VEGETATION MAPPING IN CENTRAL ASIAN DRY ECO-SYSTEMS USING LANDSAT ETM+

A CASE STUDY ON THE GOBI GURVAN SAYHAN NATIONAL PARK

With 3 figures, 4 tables and 1 supplement (III)

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Zusammenfassung: Vegetationskartierung in zentralasiatischen Trockengebieten basierend auf Landsat ETM+. – Eine Fallstudie aus dem Gobi Gurvan Sayhan National Park

Ziel der vorliegenden Arbeit war die Erstellung einer Vegetationskarte für eines der größten Schutzgebiete der semi-ariden Süd-Mongolei, den Gobi Gurvan Sayhan National Park. Der Park beherbergt mehrere seltene und gefährdete Arten und Vegetationstypen, für deren Management entsprechend detaillierte räumlich explizite Daten benötigt werden. Das Arbeitsgebiet wurde von fünf Landsat ETM+-Szenen abgedeckt. Die vorhandene Vegetation wurde durch mehr als 600 Vegetationsaufnahmen nach Braun-Blanquet belegt; die Probeflächen wurden mit Hilfe der Satellitendaten ausgewählt (unüberwachte Klassifikationen).

Die Vegetationsaufnahmen wurden mit einem pflanzensoziologischen Ansatz in vier Gruppen unterteilt: Gebirgssteppen, feuchte Wüstensteppen der oberen Pedimente, trockene Wüstensteppen und extrazonale Vegetation. Diese Gruppen wurden in insgesamt 18 Pflanzengesellschaften unterteilt, die zugeordneten Vegetationsaufnahmen dienten dann als Trainingsgebiete für eine überwachte Klassifikation der Satellitenszenen. Aufgrund der lichten Vegetationsdecke ergaben sich zwar bei einigen Gesellschaften Schwierigkeiten wegen der relativ geringen spektralen Unterschiede, aber eine Validierung der Karte mit einem unabhängigen Testdatensatz ergab nichtsdestotrotz eine Genauigkeit von über 93%. Somit erwiesen sich die hier angewandten Methoden für dieses Arbeitsgebiet geeignet; weitere Schutzgebiete der südlichen Mongolei werden zurzeit mit der gleichen Methodik kartiert.

Summary: This paper presents a vegetation map of the Gobi Gurvan Sayhan National Park, a large protected area in the semi-arid parts of southern Mongolia. The map was compiled in order to provide spatially explicit baseline data that were required for conservation management. The study area was covered by five partly overlapping Landsat ETM+ scenes. Vegetation was sampled at more than 600 sites using a modified Braun-Blanquet approach; locations were selected with the help of unsupervised classifications of the satellite scenes.

Vegetation samples were initially classified with a phytosociological approach yielding four main groups of plant communities: mountain steppes, moist desert steppes of the upper pediments, dry desert steppes and extra-zonal vegetation. These groups comprised a total of 18 plant communities, which were subsequently used for the supervised classification of satellite images. Difficulties were expected due to the sparse vegetation cover typical for semi-deserts and steppe ecosystems, resulting in minor spectral differences among the different communities. However, independent validation of the map yielded an overall accuracy above 93%. Thus, the chosen set of methods proved suitable for the study region, and is currently employed for similar surveys in other southern Mongolian nature reserves.

1 *Introduction*

Management of protected parks requires sound and spatially explicit base-line data. Over the last few decades, several of the world's largest nature reserves have been established in low-income countries which lack detailed country-wide survey schemes. Financial resources of local park administrations are usually very limited, so efforts put into particular surveys have to be kept to a minimum. Inaccessibility often adds to these difficulties and satellite-based approaches offer one of the few options available when an assessment of ecological parameters of large areas on a limited budget is desired. Maps of vegetation patterns are widely employed in conservation schemes, and several authors have successfully applied remote sensing techniques in Central Asian steppes (Burkart et al. 2000; Kogan et al. 2004; Kawamura et al. 2003; Yu et al. 2004).

Most vegetation units within the southern Gobi are characterized by low vegetation cover (Hilbig 1995), rendering spectral signatures of vegetation types difficult to differentiate. However, plant communities are very homogeneous over vast areas and are closely coupled to the relief, and therefore also to the local climate, which often shows steep altitudinal gradients (Barthel et al. 1983). Changes in the vegetation cover are rather gradual, a general problem in mapping projects (Alexander a. Millington 2000), and are only obvious when analysed on large scales.

Vegetation mapping using Landsat is a standard approach and images are widely available. Landsat ETM+ offers an adequate resolution (Dymond et al. 1996) for spatial scales which are of interest to the management of large reserves (1: 50 000–1: 250 000). Thus we opted for this sensor, and based our supervised classification on a phytosociological classification system. To our knowledge, this approach has so far not been tested in Central Asian drylands (see ZAK a. CABIDO 2002 for an application in Argentina).

The study was performed in the Gobi Gurvan Sayhan National Park in southern Mongolia. Conditions were favourable, because we could use a set of important background information. Topographic maps are available at a scale of 1:100 000. The flora is well known as most vascular plants are covered by a two-volume flora guide, that has recently been translated into English (GRUBOV 2000a); recent amendments are found in a new checklist (GUBANOV 1996), and in the successively published Plants of Central Asia (GRUBOV 2000b). Various schemes are available for the classification of Mongolian plant communities. Russian authors devised comprehensive descriptions of the Mongolian vegetation (e.g. JUNATOV 1974; LAVRENKO a. KARAMYSHEVA 1993; KARAMYSHEVA a. KHRAMTSOV 1995), including a coarse land cover map of the entire country (1:1 000 000, GUNIN a. VOSTOKOVA 1995). Distinction of vegetation units is largely based on the relative dominance of species, i.e. a hypothetical *Stipa krylovii-Poa attenuata* community would be distinct from a *Poa attenuata-Stipa krylovii* community. This leads to a large number of units whose differences are not immediately obvious to the non-expert (see HILBIG 1990). More recently, phytosociological classifications have proven increasingly more successful. These are based on the presence of so-called "diagnostic species", which are restricted to a given community but not necessarily dominant. A comprehensive system was proposed by HILBIG (1995, 2000) and has since become the benchmark reference on the vegetation of Mongolia. However, the southernmost parts of the country have rarely been visited by botanists, and our reconnaissance study (MIEHE 1998) revealed that some modifications of HILBIG's system (1995) would be necessary for an adequate survey of the region.

