Plant Soil (2011) 340:239–251
DOI 10.1007/s11104-010-0409-z

REGULAR ARTICLE

Effects of fertilization and irrigation on productivity, plant nutrient contents and soil nutrients in southern Mongolia

Katrin Ronnenberg · Karsten Wesche

Received: 2 November 2009 / Accepted: 21 April 2010 /

Abstract The study attempts to evaluate the effect of fertilization and irrigation on steppe productivity in dry southern Mongolian desert-steppes. We conducted an irrigation- and NPK fertilization experiment, irrigating at levels of +100 mm and fertilizers at amounts equivalent to 20 gN (m² year)$^{-1}$ in a factorial design. We tested the effects on soil nutrients and biomass production. Nutrients in plant tissue were analysed for *Stipa krylovii* and *S. gobica*, and for mixed subsamples of total above- and belowground biomass. Available P and K and total K increased in the soil after fertilization while irrigation reduced total N. Biomass yield almost tripled and inflorescence numbers increased by factors of 4–8 due to fertilization while irrigation alone had very restricted effects and only increased biomass of *Agropyron cristatum*. Nutrient content of biomass was elevated on fertilized plots. Results indicate that steppe productivity is severely restricted by nutrient availability even under ambient precipitation levels, raising the question whether nutrient withdrawal caused by current land use practices has detrimental effects on pasture productivity. The anticipated beneficial effect of increasing water availability however could not be confirmed. Whether there is an improvement in productivity due to increasing rainfall, as predicted by some climate change models, will depend on the distribution and intensity of rain events.

Keywords Biomass · Dryland · Nutrient limitation · Primary productivity · Steppe · Water availability

Introduction

Plant productivity and performance in drylands are water-limited (Noy-Meir 1973), and rain is the most obvious factor controlling biomass productivity in temperate grasslands, which account for ca. 8% of the terrestrial surface (Hoekstra et al. 2005). Central Asia alone hosts >4 Mio km² of dry rangelands, most of which are situated in China and Mongolia. Spatial and temporal variability in precipitation is considered as one of the most important factors determining dynamics of vegetation, productivity and thus land use of these dry steppes (Munkhtsetseg et al. 2007).

Responsible Editor: Klaus Butterbach-Bahl.

Electronic supplementary material The online version of this article (doi:10.1007/s11104-010-0409-z) contains supplementary material, which is available to authorized users.

K. Ronnenberg (✉)
Institute of Biology—Department of Geobotany
and Botanical Garden, Martin-Luther-University,
Am Kirchtor 1, Halle-Wittenberg,
06108 Halle, Germany
e-mail: katrin.ronnenberg@botanik.uni-halle.de

K. Wesche
Department of Botany,
Senckenberg Museum for Natural History Görlitz,
PO Box 300 154, 02806 Görlitz, Germany

The traditional nomadic grazing systems are still relatively intact in Mongolia, which consequently allows for flexible responses to variable conditions. Wild herbivores, as well as nomadic herders, rely each year on sufficient rainfall to provide enough fodder, and in years of drought, they are forced to leave the affected regions and migrate to better grazing grounds.

Recent climate change models predict an increase in annual precipitation for Central Asia (Christensen et al. 2007); however, models, are not very reliable as a consequence of the scarcity of reference measurements for the region (Christensen et al. 2007). For Mongolia, models and a recent analysis of trends in available climate records imply that total precipitation maybe slightly increasing, especially in the Gobi region, as is the frequency of extreme precipitation events (Dagvadorj et al. 2009). Reports vary for the region: for northwestern China, Gao et al. (2002) predict an increase in the number of individual rain events, while Dore (2005) and Groisman et al. (2005) expect the frequency of extreme rain events to increase in Siberia and China.

For the Doulon County in Inner Mongolia, China, which receives about twice the precipitation of our study area, irrigation experiments show a net gain in gross ecosystem productivity (Niu et al. 2008; Chen et al. 2009b; Liu et al. 2009; Niu et al. 2009), implying that precipitation changes should also affect the drier regions of the Gobi. While water availability is certainly important for steppe function (Le Houerou et al. 1988; Lauenroth and Sala 1992), recent studies point to a potential co-limitation by nutrients. N limitation occurs across a wide range of biomes and climatic conditions (Hooper and Johnson 1999; LeBauer and Treseder 2008), and the available studies from Central Asia also suggest that nutrient limitation may occur (e.g. Slemnev et al. 2004; Xiao et al. 2007). Livestock keeping has resulted in nutrient losses in many steppe soils suggesting that nutrient constraints are aggravated (Stumpp et al. 2005). Nutrients are withdrawn from the area as a result of organic manure being used as fuel in cooking and heating, and through the export of livestock products to the growing urban populations. Atmospheric nitrogen depositions are predicted to increase (Galloway et al. 2004); however, rates are assumed to be low and the extent to which they may offset nutrient losses has not been studied as yet.

Even on a global scale, experimental evidence on nutrient limitation is scarcely available for dry rangelands below 200 mm (see Breman and de Wit 1983 though). Most published fertilization studies apply only N (Hooper and Johnson 1999); nonetheless, studies which have incorporated a wider range of nutrients have, by and large, found a co-limitation by phosphorous (Elser et al. 2007).

This study focuses less the particular potentially limiting nutrient and more the general importance of nutrients versus water limitation. We applied a relatively high dosage of a NPK- fertilizer including micronutrients and combined this with an irrigation regime consisting of relatively low single doses (5 mm) in a factorial design. We opted for an unspecific fertilization treatment to test the effect on steppe productivity in general, without the intention to favour specific species groups.

Nutrients can accumulate in the soil, be absorbed by the plants to increase biomass and nutrient concentration, or be lost to leaching or erosion. Our experiment assessed the effects of fertilization and irrigation on the soil, assuming that a proportion of the added nutrients accumulates, and disregarded any erosion or leaching effects. In addition, we measured above and belowground biomass, as plant tissues represent the second main nutrient pool. In less severe conditions, plants are more likely to invest in aboveground vegetation and reproductive output, as opposed to mere persistence in leaner times (Peck et al. 1998). However, in the Gobi, sexual reproduction is generally very restricted and depends on erratic rainstorms (Song et al. 2002; Ronnenberg et al. 2008). Effects of fertilization on resource allocation to belowground biomass or to reproductive organs have, hitherto hardly been studied in southern Mongolian drylands.

Equally unknown are responses of plant nutrient contents, which are important for land use as well. Plant tissue contents may differ in regard to nutrient availability be it due to low nutrient contents of the soil, or because of restricted uptake under conditions of water limitation. Nutritional values may also differ among plant species and grasses are considered to be preferential fodder for livestock and small mammals in Mongolia (Jigjidsuren and Johnson 2003; Bläß et al. 2009). So far, no experimental data for specific taxonomic/ functional groups have been published.

