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GRAZING EFFECTS ON SOIL MECHANICAL STRENGTH AND PHYSICAL FUNCTIONS IN INNER MONGOLIA, CHINA

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In loving memory of my parents,

my Mother Halina (†2001)

and my Father Waldemar (†2010),

who have raised me to be the person I am today

The grasslands are like a green sea
The yurts are like white lotuses
The herders paint a happy scene
Springs spreads, pretty as a picture

Dedema "The Beautiful Grasslands"

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LIST OF ABBREVIATIONS

a	area of the hydraulic head (cm^2)
A	cross-sectional area of the cylinder (cm^2)
AC	air capacity (cm^3 cm^{-3})
BD	bulk density (g cm^{-3})
C_2, C_3	indices of pore continuity (μm^2)
$\mathbf{C_c}$	compression index
CG	continuously grazed
c_n	coefficient of cyclic compressibility
g	gravitational acceleration (m s^{-2})
G	grazed
$\mathbf{h_0}$, $\mathbf{h_1}$	the height of the hydraulic head in the beginning and in the end of the measurement of saturated hydraulic conductivity (cm)
k	hydraulic conductivity (cm d^{-1})
$\mathbf{k_a}$	air conductivity (cm s^{-1}; m s^{-1})
$\mathbf{k_{ap}}$	air permeability (μm^2)
$\mathbf{k_s}$	saturated hydraulic conductivity (cm d^{-1}; cm s^{-1})
$\mathbf{k_u}$	unsaturated hydraulic conductivity (cm s^{-1})
l	height of the hydraulic head (cm)
l	pore connectivity parameter
LCh	*Leymus chinensis* vegetation type
n, m	van Genuchten empirical shape parameters
PAW	plant available water (cm^3 cm^{-3})
$\mathbf{P_c}$	precompression stress of the statically loaded samples (kPa)
$\mathbf{P_c}$**'**	precompression stress of the samples loaded repeatedly (kPa)
PCL	pure cyclic loading test
SCL	stepwise cyclic loading test
SG	*Stipa grandis* vegetation type
SL	static loading test
t	time of discharge of the quantity of water between h_0 and h_1 (s)
TP	total porosity (cm^3 cm^{-3})
UG79	ungrazed since 1979
WG	winter grazed

LIST OF SYMBOLS

$1/\alpha$	air entry value of bubbling pressure (cm^{-1})
$\boldsymbol{\varepsilon}$	air-filled porosity (cm^3 cm^{-3})
$\boldsymbol{\eta_a}$	viscosity (Pa s)
$\boldsymbol{\rho_a}$	air density (kg m^{-3})
$\boldsymbol{\psi}$	matric potential (hPa)

CHAPTER I
(Summary)

SUMMARY

Overgrazing has become over the last decades a major cause of grassland deterioration in Inner Mongolia, China leading to a decline in its productivity and carrying capacity. Among others, an intensified grazing has significant consequences for soil structure, soil mechanical strength as well as its functions. Furthermore, together with decline of soil functions also intensification of water and wind erosion as well as loss of nutrients in soil can be observed. In order to prevent further landscape degradation of Inner Mongolian steppe ecosystems as well as to evaluate a sustainable land management knowledge about the responses of ecosystem to grazing based on scientific research is needed. Furthermore, to understand the changes in environment due to grazing it is important to consider the response of different grassland ecosystems to overgrazing.

The investigations of impact of grazing on environment, in particular on soil mechanical strength and soil physical functions, were carried out under the MAGIM (Matter fluxes in grasslands of Inner Mongolia as influenced by stocking rate) project at the Xilin River Basin in Inner Mongolia, China. Two grassland ecosystems were investigated: *Leymus chinensis* (LCh) and *Stipa grandis* (SG), which are dominant grassland types in the semiarid area in Inner Mongolia. At each site different treatments were investigated: ungrazed since 1979 (UG79), continuously grazed (CG) at the SG site and winter grazed (WG) at the LCh site. An evaluation of soil physical properties was done for different depths, representing each soil horizon, using disturbed and undisturbed (soil aggregates and bulk soil) soil samples. The disturbed soil samples were used for measurement of particle size distribution, soil organic carbon content and contact angle; the soil aggregates were used in order to determine tensile strength, repellency index and to test an influence of repeated freezing and thawing on soil tensile strength; the bulk soil was used to determine water retention characteristics, bulk density, precompression stress under static and cyclic loading conditions, parameters defining soil compressibility, saturated and unsaturated hydraulic conductivities and air conductivity.

The results indicated changes in soil mechanical properties and soil functions related to influence of animal trampling and recovery of soil from grazing as well as different response of two investigated grassland ecosystems to grazing. The studies indicated strong interrelations between soil mechanical properties and soil functions. The

results showed an increase in soil mechanical strength due to grazing on aggregate and bulk soil scale. Furthermore, it was shown that grazing causes a significant rearrangement of soil particles leading to homogenization and formation of a platy soil structure which is more pronounced the more often soil is loaded. Together with changes of soil strength also decline in soil functions could be proven as a result of destruction of continuity of soil pore network. Moreover, it was seen that grazing leads to more pronounced deterioration of soil structure as well as more intensive recovery from grazing at the LCh site compared to the SG site.

ZUSAMMENFASSUNG

In den vergangenen Jahrzehnten hat sich die Überbeweidung zu einem der Hauptgründe für den Rückgang der Produktivität und Tragfähigkeit von Weideland in der Inneren Mongolei, China entwickelt. Die Beweidungsintensivierung wirkt sich dabei unter anderem auf die Struktur und mechanische Stabilität des Bodens aus sowie auf dessen ökologische Funktionen. Des Weiteren können eine größere Anfälligkeit für Wasser- und Winderosion sowie Nährstoffverluste des Bodens beobachtet werden. Um einer weiteren Degradation der Landschaft und der Steppenökosysteme in der Inneren Mongolei entgegen zu wirken und um ein nachhaltiges Bewirtschaftungskonzept zu entwickeln, müssen auf wissenschaftlicher Grundlage basierende Erkenntnisse über die Reaktionen des Ökosystems hinsichtlich der Beweidung gewonnen werden. Für das Verständnis der beweidungsbedingten Umweltveränderungen ist es wichtig, das Verhalten unterschiedlicher Grünlandökosysteme bezüglich Überweidung zu berücksichtigen.

Untersuchungen zum Einfluss unterschiedlicher Beweidungsintensitäten auf die Umwelt, insbesondere auf die mechanische Festigkeit sowie die physikalischen Funktionen von Steppenböden wurden innerhalb des MAGIM-Projektes (Matter fluxes in Grassland of Inner Mongolia as influenced by stocking rate) im Xilin-Einzugsgebiet in der Inneren Mongolei, China, durchgeführt. Es wurden zwei Grünlandökosysteme untersucht: *Leymus chinensis* (LCh) und *Stipa grandis* (SG), beides dominierende Grünlandtypen in semiariden Gebieten der Inneren Mongolei. An beiden Standorten wurden Untersuchungen zu unterschiedlichen Bewirtschaftungsweisen durchgeführt: nicht beweidet seit 1979 (UG79) sowie fortlaufende Beweidung (CG) auf dem SG-Standort und Winterbeweidung auf dem LCh-Standort. Anhand horizontspezifischer Entnahme von gestörten und ungestörten Bodenproben (Bodenaggregate und Stechzylinderproben) wurde eine Bewertung der bodenphysikalischen Eigenschaften für die repräsentativen

Bodenhorizonte durchgeführt. Die gestörten Proben wurden für die Ermittlung von Korngrößenverteilung, Kohlenstoffgehalt und Benetzungswinkel genutzt; die ungestörten Bodenaggregate dienten der Erfassung von Zugfestigkeit und Hydrophobie sowie des Einflusses wiederholten Gefrierens und Tauens auf die Zugfestigkeit; anhand der Stechzylinderproben wurden Wasserspannungs-Wassergehalts-Beziehungen, Lagerungsdichte, Vorbelastung unter statischen und zyklischen Belastungsbedingungen, Parameter der Verdichtbarkeit, gesättigte und ungesättigte hydraulische Leitfähigkeit sowie Luftleitfähigkeit ermittelt.

Die Ergebnisse belegen Veränderungen der bodenmechanischen Eigenschaften und der physikalischen Bodenfunktionen aufgrund des Tiertritts, eine Regeneration des Bodens nach Aussetzen der Beweidung sowie verschiedene Reaktionen der beiden untersuchten Grünlandökosysteme hinsichtlich Beweidung. Die Untersuchungen zeigen einen starken Zusammenhang zwischen den bodenmechanischen Eigenschaften und der Porenfunktion der Böden. Durch die Beweidung konnte ein bedingter Anstieg der mechanischen Festigkeit sowohl auf Ebene der Aggregate als auch des gelagerten Bodens aufgezeigt werden. Des Weiteren wird gezeigt, dass Beweidung eine signifikante Umverlagerung von Bodenteilchen bewirkt, die zur Homogenisierung und anschließender Ausbildung einer Plattenstruktur führt, die desto stärker ausgeprägt ist, je öfter der Boden eine Belastung erfährt. Zusammen mit den Veränderungen der Bodenfestigkeit kann auch eine auf der Zerstörung der Kontinuität des Porensystems beruhende Verringerung der Bodenfunktionen belegt werden. Die Untersuchungen in den unterschiedlichen Grünlandökosystemen zeigten, dass der LCh- im Vergleich zum SG-Standort sowohl zu einer ausgeprägteren Degradation der Bodenstruktur bei Beweidung, als auch zu einer stärkeren Regeneration bei Aussetzen der Beweidung neigt.