Thus, before embarking on the remote-sensing study we had to devise an appropriate classification scheme for the vegetation of the Gobi Gurvan Sayhan National Park. This was based on collecting new vegetation samples. We followed a phytosociological approach which involved selecting sample plots of standardized size, recording all present vascular plants, followed by a manual classification of samples based on diagnostic species (details in WESCHE et al. 2005). Classified vegetation samples were then used as training regions for the classification of the satellite imagery.

Thus, the overall aim of the present study was to devise a reasonably accurate map of the predefined plant communities, which was required for conservation planning in the area.

2 *Study area*

At 27,000 km^2, the Gobi Gurvan Sayhan National Park is the second largest protected area in Mongolia (BEDUNAH a. SCHMIDT 2000). The topography is governed by pediment regions which cover 63% of the park and surround the south-easternmost ranges of the Gobi Altai. Steep mountainous slopes cover approximately 31% of the national park and several summits reach above 2,800 m a.s.l., while the pediments range from approximately 1,500 m up to 2,300 m.

The geological background varies. Exposed bedrock is largely restricted to the mountainous regions, while in the remaining zones the Palaeozoic and Mesozoic basements are widely covered by Quaternary deposits (CARRETIER et al. 2002). Most have a clayey to loamy texture, and only six percent of the area can be designated as sand dunes (mostly located in inter-montane depressions between 1,300 m a.s.l. and 1,500 m a.s.l.). All substrates are subject to erosive processes with frost shattering and deflation as the dominant forms today. Wind is a ubiquitous factor responsible for the wide distribution of gravel pavements in the area. Where bunch grasses and shrubs retain some wind-blown material, small Nebkahs form on the pavements. Additionally, linear erosion is widespread, and huge gullies intersect the pediments throughout the entire region. Surface water is rarely seen, but in moist periods Sayrs (the Mongolian equivalent of Wadis) are filled with ephemeral, though turbulent, rivers.

The dominant soil types in the pediment regions are Burosems and poorly developed Kastanosems, which share a matrix dominated by fine sand and silt. On mountain slopes shallower Kastanosems, Parachernosems, but also Leptosols with a coarse substrate prevail. Dune regions show Arenosols; locally Solonchaks and Solonetz with a high content of clay have formed in moist depressions. Poorly differentiated soils with a coarse matrix dominated by gravels are found in the Sayrs. Hence, soil texture shows a pronounced zonation within the landscape, which is an important determinant of the vegetation distribution (GUNIN a. VOSTOKOVA 1995).

The climate is highly continental and semi-arid. All governmental weather stations are situated within the inter-montane basins and reflect the conditions of the desert steppes (Fig. 1). Low temperatures in winter and lack of rain in spring restrict the growth period to some four months. Rains are low overall (annual means <130 mm), allowing for a diffuse but still mostly continuous vegetation cover.

The summer climate is governed by the eastern Asian monsoon, which seems to be the main influence on the climate in the southern and south-eastern parts of Mongolia (WESCHE et al. 2005). Although western disturbances (WEISCHET a. ENDLICHER 2000) influence the climate as well, within the study region conditions tend to get drier as one progresses westwards (Fig. 1), suggesting that much precipitation is brought from the east rather than from the west. Moreover, unlike in south-western Mongolia, winter precipitation is negligible, suggesting that western disturbances hardly reach the Gobi Gurvan Sayhan.

Long-term measurements for the mountains are not available, but short-term data from our project collected in the Dund Sayhan suggest that mountain sites clearly receive more rain than the pediment regions (Tab. 1). This is supported by available vegetation studies, which describe a clear altitudinal zonation and communities with higher moisture requirements occurring in the mountains (WESCHE et al. 2005; GUNIN a. VOSTOKOVA 1995). Moreover, mountains are known for being favourable grazing sites for the local populations; hence their name Gobi Gurvan Sayhan meaning “Three Beauties of the Gobi”. Thus, the vegetation zonation reflects strong altitudinal gradients in precipitation from mountain steppes on the higher slopes, to semi-desert shrub communities situated in the lower depressions where dense salt meadows grow at oases.