In an earlier simple study without irrigation, we focussed on the abundant species *Agropyron cristatum* and *Allium polyrrhizum*, and found that fertilization increases the annual biomass yield under ambient precipitation levels, especially for the preferred fodder grass *A. cristatum* (Wesche and Ronnenberg 2010). For the present study, we focussed on the net primary production of *Stipa krylovii* and *S. gobica*, which count among the dominant species of southern Mongolia (Wesche et al. 2005). Moreover, *Stipa* is the most important species group in Asian temperate grasslands. The two congeneric species *S. gobica* and *S. krylovii* differ in their habitat preferences in Mongolia: whereas *S. gobica* is a typical species of the semi deserts, *Stipa krylovii* has a much wider distribution range and also occurs in the more mesic meadow steppes of northern and central Mongolia (Hilbig 1995). Thus, we predicted that *S. krylovii* would benefit more from irrigation than the more drought tolerant *S. gobica*. We investigated the effect of irrigation versus fertilization over two consecutive years to decrease the risk of generalising from a single potentially untypical extreme year.

In particular, we were thus interested in the following questions:

- What is the effect of fertilization and irrigation, or the combination of both, on soil nutrient contents?
- Is biomass productivity and flowering activity of the dominant species groups affected by fertilization and irrigation; do responses differ among dominant taxa, and is the effect dependant on the ambient climate?
- Does the concentration of nutrients in tissues of the two important *Stipa* species depend on fertilization and irrigation, and are there differences in nutrient allocation between above- and belowground biomass?

Methods

Study site

The study region is situated in the Dund Saykhan mountain range situated in the Gobi Gurvan Saykhan National Park, southern Mongolia, at an altitude of 2,300 m asl. (N 43°36.76′; E 103°46.36′). Personal temporary measurements and climate models suggest that the region receives an estimated 180 mm mean annual precipitation (Hijmans et al. 2005), with 160 mm falling in the summer months. The vegetation period usually begins in May or June with the onset of the summer rains and ceases at the end of September with upcoming frosts. Mean winter/summer temperatures are around −9.9°C and 10.9°C. Despite its protection status, the site is regularly grazed by large livestock herds dominated by goats and sheep, in addition to horses and camels. Small mammals such as the Mongolian pika (*Ochotona pallasi*) are very abundant, but wild large herbivores are of minor importance in terms of biomass consumption (Retzer et al. 2006).

The zonal vegetation is *Stipa gobica* steppe, dominated by the two *Stipa* species *S. gobica* and *S. krylovii*, *Allium* species (mainly *A. polyrrhizum* and *A. prostratum*), *Agropyron cristatum*, and *Artemisia frigida* (Wesche et al. 2005). Soils are degraded chestnut soils with a water retaining capacity of 12–25% by weight (Ronnenberg, unpublished data), they are rich in cations and have a pH-value of about 8 (Wesche et al. 2005).

Study species

Stipa krylovii (Poaceae, section—*Leiostipa*) is distributed throughout Mongolia, China, Kazakhstan and Russia (Gubanov 1996; Wu and Raven 2006). It occurs in the grass steppes of central Mongolia and in the dry mountain steppes of southern Mongolia inhabiting a wide macroclimatic gradient. The distribution range of *S. gobica* Roshev. (section—*Stipa*) is restricted to the dry mountain steppes and semi-deserts of southern Mongolia and northern China (Wu and Raven 2006). Both overlap in their habitats in montane desert steppes such as those of the study area.

Experimental setup

We conducted a fully factorized fertilization and irrigation experiment in a randomized block-design. We used the following treatments: FI—fertilized and irrigated, F—only fertilized, I—only irrigated and C—control. There were ten blocks comprising all treatments, i.e. 10×4 plots altogether. The blocks were randomly distributed over an area of approximately 2 km² within a reasonably homogenous steppe matrix, ensuring that both *S. gobica* and *S. krylovii* were present in each plot. The treatments were applied to plots of 1 m^2. Since blocks and plots were randomly distributed, the distance between blocks varied from 10 m to 500 m, while plots within blocks were 1.5–3 m apart. We applied water-soluble NPK-fertilizer

(FLORY 2, PLANTA Germany) with the following composition: 8.5% Nitrate-N; 6.5% Ammonia-N; 5% P_2O_5; 25% K_2O; 2% MgO; and some micro elements B, Cu, Fe, Mn, Mo, and Zn. The fertilizer was dissolved in 3 l of water and applied at levels of 10 g of N $m^{2\text{-}1}$ twice a year at the end of June and again in the end of July. Thus a total of 200 kg ha^{-1} N, 66 kg ha^{-1} P and 333 kg ha^{-1} K were applied in both 2005 and 2006. For the irrigation treatment a total of 100 mm water (taken from the nearest well) was added over natural precipitation in each of the two vegetation periods in 2005 and 2006. Ambient precipitation totalled 110 mm in 2005 between May and August when we harvested the plots, and 125 mm in 2006 for the same period. However, whereas in 2005 irrigation was more or less evenly distributed over the summer months, significant rains only started on the 17th of July in 2006, and 75% of the annual precipitation fell within the next month. Irrigation was applied with hand sprinklers in doses of 5 mm precipitation, equivalent wit the daily dosage being based on personal precipitation records from July and August 2004, when 75% of daily rainfall events were below 6 mm (median 2.3 mm). The irrigation treatment commenced at the end of June and extended into mid August. Irrigation water was applied every second day, unless natural precipitation had already saturated the soils impeding infiltration. We opted for a relatively high number of small irrigation events to ensure complete infiltration and to avoid run-off from the slightly inclined slopes (1–3% inclination).

To check whether our irrigation treatment had any effect on soil moisture, we checked soil moisture contents 24 h after irrigation with a theta probe (Delta-T) on August 13th 2006. Temperature and air humidity conditions that day were representative for the summer months as they were measured by a nearby weather station (Li-Cor). Despite the high insolation and a steady wind the soil water content on irrigated plots was still on average 12%, whereas the mean soil moisture on controls was 10% ($p<0.001$); the block also had a significant effect on soil water content ($p=0.011$).

Aboveground biomass was harvested twice a year in 2005 (in mid July and at the end of August), but only once in 2006, at the end of August, because drought prevented any growth until mid July. Aboveground biomass was harvested in a circular area of 0.25 m², differentiating between the following species-(groups): *Stipa krylovii*, *S. gobica*, *Agropyron cristatum* and *Artemisia frigida*, the two *Allium* species *A. polyrrhizum* and *A. prostratum* were pooled. All the remaining species were defined as "rest". Before harvesting, all inflorescences of the target species (groups) were counted disregarding the remaining species on the plots, as comparing inflorescence numbers among morphologically different species would not provide meaningful results. In addition, a sub sample of above- and belowground biomass was sampled at $10\times10\times10$ cm^3 in 2006. Although we initially tried to separate subterraneous biomass of the species, it proved impossible as most root stock was heavily entangled. All biomass samples were air-dried; roots and other subterraneous matter was washed thoroughly to remove soil and other inorganic particles. All air-dried samples were transported to Germany where they were oven dried at 105°C for 24 h and then weighed.