CHAPTER II

(Introduction)

INTRODUCTION

STATE OF ART

Grasslands are among the largest ecosystems in the world, they can be found at each continent as they cover around 40 % of the global terrestrial area excluding Greenland and Antarctica (Sutie et al., 2005). China is one of the countries having the richest grassland resources, their total area results as the third biggest grasslands in the world, after Australia and Russia (Zizhi and Degang, 2005; FAO, 2009). Most of the grasslands in China are situated in northern arid and cold areas. The Inner Mongolian steppe is a part of the major pastoral areas in China. For centuries its ecosystems, especially its central part, were used for grazing livestock, such as sheep, goats, horses and cattle, in nomadic way (Neupert, 1999; Chen et al., 2007). Such grazing enabled the herders to prevent the sensitive areas from irreversible degradation by overgrazing. Their knowledge about climate, animal physiology and behavior and plant ecology was the background for a mobile and flexible herding strategy. Such way of nomadic grazing allowed the pastoralists to benefit for their animals without or with only few external impacts on the environment (Fernández-Giménez, 1999). However, in 1950's and 1960's, due to political changes, the pastoralists were forced to give up their nomadic way of life and to join the livestock collectivities, where they herded state-owned animals, which led to allocation of pasture, regulation of pasture use and, as a consequence, increased grazing pressure on ecosystem (Fernández-Giménez, 2000). In the 1980's until beginning of 1990's due to other political changes the herders became again responsible for their herds and could benefit from the meat and wool production. These political changes have led to reduction or even elimination of large-scale pastoral movement and, together with increased human population and demands for food, an increase in herd size, concentration of livestock on specific areas as well as increase in tendency towards a year-round grazing were observed, which resulted in an intensified grassland deterioration and decline in carrying capacity of this ecosystem (Sneath, 1998). It was reported, that since 1980 until 1997 the number of livestock in Inner Mongolia increased from the 12.6 million to 22.7 million and the grassland available per sheep unit declined from 1.42 ha in 1980 to 1.05 ha in 1990 (Li et al., 2007). Furthermore, recent studies indicated that around 21.6 % of the Inner Mongolian grasslands are described as "unusable" and 34.5 % as "deteriorated", the other 43.9 % were considered to be usable and in good conditions (Neupert, 1999; Yu et al., 2004).

Because of progressing landscape degradation in Inner Mongolia caused by an intensive grazing, the local government made some attempts to improve grassland productivity as well as to prevent further degradation of the steppe ecosystem by introducing different management strategies and regulation of a stocking rate. It was indicated that each person per household can manage fifty ha area and have maximum fifty sheep and owing goats is allowed only on defined areas. However, these regulations were not based on any scientific background. Furthermore, in reality the regulations are not obeyed, the size of the herd is very often twice as big as it is allowed and the goats account for around 10-30 % of the herd.

An intensification of grazing in Inner Mongolia has led, during the last decades, to many negative consequences for grassland environment like:

- An intensive animal trampling causes a decrease in plant cover, decline in plant height and growth, changes in above- and belowground plant productivity or changes in plant composition together with mechanical destruction of plants (Renzhong and Ripley, 1997; Scott et al., 2002; Pucheta et al., 2004; Chen et al., 2005b; Pei et al., 2008).
- The reduction in Inner Mongolian steppe productivity is attributed to changes in soil chemical and physical properties. Grazing leads to decrease in total nitrogen and total sulphur concentrations and decline in organic carbon content (Steffens et al., 2008) which is mostly related to lower inputs of diluting litter. Moreover, overgrazing can lead to decrease in surface roughness, intensification of wind erosion, further losses of organic matter and desertification (Li et al., 2000; Hoffmann et al., 2008a; Hoffmann et al., 2008b).
- Grazing affects soil physical quality due to changes in soil physical properties, mostly related to degradation and reformation of soil structure caused by intensive animal trampling through shearing and kneading (Krümmelbein et al., 2008).

The magnitude of these changes depends on stocking rate, hoof area, trampling frequency or moisture content (Hamza and Anderson, 2005). It was observed that intensive grazing leads to an increase in bulk density and decline in porosity, especially the amount of macropores, and increase in volume of finer pores, which is related to soil compaction (Baumgartl and Horn, 1991; Broersma et al., 2000; Huang et al., 2007; du Toit et al., 2009). Furthermore, it was stated that animal-induced compaction can lead to changes in soil mechanical and hydraulic properties (Tollner et al., 1990; Kurz et al., 2006).

Mechanical strength of soil depends mainly on aggregation, number of particle contacts, inter-particle strength, which includes actual and maximum pre-drying as well as composition and arrangement of the pore system. In general, the more aggregated the soil the stronger it is, the more negative the pore water pressure the more pronounced is the strength increase (Lebert and Horn, 1991; Horn et al., 1998). Changes in soil strength can be quantified by the precompression stress value. The latter defines the maximum stress or pre-drying intensity to which the soil was exposed in the past and is a very important parameter used for evaluation of soil susceptibility to compaction, load capacity and its implications to soil structure (Baumgartl and Köck, 2004; Cavalieri et al., 2008). It was estimated that the contact area pressure of one sheep hoof varies between 80 kPa (Krümmelbein et al., 2006) and 124 kPa (Tollner et al., 1990). The effect of grazing on soil structure and soil physical properties is even more pronounced when the animals are moving. Abdel-Magid et al. (1987) found that moving steers exerted on soil greater loads per unit area than when they were standing. Martínez and Zinck (2004) reported that when the animals travel the pressure exerted by their hooves on the soil can be two to four times higher than the standing loads. Furthermore, the repeated application of mechanical stresses can induce rearrangement of soil particles and further deformation and deterioration of soil structure even if the exerted stresses are lower than the precompression stress (O'Sullivan and Robertson, 1996). This can be explained mostly by alteration of soil matric potential during repeated loading and unloading which also affects shear resistance of the soil. This change in matric potential during loading-unloading events can be explained by alteration of a degree of saturation. Under compression, the particles move closer to each other, the degree of saturation increases and the water menisci tend to a convex shape, while during unloading the shape of pore water menisci becomes concave and the matric potential turns into more negative (Baumgartl and Köck, 2004; Markgraf et al., 2006). Such fluctuations of matric potential, defined by Krümmelbein et al. (2008) as a "water pumping effect", result in a decline in shear resistance between particles and aggregates followed by more intense rearrangement of soil particles, weakening of soil structure and higher sensitivity to compression. The effect of moisture content on soil strength was investigated by Horn and Rostek (2000) and Peng et al. (2004). Strength increase is more pronounced the more negative the pore water pressure. In Inner Mongolia grazing is very often practiced throughout the whole year, during drier and wetter periods, which can lead to various degrees of soil compaction and degradation, depending on the season of the year. Therefore, a question arises how far can soil degradation vary within a year or how intensive can soil deterioration be due to grazing under different moisture conditions. It was reported that grazing affects mostly the surface soil layer (Greenwood and McKenzie, 2001; Villamil et al., 2001) which is mostly proven by numerous papers. Furthermore, in strong soils mechanical stresses are more concentrated at the soil surface while the deeper soil layers are protected from compaction. However, grazing under wetter conditions leads to weakening of the soil surface and homogenization and therefore soil compaction can be found also at greater depths (Sander et al., 2008). In general, in the less aggregated, less dense and wetter soils the stress propagation can reach deeper depths, which is accompanied by recompaction of soil material (Blackwell et al., 1989; Horn et al., 2003). However, most of the measurements are carried out under static loading, while the more intense soil deformation can be expected under dynamic stress application. This is caused by a more pronounced rearrangement of soil structure within existing soil space due to frequent animal trampling. A platy soil structure is usually present at the transition from the plowed top soil horizons to the subsoil but grazing or trampling can result in identical formation of plates. In addition, if grazing is done under wetter conditions a formation of such structure type can be detected even at deeper depths. One of the ecological consequences of grazing on soil is the alteration of direction-dependent soil functions (Dörner and Horn, 2006). Another consequence of overgrazing, related to the repeated application of stresses and shear forces exerted by animal hooves, is deterioration and homogenization of soil aggregates (Horn et al., 1994; Zhao et al., 2007; Wiesmeier et al., 2009).

Thus, it is clear, that degradation of soil structure is followed by alteration of soil functions which is related mostly to changes in continuity of soil pore network:

- Existence of continuous pores is important with respect of root supply with water and gas. Additionally, a continuous pore system also affects the components of the soil water balance such as infiltration, drainage or evaporation.

- Animal trampling leads to alteration of soil conductive properties and direction-dependent soil functions. An increase in horizontal alignment of macropores and decline in amount of vertically oriented pores (like in platy soil structure) decreases the hydraulic conductivity and water infiltration and increases the susceptibility to water erosion (Pagliai et al., 2004). This effect is more pronounced the higher the stocking rate and the higher the number of loading events (Horn et al., 2003; Savadogo et al., 2007).
- Homogenization and weakening of the soil system significantly reduces the flux of gas and water into and out of soil. In addition, due to the lower internal strength, soil particles can be easier transported by wind and water (Wiermann et al., 2000; Horn et al., 2003).

Furthermore, the soil hydraulic properties can be altered due to soil hydrophobic properties related to the presence of water repellent coatings which may be interlinked with the amount and composition of organic carbon. A hydrophobic character of soil organic matter is determined by the amount of hydrophilic C=O- groups relative to that of hydrophobic CH-groups. The arrangement of the hydrophobic components within soil organic matter strongly affects soil wettability (Ellerbrock et al., 2005). A degree of soil water repellency can be changed by animal trampling which causes reduction of the vegetation cover and therefore a reduction of an input of organic matter to the soil, as well as changes in a degree of decomposition of organic material in the soil. Kölbl et al. (2010) proved that animal trampling leads to decrease in soil aggregation and the amount of fresh, litter-like particulate organic matter and enhanced mineralization of soil organic matter while the ungrazed sites are characterized by soil-organic-carbon-controlled wettability due to higher content of particulate organic matter.

Until now an open question is how far a recovery of soil structure and functions from grazing can be predicted. It is described by (Yong-Zhong et al., 2005) that it is very slow and lasts for many years although the vegetation recovery can be much faster. The time of soil recovery process can be even longer if grazing was practiced under semiarid climatic conditions. The often posed question concentrates on the time required for such recovery of soil functions which is directly linked to the management concepts under those climatic conditions with very sensitive soils.

A natural soil recovery is usually limited to the upper soil layer and begins when animals are excluded from the pasture (Drewry, 2006). Soil structure reformation after grazing appears due to aggregation processes, which corresponds to rearrangement of soil particles, flocculation or cementation (Horn and Dexter, 1989). The main factors which affect the soil aggregation and stability are: alteration of moisture and temperature conditions, soil fauna, microorganisms, roots and inorganic binding agents.

The primary aggregation of the soil occurs due to changes in moisture conditions when repeated swelling and shrinkage lead to changes in soil bulk density and soil strength and occurrence of inter- and intra-aggregate soil pores (Horn, 1993; Horn et al. 1994; Horn and Smucker 2005).