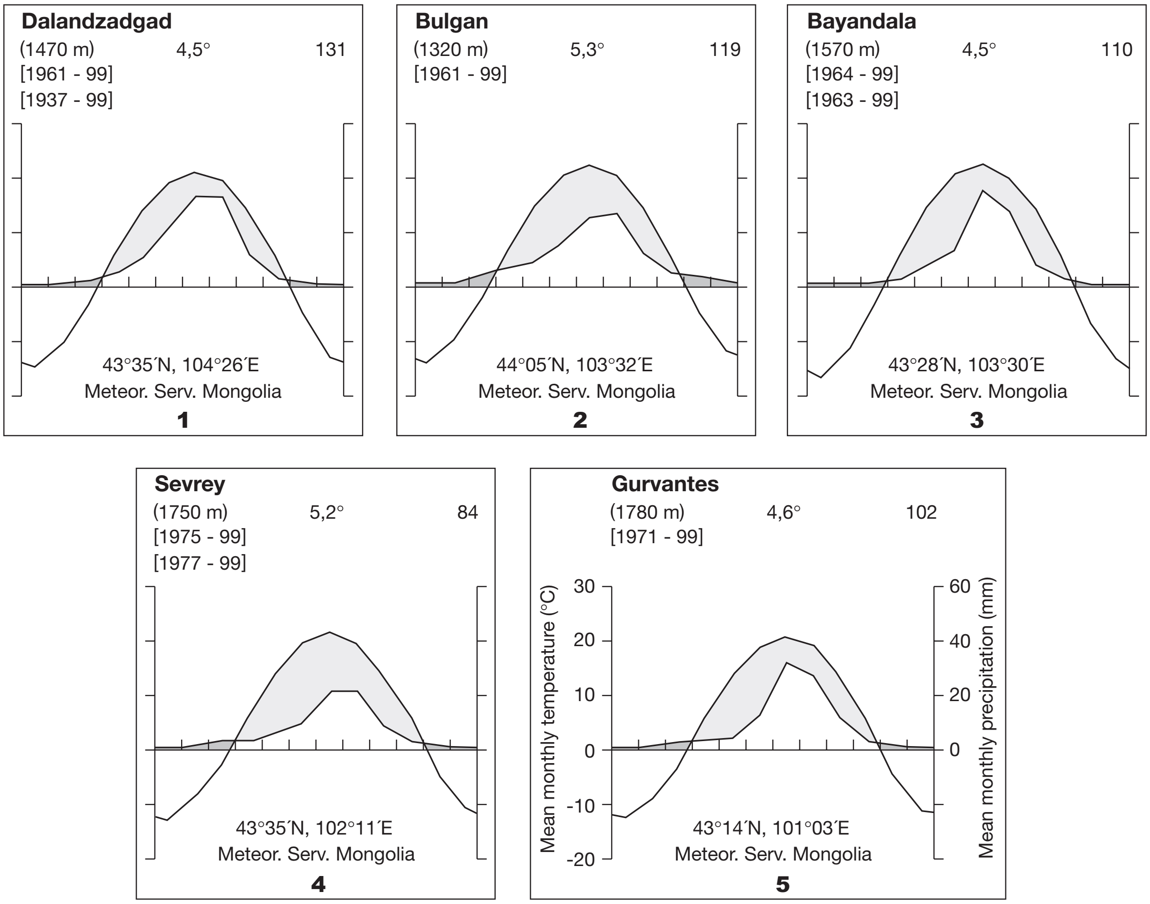

Fig.1: Walter-Lieth diagrammes for the sum centres in the Gobi Gurvan Sayhan region (after data of the Meteor. Serv. of Mongolia, draft C. ENDERLE, Marburg). For the location of sites see figure 2 (Suppl.)

Walter-Lieth-Klimadiagramme für die Sum-Zentren in der Region Gobi Gurvan Sayhan (nach Daten des Meteorologischen Dienstes der Mongolei, erstellt von C. ENDERLE, Marburg). Zur Lokalisierung der Stationen siehe Abbildung 2

As is typical of drylands, inter-annual variability of precipitation is huge, resulting in equally strong changes in biomass production (STUMPP et al. 2005; YU et al. 2003). Yet, the composition and the distribution of plant communities seems to be relatively stable compared to North-American steppes, where distribution of long and short grass prairie varies over several years (KÜCHLER 1972). In the Gobi, most of the characteristic species are long-lived and therefore develop stable communities; only the occurrence of annuals is strongly linked to the inter-annual variability of the climate.

The flora is dominated by Central-Asian elements (MALYSHEV 2000), but Uralo-Sibirean, Dzungarian and other floristic elements also occur (MEUSEL et al. 1992).

Table 1: Vertical gradients in precipitation totals along the southern slopes of the Dund Sayhan. 2001 was a year of drought, 2004 a moist year (data from RETZER 2003, measurements for 2004 are own data but only for two sites)

Vertikale Niederschlagsgradienten (in Jahressummen) entlang des Südhanges des Dund Sayhans im Dürrejahr 2001 sowie im vergleichsweise niederschlagsreichen Jahr 2004 (nach Daten von RETZER 2003, Messungen von 2004 sind nur für zwei Lokalitäten verfügbar)

Elevation	2001	2004
1,800 (m a.s.l.)	13 mm	
2,000	21 mm	117 mm
2,200	43 mm	
2,400	73 mm	
2,600	81 mm	158 mm
2,800	70 mm	

3 *Data and Methods*

3.1 Integration of field data

In the vegetation period of 2001, 334 plots were sampled using a modified Braun-Blanquet approach. Most vegetation types were very homogenous over hectares or even square kilometres, while some communities (e.g. saline meadows) occurred only in small stands. We therefore settled on relevé samples of 10 x 10 m in size; vascular plant cover was estimated in absolute percentages. In addition, 330 "fast plots" were taken en route, where only the species composition was recorded. All plots were located using a handheld GPS; see figure 2 (Suppl.) for an overview of the working area.

Satellite imagery aided selection of sample sites. The Landsat ETM+ sensor has a resolution of 28.5 metres and contains eight spectral channels. Five Landsat-scenes that covered the area of the national park were used (Path 133–134, Row 29–30 and Path 132, Row 30, Fig. 3).

Sample sites were chosen in the field based upon the results of unsupervised classifications (Isoclass) and red-green-blue images. Thus, plots were selected to cover patterns that were spectrally discernible in the unsupervised classifications. Additional plots that showed a unique species composition were also sampled to supplement the preliminary phyto-sociological classification system (MIEHE 1998). After field work in 2001, all available vegetation samples (including those from the reconnaissance in 1996) were classified into standard phyto-sociological tables (see WESCHE et al. 2005).