Soil samples mixed from three separate sub samples per plot of the uppermost 10 cm were also taken at the end of August 2006 and subsequently treated in the same fashion as the biomass samples.

Chemical analysis

Total carbon and nitrogen were analysed using a CN-Analyser (Vario EL, ELEMENTAR, Germany); total carbon figures were corrected for contents of carbonate-borne C, measured by way of a Scheibler instrument using HCl (10%). Exchangeable soil cations were extracted with Ca-Lactate at pH 3.6, and potassium was analysed with flame spectrometry (Flame AAS Vario EL, Analytik Jena, Germany). Available phosphate was extracted with the same solution, stained with Ammonium-Molybdate, and measured with a photometer (NANODROP, USA). Total soil contents of P and K were analysed in the above mentioned way after hot digestion with HNO_3. All data refer to dry (105°C) fine soil (<2 mm).

Plant tissues were only analysed for samples from 2006. Plant C and N were analysed with the same CN-Analyser and P and K were determined as described before, after hot digestion with HNO_3. All soil data were corrected for content of rest water.

Statistics

For soil analysis, a simple two-way ANOVA was employed with the factors "fertilization" and "irrigation"; the "block" factor was integrated as a random factor. The tests on above-ground biomass for all species were realized in a split-plot two-way ANOVA design with the species nested within the years. To assess differences between flowering activity in the different species, the treatment factors were nested in the species groups. Since we had missing values, statistical differences between contents of the three nutrients (NPK and the ratios of CN and NP) in plant tissues were analysed using a mixed effect model with the treatments nested in the two *Stipa* species, or in the above vs. belowground biomass and block. To guarantee homogeneity of variances, a rank-transformation was applied where necessary. Percentage values were arcsine transformed. Statistical tests were performed using the software SPSS 12.0G (SPSSInc. 2003, for windows) and the R software (R Core Development Team 2009, version 2.9.1, Vienna, Austria) employing the package "nlme" for mixed effect models.

Results

Soil nutrient contents

P and K availability was approximately twice as high on the fertilized plots ($p<0.001$) compared to the control, while irrigation or the interaction factor between fertilization and irrigation had no significant effect (Table 1). The effects on total nutrient contents in the soil were less obvious. Nitrogen was slightly lower on irrigated plots ($p=0.049$), but P showed no response due to the high variability within treatments. Total potassium was higher on fertilized plots ($p=0.004$), however, there was also some variability between sites (block factor $p=0.016$). The content of organic carbon depended on the site (block factor $p=0.033$), but none of the treatments had an effect on total C. Similarly, the CN-ratio was highly dependant on the sampling site ($p<0.001$), while fertilization narrowed the CN-ratio ($p=0.032$).

Biomass production and flowering activity

Fertilization increased aboveground biomass significantly ($p<0.001$) while irrigation had no significant effect (Fig. 1, Table A1 in Appendix). Biomass production was higher in 2005 than in 2006 ($p<0.001$). Whereas in 2005 biomass over all species totalled 810±46, 730±70, 490±28 and 480±22 kg ha^{-1} (mean ± standard error) for the treatments FI, F, I and C; in 2006 the corresponding figures were only 720±77, 680±54, 290±39 and 280±30 of total biomass. The year*fertilizer interaction was significant ($p=0.003$), indicating that the relative fertilization effect in 2006 was stronger than in 2005. Species (groups) differed in their biomass production ($p<0.001$) and in their response to fertilization ($p=0.001$; ANOVA-Table A1 see Appendix).

In terms of relative contribution to total biomass, *S. gobica* became less prolific in the fertilized plots in

Table 1 Effect of fertilization and irrigation on soil nutrient contents (columns indicate means ±1se) for the treatments FI—Fertilized and Irrigated, F—Fertilized, I—Irrigated, C—Control and significance values of a two-way ANOVA for the effects of F—fertilization, I—irrigation, F*I—interaction of fertilization and irrigation and B—Block (integrated as random factor). All variables were rank-transformed prior to analysis

treatment	mean ± 1se				statistical significance			
	FI	F	I	C	p (F)	p (I)	p (F*I)	p (B)
Exchangeable								
P (mg kg^{-1})	44.7±6.2	50.7±9.1	16.8±3.7	19.8±4.8	**<0.001**	0.669	0.827	**0.047**
K (g kg^{-1})	0.85±0.17	0.83±0.10	0.45±0.06	0.39±0.06	**<0.001**	0.307	0.924	0.302
Total								
N (%)	0.19±0.01	0.21±0.01	0.19±0.00	0.20±0.01	0.276	**0.049**	0.113	0.195
P (g kg^{-1})	1.15±0.29	2.20±0.50	1.75±0.42	1.75±0.29	0.925	0.177	0.307	0.242
K (g kg^{-1})	13.2±0.23	13.0±0.27	12.7±0.12	12.5±0.14	**0.004**	0.309	0.979	**0.016**
C (%)	1.6±0.05	1.8±0.12	1.7±0.05	1.7±0.07	0.507	0.472	0.491	**0.033**
CN ratio	8.7±0.13	8.3±0.28	8.8±0.12	8.9±0.19	**0.032**	0.72	0.445	**<0.001**

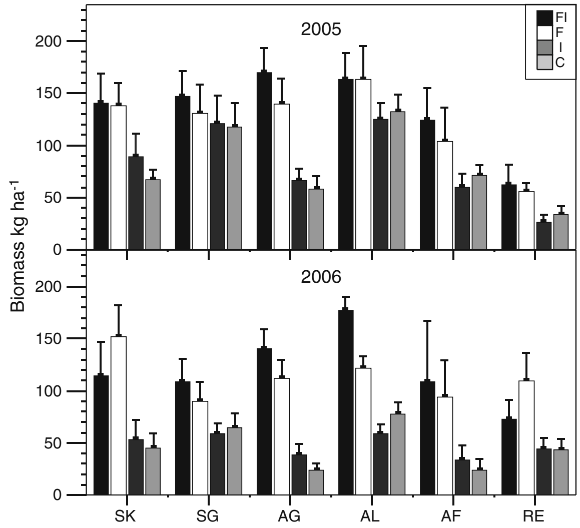

Fig. 1 Bar-graphs showing the standing crop of the main species (groups) and the treatments FI—Fertilized and Irrigated, F—Fertilized, I—Irrigated, C—Control for the years 2005 and 2006. SK—*Stipa krylovii,* SG—*Stipa gobica*, AG—*Agropyron cristatum*, AL—*Allium* spec., AF—*Artemisia frigida*, RE—rest of species

both years (interaction species*fertilization $p=0.005$) while neither irrigation, block, nor year had any effect. The percentage of biomass of *S. gobica* was 17.5±2.3%, 18.0±3.3%, 24.8±4.7%, 24.0±4.2% (mean ± 1 standard error) in 2005 and 14.7±2.2%, 14±2.7%, 27.3±6.3% and 22±4.2% in 2006 for the treatments FI, F, I and C respectively. *Stipa krylovii's* relative contribution was not affected by treatments, nor did it differ among years ($p>0.1$). With the treatments FI, F, I and C the percentages for *S. krylovii* were 18.1±3.1%, 20.4±3%, 17.7±4% and 14.4±2.4% in 2005 and 16.2 ±3.8%, 22.5±3.8%, 14.6±3.7% and 16.2±4.8% in 2006.