Other environmental variables which may play an important role in aggregate formation under the corresponding climatic conditions and land use systems are the fluctuations of the temperature, including freezing and thawing processes which all affect soil aggregate stability, microbial activity or availability of substrates (Feng et al., 2007; Freppaz et al., 2007; Henry, 2007).

Under Inner Mongolian climatic conditions freezing and thawing processes result in changes in soil strength leading to either soil aggregation or breakdown and homogenization of soil aggregates (Bisal and Nielsen, 1964). An increase in strength of soil aggregates is a result of pressing the soil particles together during the repeated freezing and thawing events which results in more compacted and less permeable structure elements. Repeated freezing and thawing events, furthermore, lead to decline in soil bulk density and stability, particularly at higher soil moisture. During the freezing process, the soil moisture is drawn to the freezing front (most negative matric potential) which is accompanied by expansion of the freezing water volume by 9% and can cause aggregate breakage. During the process of thawing, the deeper frozen layers decrease the soil permeability and the melt water from the ice is trapped in the thawed layer (Chamberlain, 1981; Shoop et al., 2008). On the other hand repeated freezing and thawing lead to increased soil permeability due to creation of inter-aggregate cracks (Konrad, 1989).

Important role in soil structure recovery from grazing play plant roots which can form macro-pores in soil during its penetration or create failure zones which contribute to the process of soil aggregation. In addition, plant roots can also lead to a local drying of soil which causes shrinkage and strengthening (Angers and Caron, 1998).

Finally, structure formation is caused by soil fauna, like earthworms, which alter soil strength due to creation of organo-mineral bindings and shear-induced aggregation. Because earthworms consume large amounts of plant remains in soil and turn it into the mineral soil and litter layer they stabilize the total soil system which is also true for the burrowing and casting because that leads to formation of biogenic soil structures; new biopores and aggregates are created (Jongmans et al., 2003).

Soil fauna, microorganisms or roots are also the source of the organic matter in soil which acts as a binding agent in creation of aggregates. An influence of organic matter on soil mechanical strength relates to the coherence of interparticle bonds. Amongst the positive binding and strengthening mechanisms by organic carbon, we have to analyze microbial and root exudates having a form of polysaccharides which can stabilize and create soil aggregates (Chaney and Swift, 1984; Amellal et al., 1998). The root and microbial mucilages (the remainders of polysaccharides) are important glues in soils. Aggregate stability increases when adding microbial polysaccharides and polysaccharide preparations into soil, while oxidation of polysaccharides can lead to degradation of aggregates (Oades, 1984). Increasing organic matter content in soil leads also to an increase in water retention over wide range of suctions which enhances aggregate strength at these suctions. A stabilizing effect of soil organic matter on soil aggregates relates also to reduction of aggregate wettability. On the other hand an increase of organic matter content in soil causes decrease in bulk density and this can lead to decrease in aggregate strength under wet and dry conditions (Zhang, 1994).

Because organic materials and clays in soil are polyanions, therefore they can be bridged by polyvalent cations (Oades, 1984). Among inorganic binding agents in the soil, the most studies have focused on calcium and oxyhydroxides (Six et al., 2004). Soil carbonates are mostly the source of calcium cations in the soil which form bridges between the organic colloids and clay surfaces and stabilize the exchange complex (Dexter, 1988). The process of flocculation and dispersion of soil colloids and therefore soil structure depends on the cation exchange capacity. A degree of cation adsorption depends strongly on its valence, hydratation and concentration. In general, the greater the valence of the cation the stronger it is adsorbed, the greater the ion’s hydratation, the weaker the adsorption (Hillel, 1998). In addition an increase in concentration of cation in soil solution leads to increase of strength of binding caused by this cation (Peng et al., 2005).

Each soil system has a dynamic nature where the processes of soil structure formation are accompanied by processes of reformation or destruction. It is important to mention that some of the factors, which influence formation of soil, can also have a destructive character on the soil structure. Intensive and sudden rainfalls can lead to occurrence of slaking which is caused by stresses produced by differential swelling, explosion of entrapped air, rapid release of heat during fast wetting or mechanical action of moving water (Lado et al., 2004). On the other hand repeated freezing and thawing can decrease the stability of aggregates.

OBJECTIVES

In order to gather the scientific information needed for evaluation of sustainable land use management in Inner Mongolia, a MAGIM project (**MA**tter fluxes in **G**rasslands of **I**nner **M**ongolia as influenced by stocking rate) was established. The MAGIM is a multidisciplinary project bringing together German and Chinese scientists from different scientific fields. The principle objective of the MAGIM is to understand how grazing of steppe ecosystems feedbacks on water, nitrogen and carbon fluxes on site and regional scales. The studies were conducted at the Xilin River watershed (3,800 km^2) which is a typical semiarid temperate steppe grassland ecosystem.

In the first phase of the project (2004-2007) the main objectives regarding soil physical properties were to investigate the effect of different grazing intensities and exclusion from grazing on soil stability, alteration of soil functions and water budgets of grassland soils on a plot scale. Within these studies four differently grazed plots situated in the *Leymus chinensis* steppe were investigated: ungrazed since 1979, ungrazed since 1999, winter grazed (with 0.5 sheep units/ha) and overgrazed (with 3 sheep units/ha). The results showed that grazing had a significant effect on soil hydraulic and mechanical properties and soil functions. Furthermore, this effect was more pronounced the higher was grazing intensity.

In the second phase of the project (2007-2010) the area of investigation was expanded, and a *Stipa grandis* steppe ecosystem was included into investigations. Comparison of the *Leymus chinensis* (LCh) and *Stipa grandis* (SG) steppe ecosystems is of importance since these two steppe ecosystems account for approximately 60 % of the Xilin River Basin and are dominant grassland types of the semiarid grassland area in Inner Mongolia (Wang et al., 2005). These two steppe ecosystems are characterized by domination of different plant species (*Leymus chinensis* and *Stipa grandis*) however their distribution in the area of the Xilin River Basin is not the same. While LCh prefers wetter and more fertile areas, the SG can grow at drier and leaner locations (Chen et al., 2005a). The main objective of the second phase of the MAGIM project was to test the portability of findings from *Leymus chinensis* steppe for *Stipa grandis* steppe and, therefore, to ensure that the land cover type "typical steppe" is well represented in experiments.

Under the framework of the MAGIM project the main objectives were:

- to investigate soil physical (hydraulic and mechanical) properties of *Stipa grandis* steppe ecosystem;
- to characterize and compare soil physical properties depending on grazing intensity and vegetation type (*Stipa grandis* and *Leymus chinensis*).

For the following analyses three major hypotheses were formulated and answered:

1) grazing leads to alteration of soil mechanical strength and functions on aggregate and bulk soil scale; the alteration of soil physical properties differs depending on the moisture conditions;
2) grazing leads to changes in soil structure and has an influence on soil compressible behavior;
3) together with changes in soil structure also direction-dependent soil functions are altered due to grazing.

A detailed analysis of described above problems is presented in this work and concerns three different problems as follows:

Objective I

Until now, the studies on the effect of grazing on soil physical properties of Inner Mongolian grassland ecosystem regarded changes in soil mechanical and hydraulic properties and soil functions depending on grazing intensity only. However, the spatial variability of soil properties depending on different vegetation type was not taken into account during previous investigations. As stated above, the *Leymus chinensis* and *Stipa grandis* steppe ecosystems are dominant grasslands at the Xilin River watershed. Furthermore, the appearance of the *Leymus chinensis* and *Stipa grandis* plant species depends on the moisture conditions. Although these two grasses are capable of drought tolerance, they prefer slightly different areas with respect to moisture. It is reasonable to assume that soil physical properties will differ depending on a water budget and a vegetation type. It is known that the wetter the soil the weaker it is, thus, one would expect that soil degradation under wetter conditions (*Leymus chinensis*) will be more pronounced compared to the drier conditions (*Stipa grandis*) and thus the strength of the soil and hydraulic properties will also vary. Furthermore, we can expect different degree of soil structure reformation after livestock removal at these two sites which is related to differences in intensities of swelling and shrinkage, differences in biological activities, root development etc. Therefore, the aim of the first part of the Chapter III (Publications) entitled: **"Influence of grazing on hydraulic and mechanical properties of semiarid steppe soils under different vegetation type in Inner Mongolia, China"** is (i) to investigate how far can the soil hydraulic and mechanical properties vary due to grazing and exclusion from grazing under different (*Leymus chinensis* and *Stipa grandis*) vegetation type on plot scale. In addition, because the properties of the whole soil system depend strongly on the properties of single aggregates, therefore the second aim was (ii) to evaluate the variability of soil hydraulic and mechanical properties on aggregate and plot scale depending on grazing intensity and vegetation type.

Objective II

Deterioration of factors defining soil physical quality induced by animal trampling relates to soil deformation through compaction and homogenization (Drewry, 2006) which lead to differentiation of soil strength. In order to define the soil sensitivity or susceptibility to compaction it is important to estimate its internal strength and the stress-dependent changes in hydraulic and pneumatic properties The compressibility of soil depends on degree of aggregation as well as the maximum stresses that soil experienced in the past. It can be expected that, when applying repeatedly the same stress to soil, higher susceptibility to compaction i.e. higher compressibility can be expected in soil which is characterized by a better structure compared to the soil which is already compacted. These expectations would be reasonable when comparing the ungrazed treatment (which is supposed to have better soil structure) with the grazed one. Since the stresses exerted by grazing animals have mostly a cyclic nature, soil deformation and differentiation of soil strength in Inner Mongolian grassland is mostly related to repeated loading and unloading. It is, therefore, important to compare the soil behavior under static and cyclic loadings. A negative influence of animal tramping on various soil physical properties was studied widely (as introduced before) while the effect of repeated loading induced by grazing animals on soil compressibility is rarely carried out (e.g., Peth and Horn, 2006). Previous studies, conducted in the *Leymus chinensis* steppe ecosystem indicated differences in soil strength between the soil loaded in static and cyclic way at this site (Krümmelbein et al., 2008). However, in order to characterize susceptibility of soil to compaction at the Xilin River Basin more accurately, it is necessary to characterize also changes in soil compressibility of the *Stipa grandis* grassland. Therefore, the aim of the second part of the Chapter III (Publications) entitled: **"Grazing effects on compressibility of Kastanozems in Inner Mongolian steppe ecosystem"** is to investigate the consequences of animal trampling on soil compressibility and stability of soil functions in the *Stipa grandis* grassland ecosystem in Inner Mongolia.

