Partitioning of Similarity Relations. R package version 2.3-0. https://CRAN.R-project.org/package=optpart

Song YC (2011) Recognition and proposal on the vegetation classification system of China. Chinese Journal of Plant Ecology 35: 882–892. [in Chinese] https://doi.org/10.3724/SP.J.1258.2011.00882

von Wehrden H, Wesche K, Miehe G (2009) Plant communities of the southern Mongolian Gobi. Phytocoenologia 39: 331–376. https://doi.org/10.1127/0340-269X/2009/0039-0331

Wesche K, Miehe S, Miehe G (2005) Plant communities of the Gobi Gurvan Sayhan National Park (South Gobi Aymak, Mongolia). Candollea 60: 149–205.

Wiser SK, De Cáceres M (2013) Updating vegetation classifications: an example with New Zealand's woody vegetation. Journal of Vegetation Science 24: 80–93. https://doi.org/10.1111/j.1654-1103.2012.01450.x

Yang Y, Guo K, Zhao LQ, Zhao HW, Qiao XG, Liu HM, Liu CC (2014) Community characteristics of *Stipa roborowskyi* in Xizang. Chinese Journal of Plant Ecology 38: 635–639. [in Chinese] https://doi.org/10.3724/SP.J.1258.2014.00059

Zemmrich A, Hilbig W, Oyuunchimeg D (2010) Plant communities along an elevation gradient under special consideration of grazing in Western Mongolia. Phytocoenologia 40: 91–115. https://doi.org/10.1127/0340-269X/2010/0040-0443

Zhao HW, Guo K, Yang Y, Liu CC, Zhao LQ, Qiao XG, Hou DJ, Gao CG (2018) *Stipa* steppes in scantily explored regions of the Tibetan Plateau: classification, community characteristics and climatic distribution patterns. Journal of Plant Ecology 11: 585–594. https://doi.org/10.1093/jpe/rtx029

Zhu YJ, Qiao XG, Guo K, Xu R, Zhao LQ (2018) Distribution, community characteristics and classification of *Stipa tianschanica* var. *gobica* steppe in China. Chinese Journal of Plant Ecology 42: 785–792. [in Chinese] https://doi.org/10.17521/cjpe.2017.0314

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Supplementary material

Supplementary material 1
Vegetation classification System of China
Link: https://doi.org/10.3897/VCS.72875.suppl1

Supplementary material 2
The cover, height, aboveground biomass, and species richness of *Stipa* alliances in China
Link: https://doi.org/10.3897/VCS.72875.suppl2

Supplementary material 3
Constancy-Importance Value table for associations and communities in each *Stipa* steppe alliance
Link: https://doi.org/10.3897/VCS.72875.suppl3

Supplementary material 4
Brief descriptions of associations and communities of *Stipa* steppes in China
Link: https://doi.org/10.3897/VCS.72875.suppl4

Supplementary material 5
Pictures of *Stipa* steppe alliances in China
Link: https://doi.org/10.3897/VCS.72875.suppl5

Supplementary material 6
Constancy-Importance Value table for *Stipa* steppe alliances in China.
Link: https://doi.org/10.3897/VCS.72875.suppl6