In 2006 there was a clear effect of fertilization on the number of inflorescences ($p<0.001$, Table A2, see Appendix), whereas irrigation and the interaction irrigation*fertilization showed no effect (Fig. 2). Species differed in the number of inflorescences ($p<0.001$) and there was a marginally different response to the addition of fertilizer (interaction term $p=0.095$). For example, *Allium* spec. and *Agropyron cristatum* increased the number of inflorescences by a factor of 4, whilst *Stipa krylovii* and *Artemisia frigida* raised their inflorescence numbers by 6 and 7 times respectively on fertilized plots. Only *S. gobica* showed no clear response.

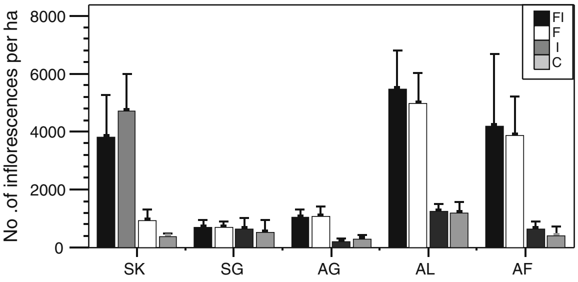

Fig. 2 Bar-graph showing the number of inflorescences in 2006 of the most important species groups within the study area for the treatments FI—Fertilized and Irrigated, F—Fertilized, I—Irrigated, C—Control. SK—*Stipa krylovii*, SG—*Stipa gobica*, AG *Agropyron cristatum*, AL—*Allium* spec., AF—*Artemisia frigida*

Plant nutrient contents

In tissues of both *Stipa* species, levels of the administered nutrients NPK were found to have increased ($p<0.001$) on fertilized plots. Irrigation alone did not facilitate the uptake of either potassium or nitrogen ($p>0.1$), whilst a slight positive effect of irrigation on phosphorus contents ($p=0.044$) was found.

The effect of fertilization was more pronounced in *S. krylovii* in terms of K levels (as indicated by the significant interaction term between the inner subject factor "species" and the fixed factor "fertilization"; $p=0.006$). *Stipa gobica* had slightly lower contents of P than *S. krylovii*, however, the response to fertilization was equivalent in both species. When analysing N, there was no significant statistical difference between species with regard to content or response to the fertilizer.

The CN and NP ratios in plant tissue were lower on fertilized plots for both *Stipa* species ($p<0.001$ and $p=0.005$ respectively, Table 2), however, again there was no difference between the species.

In the mixed samples, the aboveground biomass had much higher contents of all three analysed nutrients ($p<0.001$ Fig. 3). Potassium was significantly elevated on fertilized plots in both fractions, above- and belowground biomass ($p<0.001$, Fig. 3). The effect of fertilization on N contents differed between fractions, as aboveground biomass showed a positive response to fertilization, whereas the percentage of N in the belowground biomass showed no change (fraction* fertilization $p=0.001$). Overall, irrigation improved N uptake on fertilized plots,

Table 2 CN- and NP- ratios of plant tissue of *Stipa gobica* and *Stipa krylovii*, as well as the fraction of above- and belowground biomass of the mixed sub-samples (mean ± 1 standard error) for the treatments FI—Fertilized and Irrigated, F—Fertilized, I—Irrigated, C—Control. Also shown is the statistical significance of the main effects F—fertilization, I—irrigation, F*I—interaction of fertilization and irrigation nested within the factors (Block > species/fraction) in a split-plot linear mixed effect model after model simplification omitting 3-way interactions. All CN ratios and NP-ratios are rank transformed

	mean ± 1 se				statistical significance				
	FI	F	I	C	p (F)	p (I)	p (F*I)	species/fraction	species/fraction*F
CN-ratio									
S. krylovii	11.3±0.7	11.4±0.6	15.6±1.4	16.4±1.6	**<0.001**	0.696	0.823	0.893	0.971
S. gobica	11.2±0.5	11.9±0.3	16.2±1.0	16.6±1.3					
aboveground	10.0±0.4	10.8±0.5	11.9±0.4	11.6±0.5	0.0074	0.812	0.388	**<0.001**	0.376
belowground	20.6±0.6	20.0±0.7	21.6±0.7	21.4±0.4					
NP-ratio									
S. krylovii	17.4±1.2	20.0±1.0	23.2±1.7	23.5±1.6	**0.005**	0.153	0.823	0.217	0.982
S. gobica	20.0±1.0	21.4±1.7	24.2±2.0	31.4±4.4					
aboveground	23.0±1.4	21.7±1.6	25.9±3.0	20.3±1.2	0.962	0.306	0.929	0.101	**0.034**
belowground	22.8±1.7	20.4±2.6	26.6±1.3	29±3.5					

whereas on irrigated non- fertilized plots biomass did not benefit from irrigation (interaction fertilization* irrigation $p<0.001$). Fertilization showed a marginal effect on the CN-ratio ($p=0.074$) with values being much higher in subterraneous biomass compared to aboveground ($p<0.001$ Table 2). The treatments did not show any statistically significant effect on contents of P. There was also no change in the NP-ratios between the fractions, showing no main effects of either treatment; however, belowground biomass had lower NP-ratios on fertilized plots (interaction fraction* fertilization $p=0.034$, Tab.2).

Discussion

Soil nutrient contents

Fertilization of the soil had strong effects on soil K and P. Both total content and exchangeable potassium increased after fertilization. However, due to the overall high contents of cations, K is unlikely to limit plant growth, even on the controls (Fernandez-Gimenez and Allen-Diaz 2001; Xie and Wittig 2004). Treatments had no effect on the total phosphorus content, while exchangeable P was improved; which is especially important in slightly alkaline soils were P might quickly become immobilised (Lathja and Bloomer 1988; Cross and Schlesinger 2001). Total nitrogen contents did not show significant responses to fertilization and irrigation had a small but significantly negative effect. Reduced levels of N could be caused by leaching or water run-off as in a semi-arid environment the addition of a mere 100 mm of water can begin to cause leaching (Walvoord et al. 2003; Chen et al. 2009a). However, we expect water run-off to have limited effects as we applied relatively small amounts of water at a slow rate. Leaching also seems unlikely since other nutrients, such as potassium, did not show similar negative effects. The rate of NH_3 volatilization may have been increased due to higher water availability and activity of micro-organisms. Chen et al. (2009b) showed that the activity of micro-organisms is especially favoured at low rain pulses of 5 mm. The available data from drylands suggest that rates of NH_3 volatilization can be of a similar magnitude as was observed in our experiment (Schlesinger and Peterjohn 1991; Austin et al. 2004). The increased nitrogen uptake found in this study represents an important issue: although the *Stipa* species did not show any trends, overall tissue N pools, as represented by the mixed samples, were clearly higher on irrigated plots compared to the controls (see below).