Objective III

Intensive soil structure deterioration due to animal trampling has consequences for alteration of soil functions which depend mainly on the continuity of the soil pore system. Destruction of continuity of pore network due to grazing is related to decline in the amount of pores as well as homogenization and rearrangement of aggregates and particles. Furthermore, occurrence of platy soil structure is accompanied by changes in direction-depended soil functions. These effects can be partly or fully reversed during the process of soil reformations followed by exclusion the areas from grazing. Because the hydraulic conductivity and air permeability are the properties which define the pore continuity the best, it is important to determine these soil physical properties, especially with respect to direction. A comparison of direction-dependent soil properties at the *Leymus chinensis* and *Stipa grandis* grassland ecosystems would provide us information about alteration of soil functions depending on different moisture conditions. Therefore, the aims of the third part of the Chapter III (Publications) entitled: **"Influence of grazing on soil water and gas fluxes of two Inner Mongolian steppe ecosystems"** are (i) to determine how far does grazing affect soil functions with respect to different vegetation type; (ii) how much can exclusion from grazing improve soil functions in different steppe ecosystems; (iii) how much does anisotropy of soil functions change under different moisture conditions.

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CHAPTER III

(Publications)

INFLUENCE OF GRAZING ON HYDRAULIC AND MECHANICAL PROPERTIES OF SEMIARID STEPPE SOILS UNDER DIFFERENT VEGETATION TYPE IN INNER MONGOLIA, CHINA

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ABSTRACT

Over the last few decades, due to increase in grazing intensity, animal trampling has led to soil structure deterioration in Inner Mongolia, China. We investigated two different steppe ecosystems: *Leymus chinensis* (LCh, characterized by relatively higher precipitation) and *Stipa grandis* (SG) and two grazing intensities: ungrazed since 1979 (UG79) and grazed (continuously grazed, CG, at the *Stipa grandis* site and winter grazed, WG, at *Leymus chinensis*). Soil mechanical and hydraulic properties of semiarid steppe soils from each site and treatment were determined for soil aggregates and disturbed and bulk soil samples from different depths (4-8, 18-22, 30-34 and 56-60 cm for disturbed and bulk samples and 0-15 cm for the aggregates). Grazing causes a significant increase in tensile strength of aggregates and in the precompression stress of the bulk soil as well as a decrease in air and saturated hydraulic conductivity, irrespective of the vegetation type. Furthermore, exclusion from grazing led to more pronounced recovery of soil strength and pore continuity and hydraulic conductivity at the LCh site but it also depended on the moisture conditions of the sites. Under wetter conditions as well as after repeated freezing and thawing the soil strength declined.

Keywords: *grazing; precompression stress; aggregate tensile strength; repellency index; steppe*

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INTRODUCTION

It is well known that a good, well aggregated soil structure is important for plant development, water availability and balance, gas transport, soil workability as well as soil strength. Soil structure formation is a long-term process caused by swelling and shrinkage, flocculation or cementation and biological stabilization (Bronick and Lal, 2005). The main physical, chemical and biological processes are summed up in ***Table 3.1.1.***, based on common knowledge in the literature.

Table 3.1.1. Main processes influencing aggregate formation together with corresponding literature

Aggregate formation	
Processes	**Literature**

physical
• thermal
  ○ freezing/thawing
• hydraulic
  ○ wetting/drying
  ○ maximum drying intensity and duration
  ○ maximum hydraulic gradient
  ○ wettability, contact angle
• mechanical
  ○ stress/strain
  ○ shear effects
	○ Bachmann et al., 2003
	○ Czurda and Hohmann, 1997
	○ Feng et al., 2007
	○ Horn and Smucker, 2005
	○ Horn et al., 1994
	○ Mbagwu and Bazzoffi, 1989
	○ Oades, 1993
	○ Oztas and Fayetorbay, 2003
	○ Pires et al., 2008
	○ Shoop et al., 2008

chemical
• inorganic precipitation
• organic bonding
  ○ organic composition
  ○ root exudates
	○ Ashman et al., 2009
	○ Bullinger-Weber et al., 2007
	○ Hallett and Young, 1999
	○ Hallett et al., 2001
	○ Jastrow, 1996
	○ Semmel et al., 1990
	○ Six et al., 2004
	○ Tisdall and Oades, 1982

biological • fauna • flora → plants → roots	○ Görres et al., 2001 ○ Hallaire et al., 2000 ○ Jongmans et al., 2003

Most studies about the changes in soil structure are focused on the effect of anthropogenic processes such as plowing, amelioration or excavation and reclamation. However, when talking about a structural degradation of grassland soils, the most significant factor that leads to changes in soil properties is animal trampling (Yong-Zhong et al., 2005). It is important to mention that the stresses exerted by sheep have similar influence on soil as agricultural machinery, however, due to smaller contact area, the soil deformation restricts only to the upper 15 cm soil layer (Greenwood and McKenzie, 2001). Grazing affects the grassland environment by a reduced vegetation cover followed by decrease in organic matter content in the topsoil and an increase in soil erosion by wind and coarsening of the soil surface (Yong-Zhong et al., 2005). Furthermore, an intensive grazing leads to a significant formation of platy soil structure caused by high ground pressure of hooves. As a consequence, not only the mechanical strength but especially anisotropy of soil physical properties can take place (Krümmelbein et al., 2006). Due to shearing, intensive grazing leads to rearrangement of soil particles as well as to soil homogenization (Drewry, 2006). Thus, animal trampling results in an increase in soil bulk density and hardness, reduction in soil porosity, decrease in pore continuity, hydraulic and air conductivity or an increase in penetration resistance and precompression stress (Horn, 1986).

One of the most important and renewable, but sensitive resources in arid and semiarid regions of northern China is natural grassland (Chen et al., 2005). In the Chinese steppe regions, such as Inner Mongolia, grazing is a dominant way of land use. However, a decline in grassland productivity and serious grassland degradation in this area due to overgrazing were recently observed.

In our studies we investigated the ungrazed and grazed sites of the two main steppe types in Inner Mongolia: *Stipa grandis* and *Leymus chinenesis*. We focused on the questions: how does grazing and exclusion from grazing affect soil structure deterioration and formation and how far can these processes vary depending on the vegetation community. In order to answer these questions, we investigated soil mechanical and hydraulic properties for these two vegetation types on three scales i.e. disturbed and undisturbed soil samples and single aggregates.

MATERIALS AND METHODS

Study location

The studies were conducted in Inner Mongolia, P. R. China, at the Xilin River Catchment, around 450 km North from Beijing, close to Inner Mongolian Grassland Ecosystem Research Station (IMGERS, Institute of Botany, Chinese Academy of Sciences; 43°38' N, 116°42' E). The investigated area is situated in the semiarid steppe ecosystem at the altitude of 1,270 m above sea level. The climate in this region is typical for semiarid grasslands of China and is characterized as dry and cold in the temperate steppe zone. The mean annual temperature is around 0.7°C with the coldest and the warmest mean annual temperatures of -40°C and 33°C, respectively. The mean annual precipitation at IMGERS is 340 mm, and 75% of it falls in the summer months. A growing season lasts about 150 days from the beginning of April until late September. A frost-free period is around 100 days (Bai et al., 2004).

Two different experimental sites (steppe ecosystems), characterized by domination of the two plant species: *Stipa grandis* (SG) and *Leymus chinensis* (LCh), which are dominant at the Xilin River Basin, were investigated. Together they account for approximately 60% of the catchment (Chen et al., 2005). The SG and LCh sites were situated at a distance of approximately 30 and 8 km south-west from IMGERS, respectively. The LCh steppe ecosystem is characterized by relatively higher precipitation (408 mm) compared with the SG (361 mm) site. The soils in this area were derived from fine-sand aeolian sediments on a basalt plateau and were classified according to the World Reference Base for Soil Resources (WRB) as Calcic Chernozems and Kastanozems at the LCh and the SG, respectively.

Grazing experiments

Two treatments, characterized by different grazing intensity were studied: ungrazed since 1979 (UG79) and grazed, G (continuously grazed, CG, at the SG site and winter grazed, WG, at the LCh).

Until 1979 the whole area of the SG site was grazed with a low grazing intensity. In 1979 an area of approximately 23 ha was fenced and excluded from grazing. Since then this treatment has not been grazed and represents the state of the environment without grazing. The remaining area of 19 ha was continuously grazed and since 1995 grazing by 200 animals took place every day for 2-3 h. At this site the herd consists of around 75% sheep and 25% goats. The grazed area of the SG site is not fenced and therefore the grazing intensity can vary throughout the year.

Until 1979 the whole experimental area of LCh site was grazed with low intensity. In 1979 the area of around 24 ha was fenced and excluded from grazing. Until today no grazing was done at this treatment. After 1979 the grazing intensity on the remaining area increased to a moderate level. In 1999 another 34 ha area was fenced and grazed only during winter time with a grazing intensity of 0.5 sheep units/ha (1 sheep unit is one sheep with one lamb). The herd at the LCh site consists of 70-90% sheep and 10-30% goats.

Sampling design

The soil samples were collected in summer 2004 – 2006 (at LCh site) and 2007 – 2008 (at SG and LCh sites). Because soil physical properties can vary spatially within the sites, we took soil samples from three replicate profiles situated at a distance of approximately 15 m from each other per site and treatment. Disturbed soil samples, soil aggregates and bulk soil samples were taken under vegetation communities (SG and LCh). Disturbed and undisturbed soil samples were collected from four different depths (4-8, 18-22, 30-34 and 56-60 cm) representing each soil horizon. Soil aggregates were collected from the first 0-15 cm of the soil.

The disturbed soil samples were used to determine soil texture and the contact angle of the investigated sites. The soil texture class was determined for all investigated horizons for each treatment.

To investigate aggregate tensile strength and repellency, soil blocks (undisturbed soil) from the top 0-15 cm depth of all profiles were taken.

The water retention characteristics (total porosity, air capacity and plant available water) and saturated hydraulic conductivity (k_s) were determined for 7 undisturbed soil samples from each soil horizon using 100 cm^3 stainless steel cylinders (40 mm height and 56 mm diameter). In addition, for determination of the anisotropy of the saturated hydraulic conductivity, 7 additional soil samples were taken in horizontal direction from the topsoil.

The mechanical properties (static loading and cyclic loading) were determined for 5 undisturbed soil cores sampled using 236 cm^3 stainless steel cylinders (30 mm height and 100 mm diameter) from two topsoil horizons from each site and soil profile. The anisotropy of soil mechanical properties was measured for 5 undisturbed samples collected in the horizontal direction from two upper depths from SG, but not from LCh.