Extra- and azonal vegetation had to be excluded from the satellite classification because stands were typically smaller than the resolution of the sensor. Moreover, separate satellite-based mapping of some montane communities devised by WESCHE et al. (2005) proved to be impossible. Scattergrams of spectral signatures revealed that spectral differences of these classes were not sufficient to distinguish them. In consequence, the 23 originally identified plant communities were reduced to 18 units employed in the supervised classification of the Landsat data (see Tab. 2).

Each of the five Landsat scenes (Fig. 3) was classified individually. Since the data was provided as level-1g-data, a terrain correction was not made. However, a comparison with GPS-located sample points representing features that can be identified clearly within the Landsat scenes (e.g. small oases, salt pans etc.) suggested a high accuracy. Atmospheric corrections were impossible as the necessary climatic data was not available (SONG et al. 2001). The sun elevation angle was corrected manually within ErMapper.

In an initial step, all sample points were positioned on the Landsat data set. During the development of the signatures only samples located in homogenous region of at least 900 m^2 were chosen to account for inaccuracies in the sensor's spatial resolution and GPS-positioning. As a consequence of the chosen phyto-sociological approach, field data always had a spatial extension of less than one pixel. The necessary enlargement of the single training regions was based on knowledge of the given sites' homogeneity (photos and notes taken en route). Records were compared to an overlay of a red-green-blue composite image (LIU 1990) of the raster data. Enlargement of the test regions was performed by assigning a 3 by 3 neighbourhood to each central pixel. Afterwards, the training regions were subsequently re-

Table 2: List of plant communities for the Gobi Gurvan Sayhan region. Detailed descriptions of communities are available in WESCHE et al. *(2005), names follow* HILBIG *(2000). Numbers refer to mapped units (see Map 1, suppl.)*

Liste der Pflanzengesellschaften der Region des Gobi Gurvan Sayhans. Detaillierte Beschreibungen der Gesellschaften sind verfügbar in WESCHE et al. (2005); die Benennung folgt HILBIG (2000). Die Nummerierung entspricht den Einheiten von Karte 1 (Suppl.)

Unit	Community / Mapping Unit	Comments	Problems
Group 1) Extrazonal communities of mountain regions			
1.1	Scree formation	Steep rock slopes with hardly any vegetation	Open rocks
1.2	*Juniperus sabina* community	Patches of prostrate juniper on scree slopes	Stands relatively small but clear signal on satellite channel 1
	Betula microphylla community	Birch forests in the Zuun Sayhan	Rare very small stands, not mapped separately
	Populus laurifolia community	Poplar forest in the Zuun Sayhan	Rare very small stands, not mapped
	Kobresietum myosuroidis	Alpine *Kobresia* mats in the eastern Gurvan Sayhan	Rare very small stands, not mapped
	Androsace ovcinnikovii-Helictotrichetum schelliani	Meadow steppes in the Zuun Sayhan	Rare very small stands, not mapped
Group 2) Dry mountain steppes and their replacement communities			
2.1	Hedysaro pumili-Stipetum krylovii - *Stellaria petraea* subassociation	Mountain steppes on rocky slopes	
2.2	Hedysaro pumili-Stipetum krylovii - *Astragalus inopinatus* subassociation	Mountain steppes on the gently sloping upper pediments	Often mixed pixels within mountain ranges
2.3	*Carex stenophylla* (=*C. duriuscula*) subassociation Chenopodio prostrati-Lepidietum densiflori *Achnatherum inebrians* community *Artemisia santolinifolia* community	Heavily grazed or trampled mountains and ruderalised replacement communities	Inhomogeneous group, yet reliably classified
2.4	*Artemisia rutifolia* community	Shrub communities of the upper pediments with *Caragana leucophloea, Stipa gobica* & *Stipa krylovii*	Intermediate plant community, transient and often mixed with unit 3.1
Group 3) Relatively moist desert steppes of the upper pediments			
3.1	Artemisio xerophyticae-Caraganetum leucophloeae / Amygdalo pedunculatae-Caraganetum leucophloeae	Scrub on rocky outcrops, gully shoulders and other coarse soil substrates, no Stipa krylovii	Over-represented, difficult to differentiate from 2.4
3.2	*Stipa gobica* community – typical subcommunity	Widespread grasslands on the upper pediments in the eastern part of the Gobi Gurvan Sayhan	
3.3	*Stipa gobica* community - *Ephedra sinica* subcommunity	Widespread grasslands on the upper pediments in the drier western and central parts of the national park	
Group 4) Dry desert steppes and other semi-desert communities			
4.1	Allio polyrrhizi-Stipetum glareosae	Dry grasslands on pediments of intermediate elevation	Widespread and well defined
4.2	Stipo glareosae-Anabasietum brevifoliae	Open grasslands transient to dry scrub with Chenopodiaceae	Interfering with 4.3 and 4.4, nevertheless reliably classified
4.3	Salsolo passerinae-Reaumurietum soongoricae / Potaninio mongolicae-Sympegmetum regelii	Stands of shrubby Chenopodiaceae on dry pediments and around saline sites	Widespread yet interfering with other desert communities
4.4	*Artemisia sphaerocephala* community	Scrub along river beds (sayrs) and erosion gullies, replaces 3.1 on somewhat drier sites	Widespread but usual linear stands, thus stands often in mixed pixels
4.5	Eurotio ceratoidis-Zygophylletum xanthoxyli	Scrub along rocky outcrops and sayrs, replaces 4.4. in dry semi-desert surroundings	Homogenous sample sides
4.6	Calligono mongolici-Haloxyletum ammodendronis	Saxaul forest and open Saxaul scrub	Two subcommunities combined to gain a higher accuracy
4.7	Caragano bungei-Brachanthemetum gobici / *Psammochloa villosa* community	Largely settled sands with sparse vegetation, the few bare dunes are also included	Defined by the presence of sand
Group 5) Communities of wet habitats			
5.1	Glycyrrhizo-Achnatheretum splendentis Nitraria sibiricae-Kalidietum gracilis	*Nitraria* scrub forming small hummocks surrounding water surplus sites (often saline)	
5.2	Salsolo passerinae-Kalidietum foliati / *Salicornia europea*-community / Crypsietum aculeatae / Suaedo corniculatae-Achnatheretum splendentis	Salt-tolerant plant communities of saline depressions and clay pans (Takyrs)	
	Blysmetum rufi *Iris lactea*-community Phragmitetum communis	Saline meadows offering dense pastures	Small stands in the eastern part of the park, excluded
Group 6) Extrazonal woodlands			
	Populus diversifolia woodlands	Fragments of gallery forest along Sayrs	Rare, excluded
	Ulmus pumila stands	Fragments, often single Elm trees on the upper pediments	Only few trees, excluded