The CN ratio in the soil was slightly lower on fertilized plots, which may seem surprising considering that fertilization had no significant effect on total N levels in the soil. However, the fertilized plots

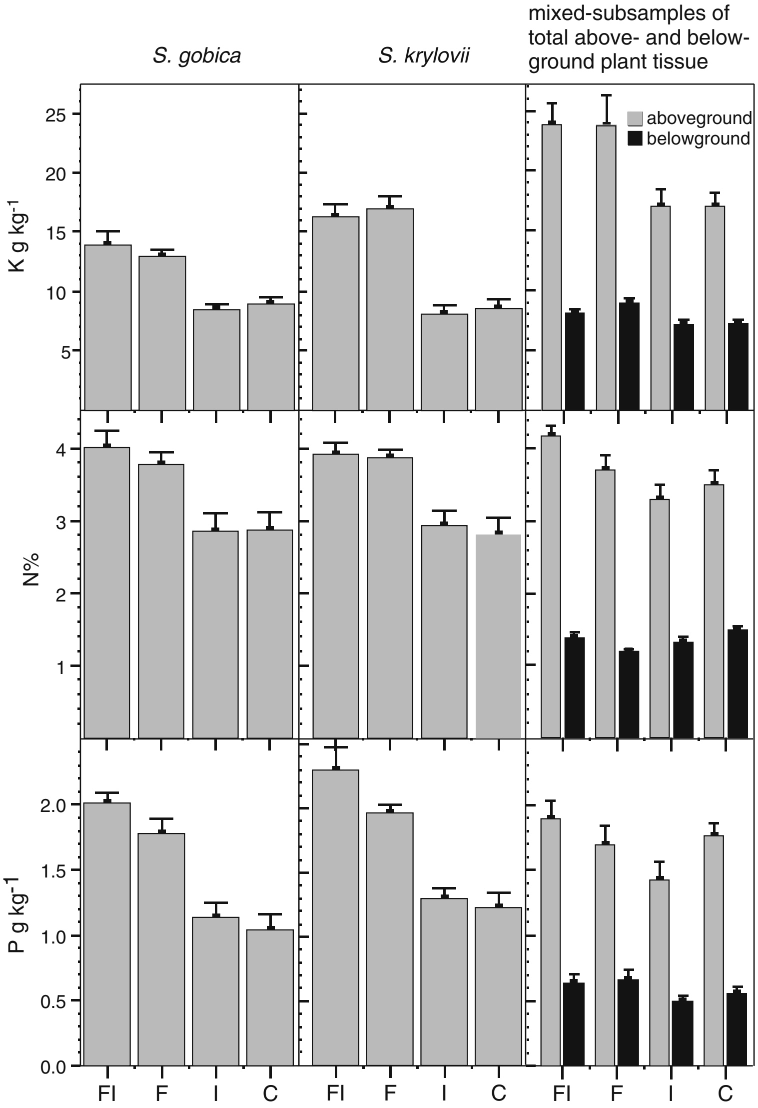

Fig. 3 Bar-graphs showing nutrient content in aboveground biomass of *Stipa gobica* and *S. krylovii* and mixed sub-samples of aboveground and belowground biomass, sampled at the edge of the plots. Treatments: FI—Fertilized and Irrigated, F—Fertilized, I—Irrigated, C—Control

tended to have slightly higher values of total N than the control plots (0.21±0.01% compared to 0.20±0.01%), thus, there might still be a slight effect of accumulating N in the soil. Differences were low overall and were near the measuring accuracy of our instrument rendering any statistical inferences difficult. Overall, CN-ratios in the soil are very narrow and indicate that there are considerable proportions of total N available in inorganic compounds, instead of being bound in organic matter.

Although we only have soil data from 1 year, a previous fertilization study in the study area covering several years demonstrates that nutrients accumulate in the topsoil (Wesche and Ronnenberg 2010), which is likely to be the case in the present study as well because the relative effect of fertilization on biomass growth was much stronger in 2006 as seen by the significant interaction of fertilization*year

Productivity and flowering intensity

Most irrigation and fertilization studies in drylands show a pronounced positive effect of irrigation (Niu et al. 2009) as well as from the combination of irrigation and fertilization (Powell et al. 1990; Drenovsky and Richards 2004; Lü and Han 2009). However, our data imply that increasing water input has no positive effect on plant productivity in our study area, which is somewhat misleading. Both years 2005 and 2006 were slightly below average with regard to precipitation. Studies on biomass in exclosures that ranged over several dryer and moister years clearly show that both flowering activity and steppe productivity are highly dependant on rainfall (Wesche and Ronnenberg 2010; Wesche et al. 2010). Although soil moisture was increased by irrigation, the effect after 24 h was rather small in absolute values and it may be possible that the threshold for an individual irrigation pulse to stimulate plant growth and reproduction is greater than 5 mm (Ogle and Reynolds 2004; Reynolds et al. 2004; Chen et al. 2009b).

Contrary to our expectations *Stipa gobica* and *Stipa krylovii* did not differ in their response to irrigation. Their distribution ranges and phytosociological affinities (Hilbig 1995) imply differing ranges of water requirements, however, irrigation as applied in this study was probably not sufficient to actually change the dominance of either species.

In contrast, the impact of fertilization was intense. Biomass productivity in general and also for the *Stipa* species, was increased by a factor of almost 2–3 (Fig. 1). Similar results were reported for *Agropyron cristatum* and *Allium polyrrhizum* from southern Mongolia (Wesche and Ronnenberg 2010), and for other slightly moister areas in Central Asia (e.g. Bai et al. 2009). Our results thus add to the growing but still rather limited body of evidence that plant growth benefits from fertilization in drylands with a mean annual precipitation well below 200 mm. We initially expected that the combination of additional nutrients and water should yield greater biomass than by fertilization alone; however, this was not the case. Apparently, nutrient uptake is possible even under ambient precipitation. Similar, non-additive effects for fertilization and irrigation were also found in Inner Mongolia (Niu et al. 2009).

Although both *Stipa* species benefited from fertilization, *S. gobica* declined in its relative contribution to the total biomass, whereas *S. krylovii* responded as strongly as the remaining species. In the study site, where both *Stipa* species co-occur *S. gobica* tends to become more abundant on poorer, stonier soils—a finding that is more apparent at higher altitudes or further north where *S. gobica* becomes increasingly restricted to rocky outcrops of the slopes and mountain peaks (Wesche and Ronnenberg 2004; von Wehrden et al. 2009). At slightly moister sites in Inner Mongolia, *S. krylovii* was shown to enhance its dominance over forb species such as *Artemisia frigida*, with increasing N availability (Huang et al. 2008). However, plant community composition did not change over the course of our experiment. Short-term addition of water and fertilizer is known to affect plant performance at the individual scale and changes in competitive interactions can only be expected if elevated nutrient and water availability is maintained over longer periods of time (Güsewell et al. 2003).