Additionally, the effect of animal trampling on air conductivity (k_a) was analyzed with 5 samples from the topsoil of each investigated site applying the cyclic loading test at defined predrying and cycles (frequency and loading duration).

Laboratory measurements

Particle size distribution, bulk density, water retention characteristics and contact angle

Soil texture was measured using the method described by Schlichting et al. (1995). Soil texture classes were defined according to FAO/USDA soil classification system.

To obtain the water retention characteristics, all undisturbed soil samples were saturated and equilibrated to a matric potential of - 3 kPa on a sand box, or the matric potentials of -6, -15, -30, -50 kPa using ceramic porous plates and to matric potential of -1,500 kPa using the pressure method (Schlichting et. al., 1995; Hartge and Horn, 2009). The bulk density (BD) values were determined by oven-drying. The air capacity (AC) was defined as the difference between the total porosity (TP) and the water content at -6 kPa matric potential. The air capacity was equivalent to the amount of wide coarse pores (diameter bigger than 50 μm) in the soil. The plant available water (PAW) was calculated from the difference between volumetric water content at field capacity (the matric potential of -6 kPa) and wilting point (the matric potential of -1,500 kPa).

The contact angle was measured with the Wilhelmy-plate method according to Bachmann et al. (2003).

Tensile strength of aggregates and repellency index

The tensile strength and repellency index of the dominant 1-2 cm soil aggregate fraction (taken from each soil block) were analyzed depending on vegetation type (SG and LCh) and grazing intensity (UG79 and G). The aggregates were saturated for 2 days using water vapor and then one set of aggregates was drained to a matric potential of -30 kPa using ceramic porous plates and another set of samples was dried at a temperature of 40˚C for 2 days. We used 60 aggregate replicates for each treatment. After adjusting the matric potentials all soil aggregates were weighted and the sorptivity of water and ethanol for each of them was measured (for more details see Hallett and Young, 1999). After the sorptivity measurement, an average diameter (3 directions) of each aggregate was measured using a caliper. Thereafter, the soil aggregates were crushed in a loading frame (INSTRON, 5569) and dried in oven at a temperature of 105˚C for 24 hours. The repellency index of the soil aggregates was calculated using a method described by Hallett and Young (1999). The values of repellency index higher than 1.95 indicated soil repellency. The tensile strength was calculated using the method described by Dexter and Watts (2000).

The influence of repeated freezing and thawing on tensile strength of the soil aggregates was determined for 60 aggregate samples from each treatment of the SG site which were separated gently from the soil blocks. Two different sets of samples were prepared: the first one (control) without- and the second one with the application of the freezing/thawing cycles. Prior to the measurement, all aggregates were saturated and then, each set of samples was adjusted to two different matric potentials: one group of samples was drained to the matric potential of - 30 kPa while the second group was air dried for a period of 2 weeks. After adjusting the matric potentials, the tensile strength was measured for the first set of aggregates. The other set of aggregates was placed into a freezer and 15 freezing/thawing cycles (1 freezing/thawing cycle consisted of one day freezing at temperature of -10˚C and one day of thawing at room temperature) were adjusted. After the last freezing/thawing cycle the aggregate tensile strength was determined.

Precompression stress

The mechanical properties of the bulk soil were determined using static and cyclic loading tests. Before the tests, the soil samples were saturated and then equilibrated to a standard matric potential of -30 kPa. The static loading test was performed by a standard oedometer device. The cyclic loading test (repeated loading and unloading) was performed using a multistep-oedometer device. Both tests were done under confined and drained conditions (for more details see Peth et al., 2010).

The precompression stress for static and the repeated loading (the first and the last, 20th, cycle of each load) was calculated using the method introduced by Casagrande (1936), described by Hartge and Horn (2009).

Air conductivity

The air conductivity (k_a) was measured on soil samples predrained to a matric potential of -30 kPa before and after each load of the repeated loading test (the method: see Peth, 2004). Each sample was stressed dynamically within 40 to 400 kPa with a frequency of 20 cycles (30 s loading and 30 s unloading each).

Saturated hydraulic conductivity

The saturated hydraulic conductivity (k_s) was measured by the falling head method described by Hartge and Horn (2009).

The anisotropy coefficient for the saturated hydraulic conductivity was calculated as the ratio of the values measured in horizontal direction to values measured in vertical direction.

Statistical analyses

The statistical analyses were done using the R 2.5.1 software (Venables et al., 2009). The normal distribution of data was tested using Shapiro-Wilk test of normality. The statistically significant differences between samples were determined in Wilcoxon and T-tests. The results were classified as statistically significantly different at $p<0.05$. For graphical visualization of soil mechanical properties as well as air and saturated hydraulic conductivity, box plots were chosen. In each box plot the information about the median value (black line across each box), lower and upper hinges (defined as the 25th and 75th percentiles), minimum and maximum values as well as outliers were shown. The notches indicated 95% confidence interval of differences between medians (further information, see: McGill et al. 1978). The box plots can be used not only for presenting normally distributed data but are an appropriate method of presenting not-normally distributed data for which no additional transformation into logarithms is needed.

RESULTS

Particle size distribution, bulk density, water retention characteristics and contact angle

The soil texture classes of the SG and LCh sites are identical (***Table 3.1.2.***) and are classified as sandy loam (FAO/USDA).

In the first depth at both treatments the bulk density (BD) was significantly higher at the SG compared with the LCh; furthermore the bulk density was significantly higher in the top 4-8 cm depth of SG CG compared to the SG UG79. At LCh the bulk density was significantly higher in the second depth compared with the topsoil (4-8 cm) which was true for both investigated treatments. At SG the bulk density differed significantly between both depths at UG79.

Table 3.1.2. Particle size distribution, bulk density (BD), water retention characteristics (total porosity, TP; air capacity, AC and plant available water, PAW) and contact angle of two investigated sites (*Leymus chinensis* and *Stipa grandis*) and two different treatments: ungrazed since 1979 (UG79) and grazed (continuously grazed, CG, at the *Stipa grandis* site and winter grazed, WG, at *Leymus chinensis* site) for four depths: 4-8 cm, 18-22 cm, 30-34 cm and 56-60 cm; numbers in bold indicate the mean values; italic numbers indicate median values; standard deviation is shown in brackets; n.d. – not determined.

Site	**Treatment**	**Depth (cm)**	**Sand (%)**	**Silt (%)**	**Clay (%)**	**BD (g cm^{-3})**	**TP (vol %)**	**AC (vol %)**	**PAW (vol %)**	**Contact angle (˚)**
Stipa grandis	**UG79**	**4–8**	**62.3**	**25.1**	**12.6**	**1.27,** *1.29* (±0.08)	**52.0,** *51.4* (±2.8)	**11.9,** *10.9* (±4.1)	**31.5,** *31.6* (±3.3)	**45.7,** *45.1* (±4.9)
		18–22	**60.0**	**26.0**	**14.0**	**1.33,** *1.34* (±0.07)	**49.8,** *49.6* (±2.6)	**11.5,** *11.3* (±3.3)	**28.2,** *27.5* (±2.3)	**32.6,** *30.3* (±7.6)
		30–34	**55.7**	**28.7**	**15.7**	**1.37,** *1.33* (±0.08)	**48.5,** *49.8* (±3.1)	**9.5,** *9.9* (±2.6)	**28.1,** *27.4* (±2.8)	**28.2,** *28.9* (±5.0)
		56–60	**54.7**	**28.0**	**17.2**	**1.36,** *1.36* (±0.08)	**48.5,** *48.7* (±3.1)	**9.6,** *9.5* (±3.1)	**28.1,** *28.5* (±2.8)	**25.6,** *26.2* (±4.9)
	CG	**4–8**	**65.6**	**21.4**	**13.1**	**1.36,** *1.34* (±0.07)	**48.8,** *49.3* (±2.5)	**8.9,** *9.3* (±4.2)	**30.9,** *31.4* (±2.6)	**28.9,** *31.8* (±7.4)
		18–22	**62.3**	**24.1**	**13.6**	**1.35,** *1.35* (±0.06)	**49.2,** *48.9* (±2.3)	**13.5,** *12.6* (±3.2)	**24.8,** *24.0* (±4.3)	**22.3,** *19.7* (±11.2)
		30–34	**58.1**	**27.9**	**14.0**	**1.44,** *1.45* (±0.06)	**45.6,** *45.3* (±2.3)	**10.7,** *10.3* (±3.2)	**22.8,** *22.1* (±2.1)	**18.8,** *19.2* (±5.7)
		56–60	**65.5**	**21.4**	**13.1**	**1.41,** *1.43* (±0.09)	**46.7,** *46.2* (±3.4)	**12.7,** *12.6* (±3.8)	**24.6,** *24.4* (±2.4)	**14.6,** *12.7* (±8.0)
Leymus chinensis	**UG79**	**4–8**	**60.9**	**24.9**	**14.2**	**1.14,** *1.14* (±0.03)	**56.9,** *56.8* (±1.1)	**14.9,** *15.3* (±3.6)	**33.6,** *35.3* (±4.3)	**52.2,** *47.2* (±14.7)
		18–22	**64.5**	**21.8**	**13.8**	**1.39,** *1.41* (±0.09)	**47.6,** *46.6* (±3.5)	**11.3,** *10.5* (±4.8)	**33.0,** *33.0* (±0.6)	**35.8,** *36.8* (±2.4)
		30–34	**76.5**	**14.3**	**9.1**	**1.44,** *1.43* (±0.04)	**45.7,** *46.1* (±1.7)	**7.4,** *7.1* (±3.7)	**35.3,** *35.2* (±2.3)	**n.d.**
		56–60	**78.0**	**13.5**	**8.5**	**1.43,** *1.45* (±0.09)	**45.9,** *45.9* (±3.3)	**9.1,** *7.9* (±3.8)	**31.1,** *31.0* (±1.7)	**n.d.**
	WG	**4–8**	**51.6**	**30.2**	**18.2**	**1.17,** *1.17* (±0.06)	**55.8,** *55.9* (±2.3)	**15.2,** *17.2* (±5.0)	**30.5,** *29.9* (±2.7)	**87.4,** *87.8* (±1.73)
		18–22	**55.9**	**27.1**	**17.0**	**1.28,** *1.29* (±0.08)	**51.5,** *51.3* (±3.0)	**16.0,** *15.4* (±1.2)	**22.7,** *21.7* (±2.7)	**73.5,** *68.0* (±10.6)
		30–34	**55.1**	**28.8**	**16.4**	**1.27,** *1.26* (±0.07)	**51.9,** *52.5* (±2.7)	**4.2,** *3.8* (±1.2)	**38.1,** *37.6* (±2.0)	**n.d.**
		56–60	**56.2**	**27.7**	**16.1**	**1.33,** *1.32* (±0.10)	**49.9,** *50.1* (±3.6)	**1.9,** *1.4* (±1.3)	**32.6,** *31.9* (±3.1)	**n.d.**

The air capacity (AC) was significantly higher in the first depth of LCh WG than at SG CG while at SG CG the top 4-8 cm soil layer had a significantly lower air capacity compared with the second depth. At both treatments of SG the significantly lower plant available water (PAW) was found in the second depth. The same result was obtained for LCh WG.