duced in size to include only areas with comparable spectral signatures. This was based upon the unsupervised classification and visual image analysis.

3.2 Classification scheme

In the easternmost scene we had the highest density of training regions, so this scene was used to test the methods for the supervised classification. A maximum likelihood algorithm was chosen since it is a well known and efficient standard algorithm for supervised classifications (CAMPBELL 1996; CINGOLANI et al. 2004).

The results of a supervised classification are influenced by the employed satellite data, the specific algorithm and the training regions involved. The classification of the latter poses specific problems in itself, since an essentially continuously changing vegetation is classified into distinct, somewhat artificial, plant communities (Abeyta a. Franklin 1998). Fuzzy classifications offer an alternative, but in our case the park administration required a map with clearly discrete units. In any case, accuracy checks based on the data classified with the same (phyto-sociological) method as the training region should still be reliable (Congalton 1991).

To avoid statistical artefacts during the maximum likelihood classification, Bayesian prior probabilities were used to arrive at more realistic weightings of the training regions. Weightings within the supervised classifications were adjusted, based on the corresponding field observations (see Tab. 4), i.e. on the altitudinal distribution of the vegetation communities and their exposure and inclination. However, the overall accuracy (see below) would still be above 75% if the Bayesian prior probabilities were not used. The final classification results presented were generalized applying a mean filter, since the raw data was too detailed for the desired scale (1:100 000) of the park administration's GIS.

Validation of the results was performed in two ways. First, among scenes the overlapping regions were cross-checked to assess the comparability of the different supervised classifications. Secondly, the classification results were validated against an independent field data set collected during a similar phyto-sociological survey in 1996 (Miehe 1996). The available 270 samples were classified into plant communities along the same line as the data collected in 2001 and were used independently to assess the accuracy of the map. Due to the lower GPS accuracy available in 1996, several plots were excluded from the validation data set, since they were situated within heterogenous vegetation units. Reliability of the map was additionally checked when revisiting the study area several times after the vegetation map was compiled (trips in 2002, 2004, 2005).

The results were combined together into one raster data set that also covered the surrounding buffer zone of the park. The final classification was combined with vector layers containing cities and villages as well as roads and national park borders. Clouds in the two middle scenes were masked manually within Arc Map 8.2.

4 *Results – description of vegetation units*

Here, we offer only a brief overview of the spatial distribution of plant communities. Naming of communities follows terms suggested in the country-wide assessment by Hilbig (1990, 1995) wherever possible.

The upper mountain slopes above some 2,300 m host vegetation types that benefit from the extrazonally moist conditions. Among the predominantly woody vegetation types, only *Juniperus sabina* shrubs is spatially

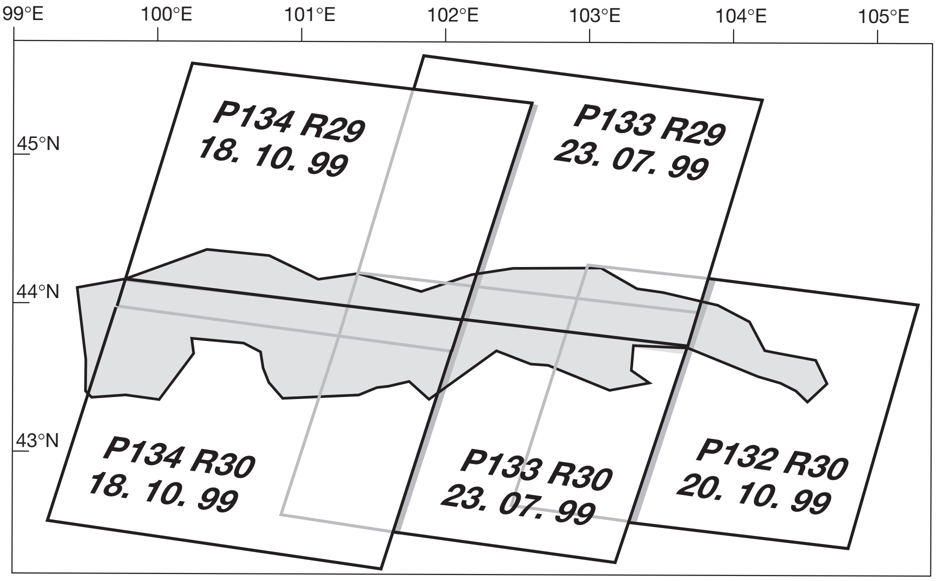

Fig. 3: Location of the five Landsat ETM+ scenes in relation to the National Park area. The date indicates the day the Landsat-scene was taken