The number of inflorescences showed a similar trend as biomass. In most species groups the number of inflorescences increased dramatically in response to soil fertilization. Only *S. gobica* did not respond, which might be related to its generally very low numbers of inflorescences (pers. observations). The fact that seed-set benefits from nutrient addition (especially P) is well known (e.g. Marschner 1995), fertilization may thus lead to increased reproduction of certain species and change the species composition. However, no data on this issue are available from Central Asia and the duration of our experiment was certainly too short to show changes in plant community composition. Moreover, effects described here are relatively slight when compared against effects of direct grazing impact. Under normal conditions almost all inflorescences are eaten by herbivores (Wesche et al. 2007; Bläß et al. 2009). This adds to the generally very low rate of reproduction in perennial species in Central Asia (Lavrenko and Karamysheva 1993). Moreover, on the more severely degraded steppes of Inner Mongolia genetic diversity is affected by habitat fragmentation and reduced exchange of pollen and diaspores between populations of *Stipa krylovii* (Wang et al. 2006; Zhao et al. 2006).

Plant nutrient content

Tissue nitrogen content was already high in both *Stipa* species at about 3%, and even increased with fertilization by one more percent. Thus, fodder quality should be enhanced as biomass nitrogen is related to leaf protein content (Marschner 1995).

Contents of K in *Stipa* species were mainly affected by fertilization. Similarly, P content benefited from fertilization but was increased by irrigation as well. This effect was also apparent in the NP ratio, which decreased with irrigation. The NP ratio is regarded as an indication of the relative importance of N vs. P limitation (Koerselman and Meuleman 1996; Güsewell et al. 2003). This points to co-limitation by P in both analysed species, because even on the fertilized plots, the ratio is still above the optimal ratio of 15. In the control treatment, especially in *S. gobica*, the NP ratio is 31, which is at the upper end of Central Asian species (Han et al. 2005; He et al. 2008). However, assessing merely the NP ratio can be misleading in predicting the limiting factor in desert plants (Drenovsky and Richards 2004) and differential fertilization studies would be required to ultimately answer this question.

The total nutrient pools in the biomass were estimated using a densely vegetated mixed sub-sample of 1,000 cm^3. According to these measurements, aboveground biomass would total approximately 1,900 kg ha^{-1}, 900 kg ha^{-1}, 600 kg ha^{-1} and 500 kg ha^{-1} for the treatments FI, F, I and C respectively. Belowground biomass indicated a total biomass of ca. 15, 000 kg/ha, 15, 000 kg ha^{-1}, 12, 500 kg ha^{-1} and 8,000 kg ha^{-1} for the treatments FI, F, I and C respectively. These values certainly represent an overestimation, especially as the aboveground biomass on the small 10×10 cm² was much higher than in the larger, more representative plots. We nonetheless tried to make some crude estimates of the nutrient pools: for the 200 kg ha^{-1} nitrogen applied in 2006, we thus estimated that total N uptake compared to the control treatment was elevated by 150 kg ha^{-1}, 75 kg ha^{-1} and 60 kg ha^{-1} for the treatments FI, F and I. This implies that plants in fertilized and irrigated treatment (FI) had utilized a large part of the nitrogen originally administered, and that plants on irrigated plots were able to take up nitrogen, which is otherwise not available. Similar results were found for *Agropyron cristatum*, *Achnatherum sibiricum*, *Stipa grandis* and *Potentilla bifurca*, which showed increased N concentrations in green leafs after water and N addition in the Inner Mongolian typical steppe (Lü and Han 2009). For P, a much lower percentage of the applied fertilizer was utilised. Estimated uptake for the treatments FI, F and I were 8 kg ha^{-1}, 6.5 kg ha^{-1} and 2.5 kg ha^{-1} compared to the control treatment. This corresponds to 12%, 10% and 4% of the applied 66 kg ha^{-1} P. The uptake of K was intermediate. The treatments FI, F and I increased their K content compared to the control treatment by 100 kg ha^{-1}, 90 kg ha^{-1} and 40 kg ha^{-1} respectively, which is always less than a third of the total 333 kg ha^{-1} K applied in 2006. Even if taken with caution, our figures imply that a high percentage of the nitrogen was actually utilised by the plants, which may explain why soil N pools were not increased after fertilization, and even decreased after irrigation. The fact that only 12% of the applied P was utilised seems to contradict the assumption of P limitation, but P is likely to be bound in plant unavailable compounds in alkaline soils, which complicates uptake by the plants.

The lower relative content of nutrients in the belowground biomass might be an effect of the remaining dead biomass in the soil, which we could not separate from living roots with our coarse method. However, we found that only 11±2%, 6±2%, 4±1% and 6±1% for the treatments FI, F, I and C respectively of the biomass are situated aboveground. Thus, at least for the fertilized and irrigated treatment, aboveground vegetation increased in relation to belowground vegetation. A high root-shoot ratio often indicates nutrient limitation (Gedroc et al. 1996) and lower ratios could tentatively be interpreted as an alleviation of this limitation. In a study on *Leymus chinensis*, common in the slightly moister Inner Mongolia, above-ground biomass accounted for ~16% of total biomass on control plots, and for ~25% in plots fertilized with 17.5 g N m$^{2-1}$ over 2 years (Pan et al. 2005).

Conclusion

Global change scenarios indicate potentially increasing rainfall for the region (Christensen et al. 2007). The positive effect of this change is likely to be limited unless the number of events of heavy rainfall increases as well (Chen et al. 2009b). Given that our artificial irrigation did not improve plant vigour, most of the natural rain events with a median of 2.3 mm will also have very little effects on steppe productivity. This underlines the importance of distribution and intensity of rainy events, which has been repeatedly shown in drylands (Fisher et al. 1988; Fravolini et al. 2005; Patrick et al. 2009) and also for reproduction of *Stipa* species in our area (Ronnenberg et al. 2008).

Our results imply that nutrient limitation is an important constraint for plant biomass productivity even in desert steppes. This raises new concerns on land use practices. In southern Mongolia, steppe degradation in the sense of the impoverishment of plant community composition under heavy grazing could not be detected (Wesche et al. 2010). Several studies did, however, prove nutrient translocation and nutrient depletion as a consequence of grazing (Fernandez-Gimenez and Allen-Diaz 2001; Stumpp et al. 2005; Holst et al. 2007). Our results confirm that this may affect biomass productivity and deteriorate pasture quality. Thus, management strategies should consider effects of nutrient translocation and increased wind erosion as a result of reduced vegetation cover under heavy grazing (Yong-Zhong et al. 2005). In general, a decrease in livestock densities and a consequent halt in soil depletion would be beneficial for overall steppe productivity. Wide ranging artificial amelioration measurements, such as fertilization are unfortunately unrealistic when considering the vast extension of the Mongolian drylands.