In the top 4-8 cm soil layer of the UG79 treatments the contact angle remained similar for both vegetation types while the SG CG had significantly lower contact angle values than the SG UG79. If the two vegetation types are compared, the values of the contact angle of the topsoil at the grazed sites were significantly higher under LCh than under SG.

Tensile strength of aggregates and repellency index

The tensile strength values differed depending on the site, treatment and moisture conditions. Under wetter conditions (matric potential -30 kPa) the tensile strength was quite low for all investigated treatments (***Fig. 3.1.1.***) even if the LCh WG was characterized by significantly higher strength than the LCh UG79.

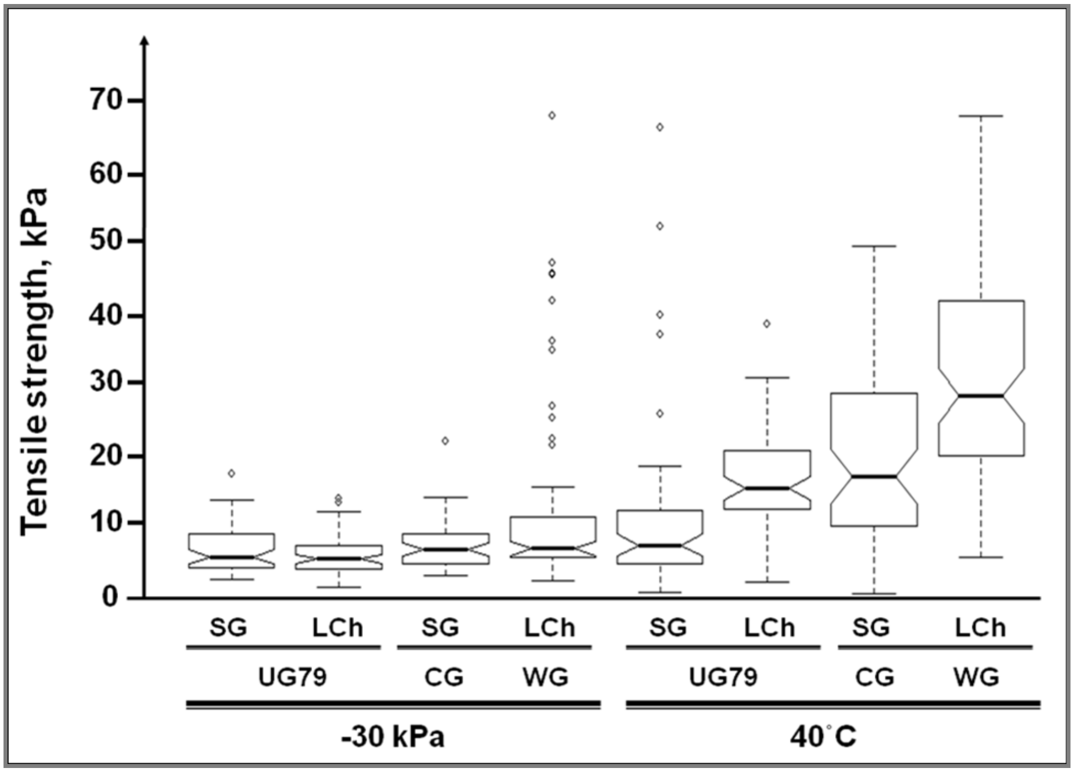

Fig. 3.1.1. Tensile strength of aggregates of two investigated sites (*Leymus chinensis*, LCh, and *Stipa grandis*, SG), two different treatments (ungrazed since 1979 (UG79) and continuously grazed (CG) for the *Stipa grandis* site and winter grazed (WG) for the *Leymus chinensis* site), and two different moisture conditions (-30 kPa and 40˚C); depth: 0-15 cm; n=60

With drying (40°C) the tensile strength values increased. Under drier conditions significantly higher tensile strength was found at LCh site compared with the SG in both treatments and at WG and CG sites compared with the UG79. Repeated freezing and thawing significantly reduced the aggregate tensile strength irrespective of the treatment (***Fig. 3.1.2.***).

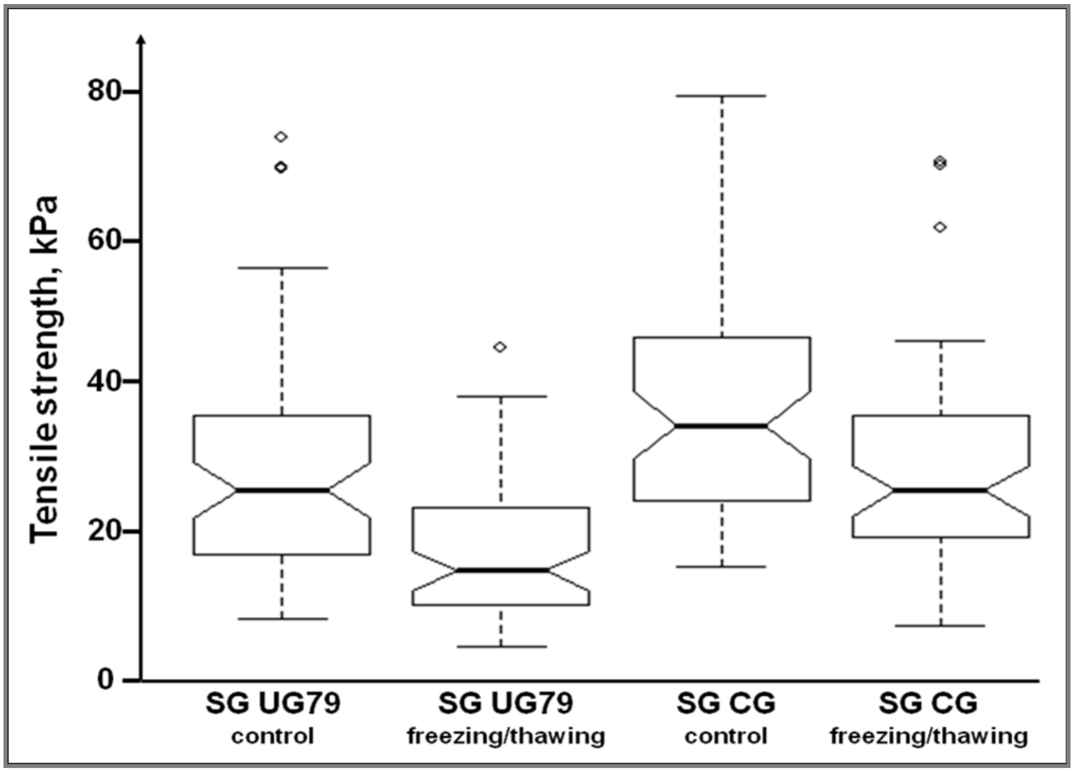

Fig. 3.1.2. Tensile strength of air dried aggregates for the *Stipa grandis* (SG) site for two different treatments (ungrazed since 1979, (UG79), and continuously grazed (CG)) without (control) and with the application of freezing/thawing cycles, depth: 0-15 cm; n=60

Furthermore, the LCh site was characterized by significantly higher values of repellency index compared with the SG irrespective of the moisture conditions (***Fig. 3.1.3.***). At the matric potential of -30 kPa the grazed and ungrazed treatments did not differ significantly. Under drier conditions, however, the repellency index of the LCh UG79 was significantly higher compared with the LCh WG.

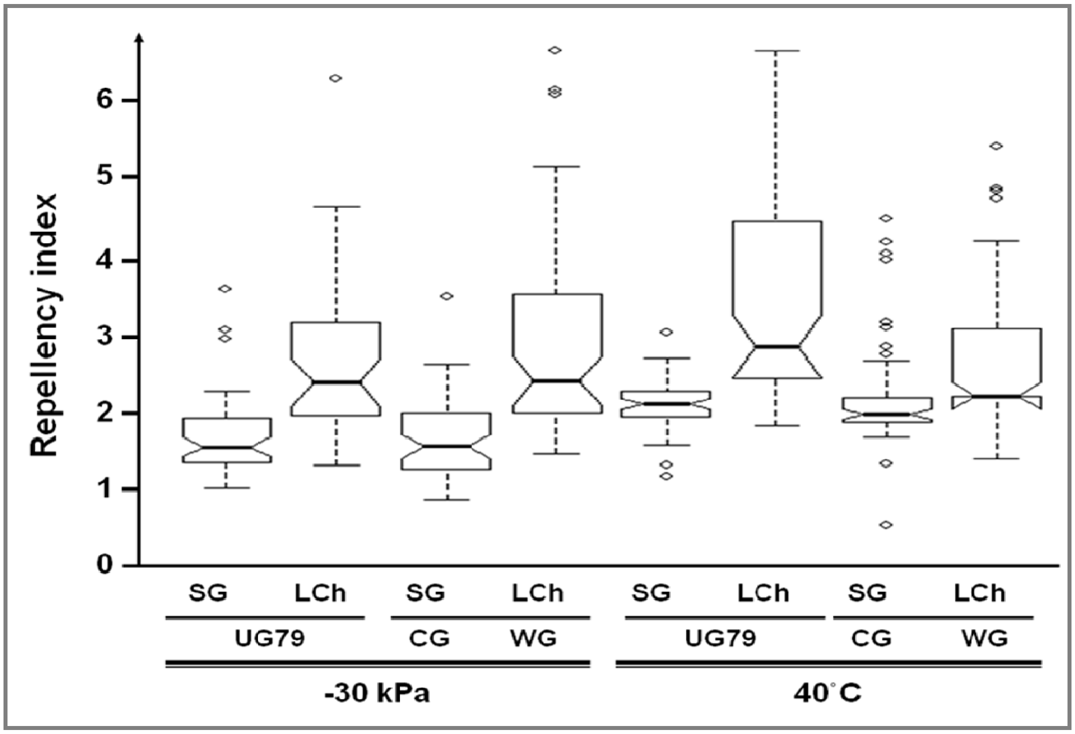

Fig. 3.1.3. Repellency indices of aggregates for two investigated sites (*Leymus chinensis*, LCh, and *Stipa grandis*, SG), two different treatments (ungrazed since 1979 (UG79) and continuously grazed (CG) for the *Stipa grandis* site and winter grazed (WG) for the *Leymus chinensis* site) and two different moisture conditions (-30 kPa and 40°C); depth: 0-15 cm; n=60

Precompression stress

The precompression stress values at the SG site were higher than at LCh for both treatments and depths (***Fig. 3.1.4.***). The highest values of precompression stress were found in the topsoil of SG CG (median value of 106 kPa) and the lowest in the topsoil of LCh UG79 (median value of 30 kPa). In the 4-8 cm soil layer the precompression stress was significantly higher at the WG and CG treatments than at the UG79 ones. All further data between depths and treatments did not differ significantly.