Lage der fünf verwendeten Landsat ETM+-Szenen im Verhältnis zur Fläche des Nationalpark. Das Datum zeigt den Aufnahmenzeitpunkt der jeweiligen Satellitenszene

Table 3: Accuracy of the classification. The community numbers correspond to table 2. Line two gives the number of plots used for the accuracy check; line three shows the accuracy in percent

Die Genauigkeit der Klassifikation. Die Gesellschaftsnummern entsprechen der Nummerierung aus Tabelle 2. Zeile 2 gibt die Anzahl von Aufnahmen an, die zur Validierung der Klassifikationsgenauigkeit verwendet wurden. In Zeile 3 ist die Klassifikationsgenauigkeit für die jeweilige Kartiereinheit in Prozent angegeben

Mapping unit	1.1	1.2	2.1	2.2	2.3	2.4	3.1	3.2	3.3	4.1	4.2	4.3	4.4	4.5	4.6	4.7	5.1	5.2	Sum of plots used from Miehe 1996
No. of samples for validation	2	7	17	22	19	11	27	3	5	19	37	3	2	1	15	4	0	0	179
Accuracy (%)	100	86	88	86	78	81	93	100	100	95	95	100	100	100	93	100			Overall: 93.4%

Table 4: Values of the Bayesian prior probabilities employed in the supervised classification within the individual scenes. The numbers in line one correspond with the communities from table 2

Werte der für die überwachten Klassifikationen verwendeten (Bayesian prior probability-)Gewichtungen für die jeweiligen Einzelszenen. Die Nummerierung in Zeile 1 entspricht den Pflanzengesellschaften aus Tabelle 2

	1.1	1.2	2.1	2.2	2.3	2.4	3.1	3.2	3.3	4.1	4.2	4.3	4.4	4.5	4.6	4.7	5.1	5.2	Bayesian prior probability
P132R30	0.004	0.001	0.002	0.045	0.025	0.054	0.143	0.044	0.102	0.122	0.23	0.065	0.003	0.004		0.096	0.002		0.943
P133R29	0.003	0.001	0.002	0.035	0.013	0.059	0.143	0.038	0.088	0.103	0.193	0.044	0.003	0.007	0.057	0.096	0.003	0.003	0.889
P133R30		0.002	0.002	0.047	0.021	0.079	0.155	0.035	0.097	0.111	0.184	0.044	0.005	0.064	0.049	0.097	0.001	0.003	0.993
P134R29			0.006	0.045		0.076	0.178	0.021	0.092		0.205	0.035	0.003	0.005	0.046	0.087	0.002	0.002	0.803
P134R30	0.005		0.013				0.182	0.035	0.105		0.231	0.037	0.005	0.005	0.049	0.089	0.002	0.003	0.761

extensive enough to be mapped. Juniper covers large areas on south-facing scree slopes in the eastern Gobi Gurvan Sayhan.

Stipa krylovii characterises the Hedysaro pumili-Stipetum krylovii; i.e. the typical association of mountain steppes in the region (Tab. 2). The *Stellaria petraea* subassociation of the Hedysaro-Stipetum covers steep mountain slopes and is characterised by a high amount of moving rock debris and/or bare rocks (20–60%). Stands are also occasionally found on moist pediment sites. The *Astragalus inopinatus* subassociation of the Hedysaro-Stipetum is typical for weakly inclined slopes in moister mountain ranges. If disturbed by heavy grazing, trampling, small mammal burrowing activity or with occurrence along gullies, mountain steppes are replaced by a heterogeneous group of communities dominated by *Achnatherum inebrians, A. splendens*, various *Chenopodiaceae, Artemisia santolinifolia* and others. *Artemisia rutifolia* scree vegetation is characterised by debris movement (30–90%), and a high cover of shrubs *(Ephedra sinica, Eurotia ceratoides, C. leucophloea)*, as well as some typical mountain species such as *Stipa krylovii* and *Artemisia frigida*.

The upper pediment sites are mainly covered by moderately dense semi-desert steppes which benefit from still relatively high precipitation at this altitude (2,000–2,300 m). True mountain species are absent, as are desert species. Stands are intermediate in the altitudinal gradient. *Stipa gobica – Allium polyrrhizum* steppes are the most common community. They are typically dominated by grasses and cover large parts of the upper pediments. A distinct subcommunity with *Ephedra sinica* replaces the previous *Stipa gobica* steppes on drier locations and in intra-montane valleys. Two associations with *Caragana leucophloea,* which are characterized by more than 10% of shrub-cover, are constituted by not just the name-giving species but also by *Eurotia ceratoides, Caryopteris mongholica* and *Artemisia caespitosa*. More than 60% of plot surface is nonetheless covered by rocks and stones. Along river beds, these communities extend to lower elevations, where semi-deserts prevail.