Acknowledgements We thank F. Hass and J. Treiber for their assistance with the lab work and B. Turuu and C. Bläß for their help harvesting the biomass. H. von Wehrden and J. Hanspach gave advice on statistical questions and H. Brett and D. McCluskey corrected our English. B. Oyuna and U. Tuvshin organized permissions for field work and for the export of samples. The Gobi Gurvan Saykhan National Park granted research permission within the protected area. The DFG (German Science Foundation) and DAAD (German Academic Exchange Service) provided funding for the project. This is contribution number 298 in the series "Results of the Mongolian-German Biological Expedition since 1962"

References

Austin AT, Yahdjian L, Stark JM, Belnap J, Porporato A, Norton U, Ravetta DA, Schaeffer SM (2004) Water pulses and biogeochemical cycles in arid and semiarid ecosystems. Oecologia 141:221–235

Bai YF, Wu Y, Clark CM, Naeem S, Pan Q, Huang J, Zhang L, Han X (2009) Tradeoffs and thresholds in the effects of nitrogen addition on biodiversity and ecosystem functioning: evidence from Inner Mongolia grasslands. Glob Chang Biol 16:358–372

Bläß C, Ronnenberg K, Hensen I, Wesche K (2009) Grazing impact on plant seed production in Southern Mongolia. Mongolian Journal of Biological Sciences 6:3–9

Breman H, de Wit CT (1983) Rangeland productivity and exploitation in the Sahel. Science 221:1341–1347

Chen B-M, Wang G-X, Peng S-L (2009a) Role of desert annuals in nutrient flow in arid area of Northwestern China: a nutrient reservoir and provider. Plant Ecol 201:401–409

Chen S, Lin G, Huang J, Jenerette GD (2009b) Dependence of carbon sequestration on the differential responses of ecosystem photosynthesis and respiration to rain pulses in a semiarid steppe. Glob Chang Biol 15:2450–2461

Christensen JH, Hewitson B, Busuioc A, Chen A, Gao X, Held I, Jones R, Kolli RK, Kwon W-T, Laprise R, Magaña Rueda V, Mearns L, Menéndez CG, Räisänen J, Rinke A, Sarr A, Whetton P (2007) Regional climate projections. In: S Solomon, D Qin, M Manning, Z Chen, M Marquis, KB Averyt, M Tignor, HL Miller (eds) Climate change 2007: The physical science basis. Contribution of working group I to the fourth assessment report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp 847–940

Cross AF, Schlesinger WH (2001) Biological and geochemical controls on phosphorus fractions in semiarid soils. Biogeochemistry 52:155–172

Dagvadorj D, Khuldorj B, Aldover R (eds) (2009) Mongolia assessment report on climate change 2009. Ministry of Nature, Environment and Tourism, Mongolia, Ulaanbaatar, 228 p

Dore MHI (2005) Climate change and changes in global precipitation patterns: what do we know? Environ Int 31:1167

Drenovsky RE, Richards JH (2004) Critical N:P values: predicting deficiencies in desert shrublands. Plant Soil 259:59–69

Elser JJ, Bracken MES, Cleland EE, Gruner DS, Harpole WS, Hillebrand H, Ngai JT, Seabloom EW, Shurin JB, Smith JE (2007) Global analysis of nitrogen and phosphorus limitation of primary producers in freshwater, marine and terrestrial ecosystems. Ecol Lett 10:1135–1142

Fernandez-Gimenez ME, Allen-Diaz B (2001) Vegetation change along gradients from water sources in three grazed Mongolia ecosystems. Plant Ecol 157:101–118

Fisher FM, Zak JC, Cunningham GL, Whitford WG (1988) Water and nitrogen effects on growth and allocation patterns of creosotebush in the northern Chihuahuan desert. J Range Manage 41:387–391

Fravolini A, Hultine KR, Brugnoli E, Gazal R, English NB, Williams DG (2005) Precipitation pulse use by an invasive woody legume: the role of soil texture and pulse size. Oecologia 144:618–627

Galloway JN, Dentener FJ, Capone DG, Boyer EW, Howarth RW, Seitzinger SP, Asner GP, Clevelands CC, Green PA, Holland EA, Karl DM, MA F, Porter JH, Townsend AR, Vörösmarty C (2004) Nitrogen cycles: past, present, and future. Biogeochemistry 70:153–226

Gao X, Zhao Z, Giorgi F (2002) Changes of extreme events in regional climate simulations over East Asia. Adv Atmos Sci 19:927–942

Gedroc JJ, McConnaughay KDM, Coleman JS (1996) Plasticity and root/shoot partitioning: optimal, ontogenetic, or both? Funct Ecol 10:44–50

Groisman PY, Knight RW, Easterling DR, Karl TR, Hegerl GC, Razuvaev VN (2005) Trends in intense precipitation in the climate record. J Climate 18:1326–1350

Gubanov IA (1996) Conspectus of the flora of outer Mongolia (vascular plants). Valang Publishers, Moscow, 136 p

Güsewell S, Koerselman W, Verhoeven JTA (2003) Biomass N:P ratios as indicators of nutrient limitation for plant populations in wetlands. Ecol Appl 13:372–384

Han W, Fang J, Guo D, Zhang Y (2005) Leaf nitrogen and phosphorus stoichiometry across 753 terrestrial plant species in China. New Phytol 168:377–385

He JS, Wang L, Flynn DFB, Wang XP, Ma WH, Fang JY (2008) Leaf nitrogen: phosphorus stoichiometry across Chinese grassland biomes. Oecologia 155:301–310

Hijmans RJ, Susan E, Cameron JL, Parra PG, Jones AJ (2005) Very high resolution interpolated climate surfaces for global land areas. Int J Climatol 25:1965–1978

Hilbig W (1995) The vegetation of Mongolia. SPB Academic Publishing, Amsterdam, 258 p

Hoekstra JM, Boucher TM, Ricketts TH, Carter R (2005) Confronting a biome crisis: global disparities of habitat loss and protection. Ecol Lett 8:23–29

Holst J, Liu C, Yao Z, Bruggemann N, Zheng X, Han X, Butterbach-Bahl K (2007) Importance of point sources on regional nitrous oxide fluxes in semi-arid steppe of Inner Mongolia, China. Plant Soil 296:209–226

Hooper DU, Johnson L (1999) Nitrogen limitation in dryland ecosystems: responses to geographical and temporal variation in precipitation. Biogeochemistry 46:247–293

Huang J-Y, Zhu X-G, Yuan Z-Y, Song S-H, Li X, Li L-H (2008) Changes in nitrogen resorption traits of six temperate grassland species along a multi-level N addition gradient. Plant Soil 306:140–158

Jigjidsuren S, Johnson DA (2003) Forage plants in Mongolia. Admon Publishing, Ulaanbaatar

Koerselman W, Meuleman AFM (1996) The vegetation N:P ratio: a new tool to detect the nature of nutrient limitation. J Appl Ecol 33:1441–1450