The treatment dependent anisotropy of the precompression stress values showed significantly higher precompression stress values in vertical direction for the SG CG site in the topsoil while neither the SG UG79 (***Fig. 3.1.5.***) nor the second soil horizon showed significant differences between the precompression stress values in vertical and horizontal direction.

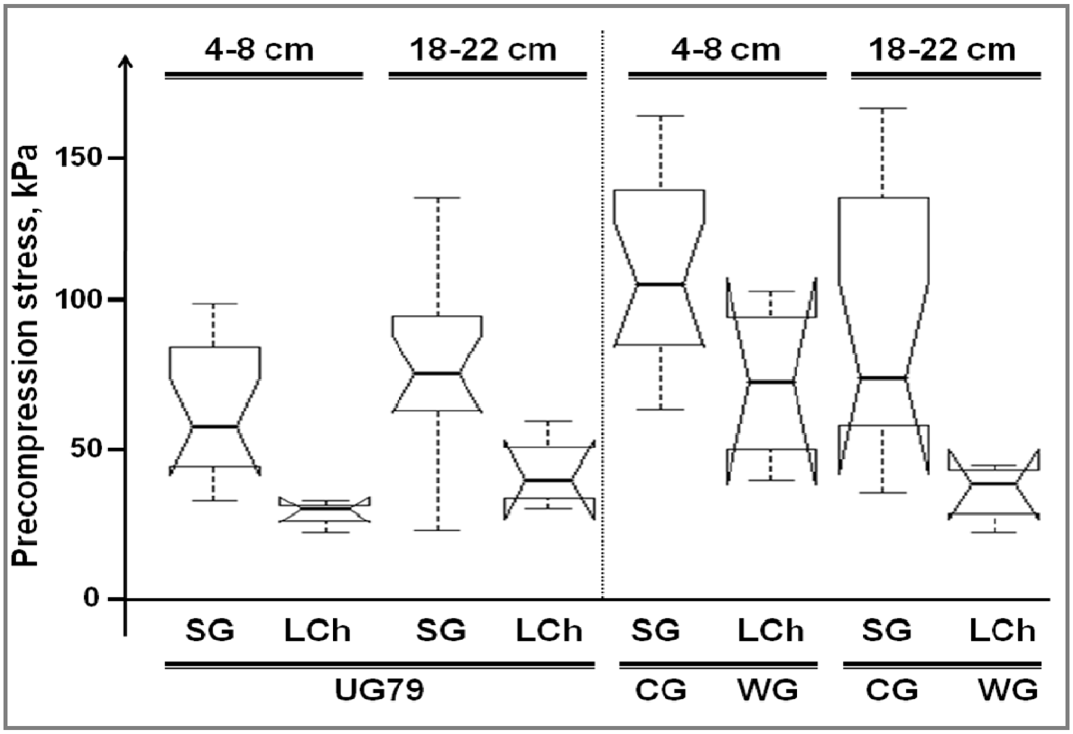

Fig. 3.1.4. Precompression stress values (static loading) for two investigated sites (*Leymus chinensis*, LCh, and *Stipa grandis*, SG), two different treatments (ungrazed since 1979 (UG79) and continuously grazed (CG) for the *Stipa grandis* site and winter grazed (WG) for the *Leymus chinensis* site) and two depths: 4-8 and 18-22 cm; n=15

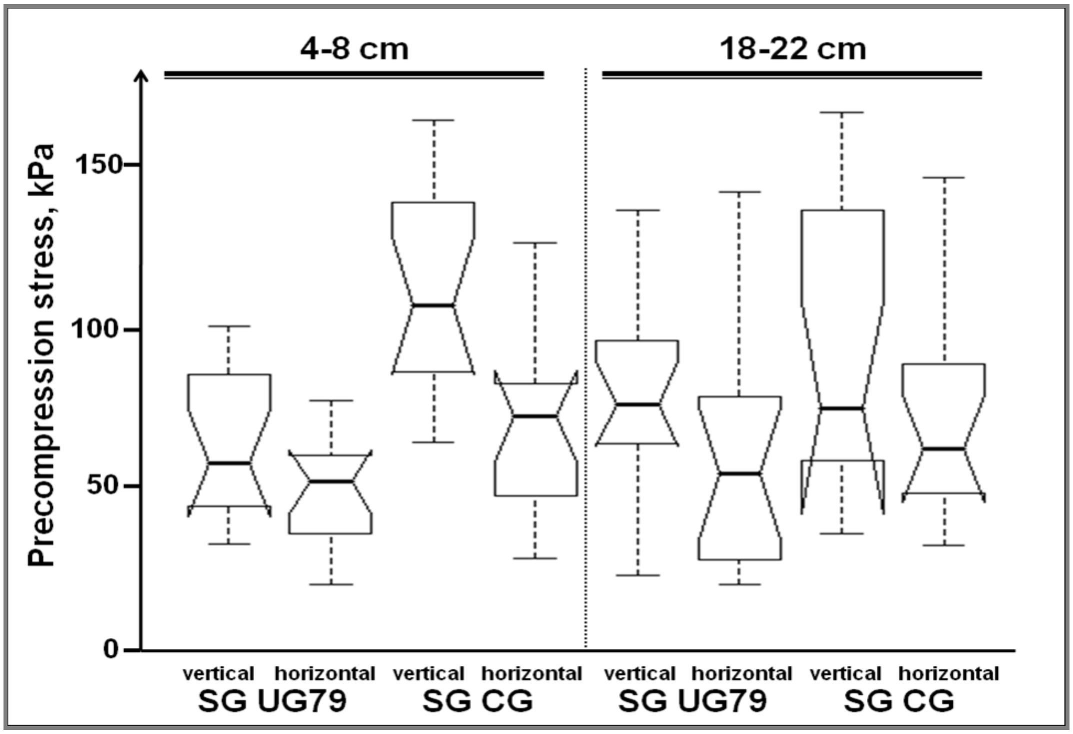

Fig. 3.1.5. Precompression stress values (static loading) of the *Stipa grandis* site (SG) for two different treatments: ungrazed since 1979 (UG79) and continuously grazed (CG) and two different directions (vertical and horizontal); depths: 4-8 and 18-22 cm; n=15

The comparison of the precompression stress values determined via static or cyclic loading (1st cycle and 20th cycle) tests showed a general trend that for the UG79 sites the precompression stress of the cyclically loaded samples was higher than of those loaded statically (***Fig. 3.1.6.***). Furthermore the precompression stress obtained from the settlement of the 1st cycle was significantly higher compared with the last, i.e. the 20th cycle. At SG CG a general trend of a decrease in precompression stress due to application of repeated loading was found. At the LCh WG site the values of precompression stress remained similar for both types of loading tests.

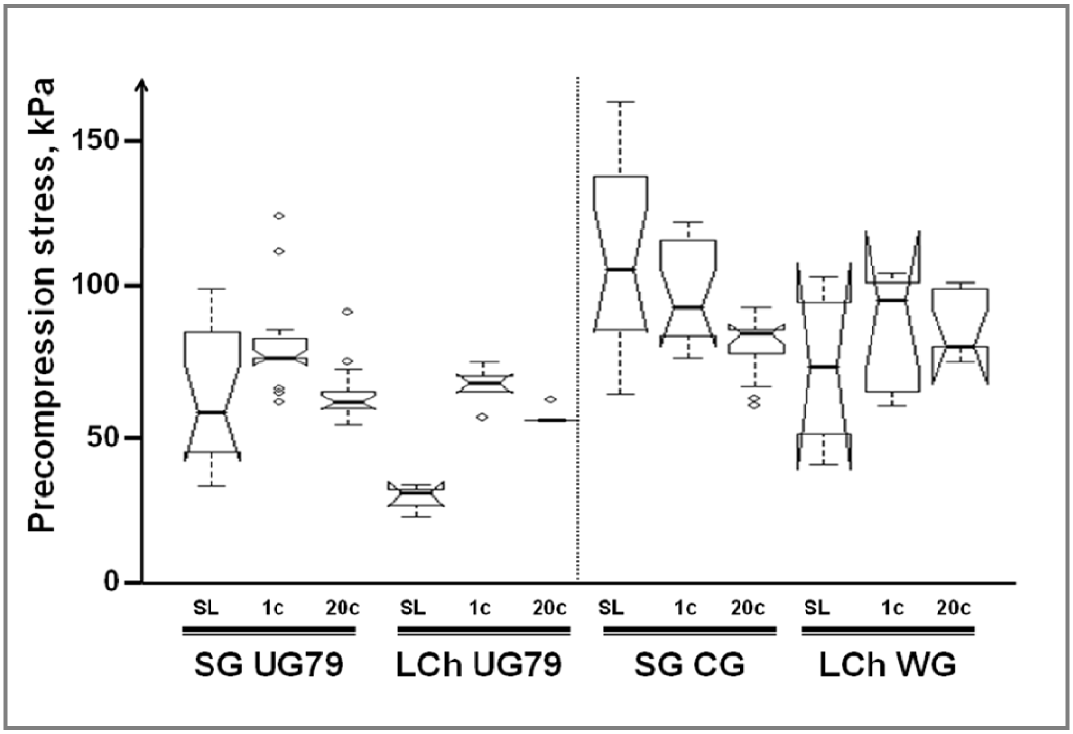

Fig. 3.1.6. Precompression stress values determined via static loading (SL) and cyclic loading (1st and 20th cycle) for the *Stipa grandis* (SG) and *Leymus chinensis* (LCh) sites and two treatments (ungrazed since 1979 (UG79) and continuously grazed (CG) for the *Stipa grandis* site and winter grazed (WG) for the *Leymus chinensis* site); depth: 4-8 cm; n=15

Air conductivity

The original air conductivity values of the WG and CG treatments were smaller than of UG79 ones and differed significantly at LCh site between both treatments. The air conductivity (k_a) as a function of the cyclic stress differed between SG and LCh sites (***Fig. 3.1.7.*** and ***3.1.8.***) but the decline in air conductivity after each load was smaller at the SG UG79 than at LCh UG79. If we consider the effect of the cyclic loading with 40 kPa a high decline in air conductivity at SG CG was observed. Higher stresses applied did not lead to further remarkable changes in air conductivity at this site.