The remaining group of semi-desert communities includes seven communities ranging from bunch grass steppes to scrub vegetation. Desert steppes of the Allio polyrrhizi-Stipetum glareosae replace the *Stipa gobica* steppes at drier locations / lower elevations. The next association of desert steppes along the hygric gradient is the *Stipo glareosae – Anabasietum brevifoliae*, where grasses begin to be replaced by woody perennials. This association increases along the lower pediments of the park, but avoids extremely dry locations. The dwarf shrubs *Reaumuria soongorica* and *Salsola passerina* occur locally in the Stipo-Anabasietum, but form a separate community at dry or saline situations. Open shrublands of the Salsolo passerinae-Reaumurietum soongoricae form the most common vegetation unit in lower desert areas within the national park. Dry river beds in the western parts or at lower altitudes are covered by a scrub community dominated by *Artemisia sphaereocephala*. Scrub of the Eurotio ceratoidis-Zygophylletum xanthoxyli occurs in depressions and also in Sayrs. The lowermost stands of woody perennials are composed of *Haloxylon ammodendron* (Saxaul), which can grow up to five metres in height where plants are not harvested for fuel wood and have ample access to ground water. Most saxaul shrubs are usually much smaller, but all stands belong to the Calligono mongolici-Haloxyletum ammodendronis. This association grows on sands as well as in clayey pans, so companions include plants typical for fine, but also for coarse substrates: *Anabasis brevifolia, Micropeplis arachnoida, Lycium ruthenicum, Convolvulus gortschakovii* are the most common ones. Finally, flat sand dunes host stands with the grass *Psammochloa villosa*, and the shrubs *Caragana bungei* and *C. korshinskii*. Higher dunes are virtually free from vegetation.

Azonal communities of saline meadows and wet salt pans are rare, since they are restricted to extreme water-surplus sites. Their phyto-sociological position is not always clear, but *Nitraria sibirica* scrub is found in plains with moderately high groundwater tables. The dominant species forms small dunes; thus this is easily recognized and normally found bordering saline pans. The highly saline, temporarily flooded clay itself is covered by Takyr communities, where *Kalidium foliatum* and *Salicornia europaea* are characteristic species. Due to their limited spatial extent, saline meadows were not separately mapped.

An additional group was introduced into the data set to capture the highest peaks that have very open vegetation. This class was labelled as "open scree" including rocky areas as well as the summit areas. This class represents habitats of a wide range of mountain species, generally dominated by some Poaceae, a few Cyperaceae and several herbs. However, all of them are rare and have low plant cover. For technical reasons, two steep valleys representing the only shaded sites in the satellite data were also assigned to this group, all the more credible for the low vegetation cover along those valleys' shoulders.

5 *Results – the classification process*

The following briefly presents the results of the satellite data classifications. The overall accuracy was above 93%, according to the validation against an independent data set (see Tab. 3 for details).

The accuracy was somewhat lower for the mountain steppes compared to the desert steppes and other semi-desert communities. This is probably explained by the more heterogeneous terrain and the occurrence of small-scale mosaics of vegetation types. The drier semi-desert communities are more homogenous and spatially extensive. However, accuracy was above 75% for all units, which seemed acceptable for management purposes (see Tab. 3).

The final vegetation map covers the entire national park and is available in digital format. The diversity of vegetation patterns is much higher in the eastern compared to the western half of the study area. Thus, only the eastern part of the map was printed here to represent the main patterns (Map 1, Suppl.). The western part, which is mainly dominated by semi-desert vegetation also occurring in the eastern half, is available on request.

6 *Discussion and ecological inferences*

The final map supported earlier ecological inferences. In this dry region, vegetation patterns are largely controlled by moisture availability (WESCHE et al. 2005), and vegetation patterns in the printed map (Map 1) confirm that clear climatic gradients are found in the park. This is exemplified in the mountains, where moist mountain steppes are more common in the eastern ranges, but rare or missing in the central and western parts. This corresponds to the idea that a large proportion of the precipitation is brought in from easterly directions (WESCHE et al. 2005), though precipitation could plausibly originate from northern directions as well (BARTHEL et al. 1983). Superimposed on this large-scale gradient are the vertical gradients, with mountains generally receiving more precipitation than the lowlands. Towards the central parts of the park, vegetation belts shift upwards with increasing dryness: Juniper is very common above 2,350 m a.s.l. in the eastern Dund and Zuun Sayhan, but is restricted to the summit regions of the dry mountain ranges in the western part of map 1, and becomes increasingly rare in the western part of the park (map not shown), where stands are confined to elevations above 2,600 m a.s.l. In a parallel manner, the area covered by the *Stellaria petraea* subassociation of mountain steppes (Hedysaro pumili-

Stipetum krylovii) decreases from the eastern to the western mountain ranges on the map.

Comparable effects can be described for other plant communities, but differences in the local topography, e.g. the position of the upper boundary of the pediments, modify the general trend. The pediments in the eastern part are dominated by dry bunch grass steppes with *Stipa glareosa* and *Allium polyrrhizum*, while this vegetation unit is less widespread in the western part of map 1 where it is substituted by more drought-resistant semi-desert communities with fewer grasses and more dwarf shrubs (*Anabasis brevifolia*, *Reaumuria soongorica*). Nevertheless, the lowest, often clayey or sandy depressions are covered by the same vegetation all over the park; presumably because of their similar soil conditions. Precipitation is very low, and therefore the lowest parts are normally covered by the drought-resistant Saxaul (*Haloxylon ammodendron*) or, where groundwater temporarily accumulates, Takyr communities with succulent or annual Chenopodiaceae.

As a consequence of these patterns, the complexity of vertical vegetation zonation changes from east to west. In the easternmost mountain range, 17 mapping units are found along the full vertical gradient from the lowlands to the peaks, while this figure decreases to a mere nine units in the drier westernmost mountain range shown in the map.

Another interesting point is the importance of soil substrates. Scrub vegetation with *Caragana leucophloea* is restricted to gravely sites in erosion gullies (Sayrs) or to rocky outcrops, where they benefit from the absence of the highly competitive bunch grasses and perennial herbs. These form dense root systems in fine topsoil and consume all surface water, while on coarse substrates water quickly percolates to lower soil horizons where it becomes available to the deep root systems of shrubs (Lavrenko a. Karamysheva 1993). A similar phenomenon is probably responsible for the distinct shrub vegetation found in beds of temporary rivers where disturbances removing the hemicryptophytes, rather than water-surplus, appear to be the dominating factors.