Lathja K, Bloomer SH (1988) Factors affecting phosphate sorption and phosphate retention in a desert ecosystem. Soil Sci 146:160–167

Lauenroth WK, Sala OE (1992) Long-term forage production of north American shortgrass steppe. Ecol Appl 2:397

Lavrenko EM, Karamysheva ZV (1993) Steppes of the former soviet union and Mongolia. In: Coupland RT (ed) Natural Grasslands. Ecosystems of the world 8b. Elsevier, Amsterdam, pp 3–59

LeBauer DS, Treseder KK (2008) Nitrogen limitation of net primary productivity in terrestrial ecosystems is globally distributed. Ecology 89:371–379

Le Houerou HN, Bingham RL, Skerbak W (1988) Relationship between the variability of primary production and the variability of annual precipitation in world arid lands. J Arid Environ 15:1–18

Liu W, Zhang Z, Wan S (2009) Predominant role of water in regulating soil and microbial respiration and their responses to climate change in a semiarid grassland. Glob Chang Biol 15:184–195

Lü X-T, Han X-G (2009) Nutrient resorption responses to water and nitrogen amendment in semi-arid grassland of Inner Mongolia, China. Plant Soil. doi:10.1007/s11104-009-0078-y

Marschner H (1995) Mineral nutrition of higher plants. Academic Press, London, 889 p

Munkhtsetseg E, Kimuraa R, Wanga J, Shinoda M (2007) Pasture yield response to precipitation and high temperature in Mongolia. J Arid Environ 70:94–110

Niu S, Wu M, Han Y, Xia J, Li L, Wan S (2008) Water-mediated responses of ecosystem carbon fluxes to climatic change in a temperate steppe. New Phytol 177:209–219

Niu S, Yang H, Zhang Z, Wu M, Lu Q, Li L, Han X, Wan S (2009) Non-additive effects of water and nitrogen addition on ecosystem carbon exchange in a temperate steppe. Ecosystems 12:915–926

Noy-Meir I (1973) Desert ecosytems: environment and producers. Annu Rev Ecol Syst 4:25–41

Ogle K, Reynolds JF (2004) Plant responses to precipitation in desert ecosystems: integrating functional types, pulses, thresholds, and delays. Oecologia 141:282–294

Pan Q, Bai YF, Han XG, Yang J-C (2005) Effects of Nitrogen additions on a *Leymus chinensis* population in typical steppe of Inner Mongolia. Acta Phytoecologica Sinica 29:311–317

Patrick LD, Ogle K, Bell CW, JZA K, Tissue D (2009) Physiological responses of two contrasting desert plant species to precipitation variability are differentially regulated by soil moisture and nitrogen dynamics. Glob Chang Biol 15:1214–1229

Peck JR, Yearsley JM, Waxman D (1998) Explaining the geographic distributions of sexual and asexual populations. Nature 391:889–892

Powell KB, Vincent RB, Depuit EJ, Smith JE, Parady FE (1990) Role of irrigation and fertilization in revegetation of cold desert mined lands. J Range Manage 43:449–455

Retzer V, Nadrowski K, Miehe G (2006) Variation of precipitation and its effect on phytomass production and consumption by livestock and large wild herbivores along an altitudinal gradient during a drought, South Gobi, Mongolia. J Arid Environ 66:135

Reynolds JF, Kemp PR, Ogle K, Fernandez RJ (2004) Modifying the ‘pulse-reserve’ paradigm for deserts of North America: precipitation pulses, soil water, and plant responses. Oecologia 141:194–210

Ronnenberg K, Wesche K, Hensen I (2008) Germination ecology of Central Asian Stipa spp: differences among species, seed provenances, and the importance of field studies. Plant Ecol 196:269–280

Schlesinger WH, Peterjohn WT (1991) Processes controlling ammonia volatilization from Chihuahuan desert soils. Soil Biol Biochem 23:637–642

Slemnev NN, Sanjid D, Khongor T, Tsooj S (2004) The features of desertified steppes development in Mongolia at the gradient of ecotopes’ moistoning. Arid Ecosystems 10:172–182

Song M, Dong M, Jiang G (2002) Importance of clonal plants and plant species diversity in the Northeast China Transect. Ecol Res 17:705–716

SPSSInc. (2003) SPSS for Windows 12.0G. SPSS Inc., Chicago.

Stumpp M, Wesche K, Retzer V, Miehe G (2005) Impact of grazing livestock and distance from water points on soil fertility in southern Mongolia. Mt Res Dev 25:245–252

von Wehrden H, Zimmermann H, Hanspach J, Ronnenberg K, Wesche K (2009) Predictive mapping of plant species and communities by using GIS and Landsat data in a southern Mongolian mountain range. Folia Geobot 44:211–225

Walvoord MA, Phillips FM, Stonestrom DA, Evans RD, Hartsough PC, Newman BD, Striegl RG (2003) A reservoir of nitrate beneath desert soils. Science 302:1021–1024

Wang JL, Zhao NX, Gao YB, Lin F, Ren AZ, Ruan WB, Chen L (2006) RAPD analysis of genetic diversity and population genetic structure of *Stipa krylovii* Reshov. in Inner Mongolia steppe. Russ J Genet 42:468–475

Wesche K, Ronnenberg K (2004) Phytosociological affinities and habitat preferences of *Juniperus sabina* L. and *Artemisia santolinifolia* Turcz. ex Bess. in mountain sites of the south-eastern Gobi Altay, Mongolia. Feddes Repertorium 115:585–600

Wesche K, Ronnenberg K (2010) Effects of NPK fertilisation in arid southern Mongolian desert steppes. Plant Ecol 207:93–105

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

Wesche K, Nadrowski K, Retzer V (2007) Habitat engineering under dry conditions: the impact of pikas (*Ochotona pallasi*) on southern Mongolian mountain steppes. J Veg Sci 18:665–674

Wesche K, Ronnenberg K, Retzer V, Miehe G (2010) Effects of large herbivore exclusion on southern Mongolian desert steppes. Acta Oecologica 36:234–241

Wu Z-Y, Raven PH (2006) Poaceae. Science Press, Beijing

Xiao CW, Janssens IA, Liu P, Zhou ZY, Sun OJ (2007) Irrigation and enhanced soil carbon input effects on below-ground carbon cycling in semiarid temperate grasslands. New Phytol 174:835–846

Xie YZ, Wittig R (2004) The impact of grazing intensity on soil characteristics of Stipa grandis and Stipa bungeana steppe in northern China (autonomous region of Ningxia). Acta Oecologica-International Journal of Ecology 25:197–204

Yong-Zhong S, Yu-Lin L, Jian-Yuan C, Wen-Zhi Z (2005) Influences of continuous grazing and livestock exclusion on soil properties in a degraded sandy grassland, Inner Mongolia, northern China. CATENA 59:267

Zhao N-X, Gao Y-B, Wang J-L, Ren A-Z (2006) Genetic diversity and population differentiation of the dominant species *Stipa krylovii* in the Inner Mongolia steppe. Biochem Genet 44:504–517