7 *Methodological issues*

It is questionable as to whether or not the actual vegetation (Girard a. Isavwa 1990; Smith et al. 1997) was mapped, or whether its distribution is merely linked to soil (Gilabert et al. 2002; Rondeaux et al. 1996) and/or geomorphological patterns, which were then classified. Constraints in budget and time did not allow for measurements which would break down the spectral signatures obtained from the satellite into the various sources of vegetation, soil substrate, moisture etc. However, joint analyses of vegetation composition and local-scale measurements of site conditions suggest a close coupling; multivariate analyses on the scale of a few km^2 (Wesche a. Ronnnenberg 2004), but also tentative ordinations using hundreds of vegetation samples point in the same direction (von Wehrden unpubl.). Thus, we have reasons to trust our results, and this is supported by the generally high accuracy inferred from the validation (see Tab. 3).

An atmospheric correction of the pictures would improve the results (Zhang et al. 2002; Song et al. 2001), but due to the lack of adequate climatic data from the time of the scene acquisition, this was not possible. Based on a digital elevation model (Bolstad a. Stowe 1994), test data could have been stratified using altitudinal intervals within which each vegetation community occurs (see Hinton 1999; Keuchel et al. 2003). Unfortunately, elevation data such as SRTM sets only became available when the largest part of the present work had already been completed.

In terms of park management, one of the most promising approaches is the incorporation of multitemporal information. This could involve the use of Landsat scenes from various years, possibly also in combination with other sensor platforms. These typically have a relatively coarse spatial scale (NOAA-AVHRR, MODIS), but the available vegetation map could be used to stratify the obtained data in order to get insights into the seasonal behaviour of the occurring vegetation types (e.g. Zhang et al. 2003; Langley et al. 2001; Doraiswamy et al. 2004). This would undoubtedly yield additional benefits for basic and applied questions of nature conservation and management (Leprieur et al. 2000; Reese et al. 2002).

8 *Implications for resource management and nature conservation*

Gunin et al. (1999) noted that the management of Mongolian steppes requires detailed, yet reasonably accurate maps of ecological conditions in Mongolia, and goes on to recommend remote sensing approaches for this purpose. However, few data are available so far (Atlas of Mongolia 1990; Gunin a. Vostokova 1995; NATIONAL REMOTE SENSING CENTER, MONGOLIA a. UNEP/ ENVIRONMENT ASSESSMENT PROGRAMME FOR ASIA AND THE PACIFIC BANGKOK 1998; Burkart et al. 2000) and our project is one of the first steps towards achieving this goal on a regional scale.

Time will demonstrate whether appropriate maps will in fact help to balance contrasting interests of nature-conservation and livestock owners (Gunin et al. 1999; NATIONAL STATISTICAL OFFICE OF MONGOLIA 2001). Practically the entire park is under use to some extent, although several habitats would be worth protecting from human impact. These zones could be accurately designated based on the present map, if evaluated with the original data from the vegetation checks and information gained from other surveys (e.g. Reading et al. 1999). GIS systems are important in this respect (Bridgewater 1993; Walsh et al. 1994; Goodchild 1994), and have already been used to propose further special protected zones (Chimedregzen 2000). These included not only the mountain sites with their rich and unique species-composition, but also wide semi-desert areas containing habitats for many globally endangered species such as Khulans (*Equus hemionus hemionus*), Gazelles (*Procapra gutturosa* and *Gazella subgutturosa*; Reading et al. 1999) and Wild Sheep (*Ovis ammon*; Schaller 2000). Thus, biodiversity mapping as a base for protection could be an important aim of further GIS-based studies (Muldavin et al. 2001).

The boundary of the national park is currently determined by political factors such as the locations of cities and villages, mining concessions, or interests of local herders surrounding the national park. By using the vegetation map, these boundaries could be modified to follow ecological considerations.

Comparable works in other southern Mongolian nature reserves are currently underway (von Wehrden 2005; von Wehrden 2004; von Wehrden a. Wesche 2002), and are already used for habitat mapping of globally endangered equids. A tentative vegetation map for the Great Gobi B Special Protected area has already proved valuable for selecting new sites for re-introduction of the rare Przewalski horse (von Wehrden a. Wesche 2005; Kaczensky et al. in prep.), and a project on habitat modelling for the also equally endangered Asiatic Wild Ass is currently underway.

Acknowledgements

We are grateful for the support of several persons and institutions in Mongolia and in Germany. The administration of the Gobi Gurvan Sayhan National Park and the associated GTZ-run Buffer Zone Development Project initiated the vegetation survey and gave organisational as well as financial assistance. The late S. Tluczykont, S. Schmidt, Mr. Ravjir, Mrs. Myadag and Mrs. Chimgee assisted us in Ulaan Baatar and Dalanzadgad. We additionally received financial support from the DFG, DAAD, FWF and the BMZ. Fieldwork would not have been possible without our drivers, and the continuous help offered by V. Retzer, K. Nadrowski and the late R. Undrakh from the Gobi Gurvan Sayhan Research Project. Satellite images were provided by M. Thornton and D. Bedunah. Identifications of several difficult plant species were cross-checked by E. Jäger; C. Sanchir and N. Friesen. All stages of the project benefited tremendously from the continuous and tireless support of our counterparts R. Samjaa and Z. Tschamsran at the National University of Mongolia, Ulaan Bataar. The paper benefited from suggestions by two anonymous referees, D. McCluskey kindly checked our English. This is contribution No. 268 in the series "Results of the German-Mongolian Biological expeditions since 1962".

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