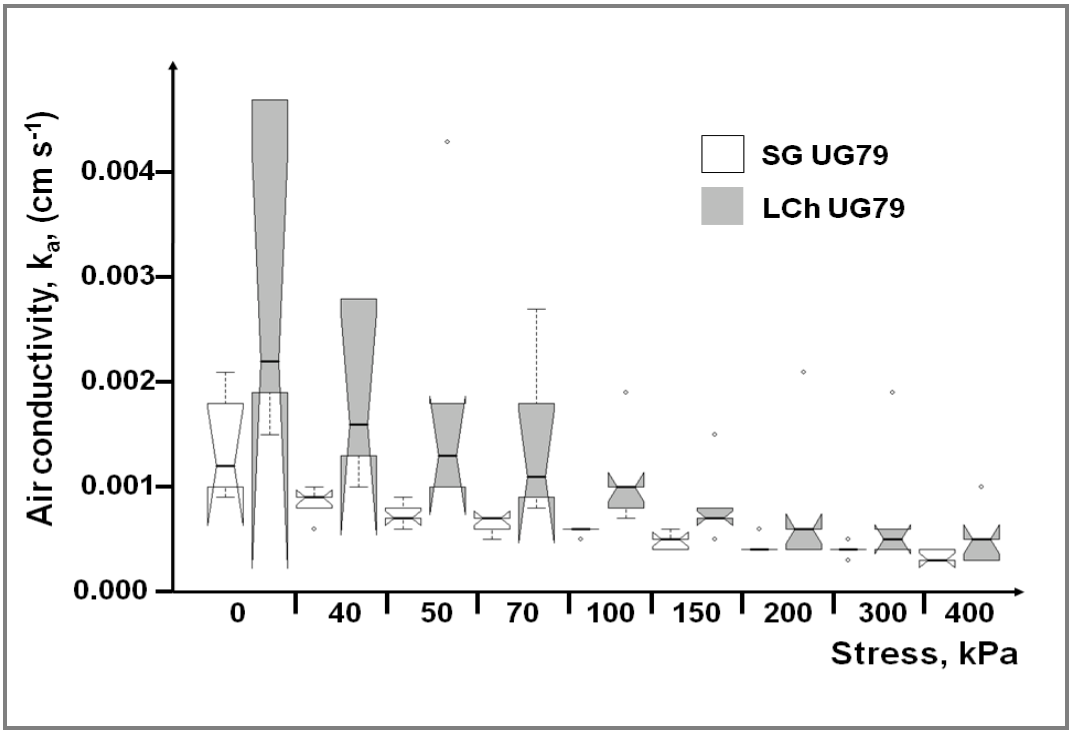

Fig. 3.1.7. Air conductivity of ungrazed (UG79) treatment of *Stipa grandis* (SG) and *Leymus chinensis* (LCh) sites determined before (0 kPa) and after each load; depth: 4-8 cm; n=5

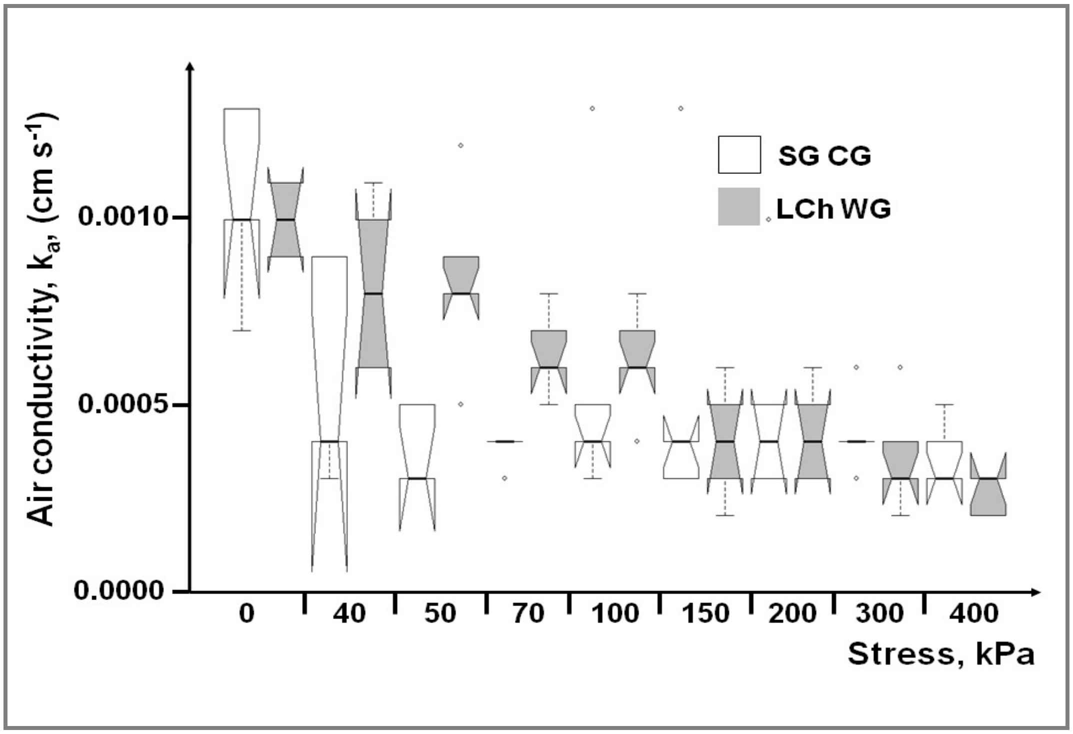

Fig. 3.1.8. Air conductivity of grazed treatment of *Stipa grandis* (SG CG) and *Leymus chinensis* (LCh WG) sites determined before (0 kPa) and after each load; depth: 4-8 cm; n=5

Saturated hydraulic conductivity

The saturated hydraulic conductivity (k_s) was significantly higher at SG compared to LCh site and significantly higher at UG79 treatments compared with WG and CG (***Fig. 3.1.9.***). Furthermore, at the SG UG79 site, slightly higher k_s values in horizontal compared with the vertical direction were found. At SG CG, the anisotropy in horizontal direction was detected while the opposite was found at LCh WG.

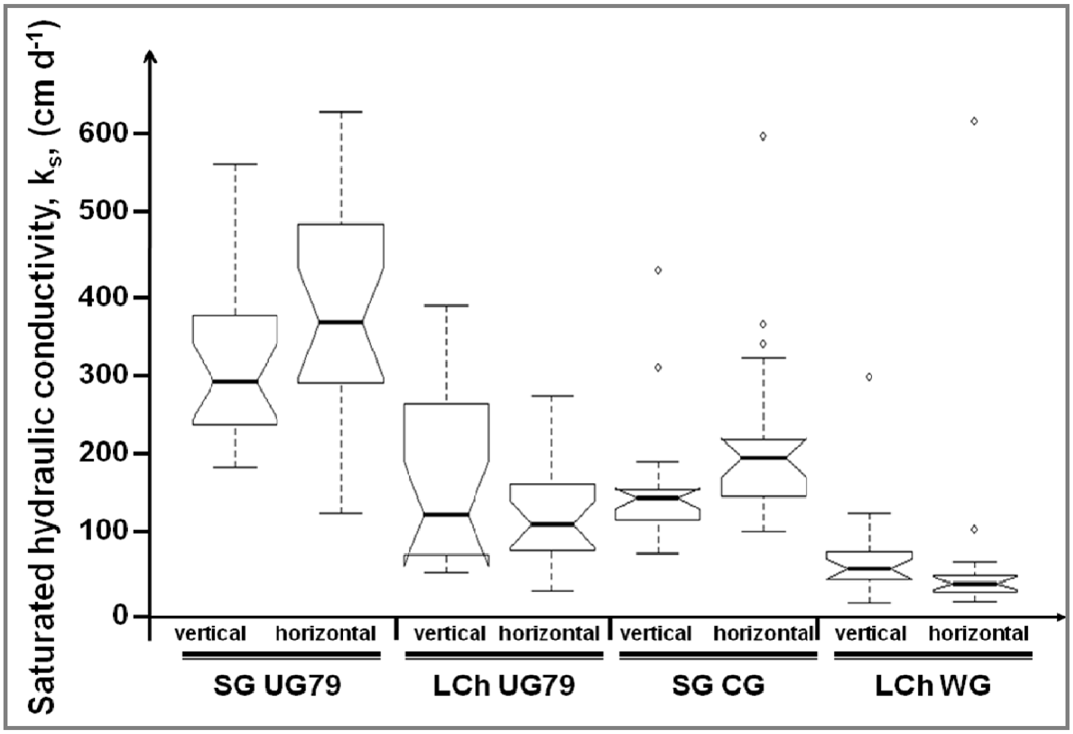

Fig. 3.1.9. Saturated hydraulic conductivity (k_s) for two sites *Stipa grandis* (SG) and *Leymus chinensis* (LCh), two treatments (ungrazed since 1979 (UG79) and continuously grazed (CG) for the *Stipa grandis* site and winter grazed (WG) for the *Leymus chinensis* site) and two different directions (vertical and horizontal); depth: 4-8 cm; n=21

DISCUSSION

It is known that mechanical properties of aggregates can indicate the response of a soil system to compaction, tillage or plant growth (Blanco-Canqui et al., 2005). The tensile strength is described as a mode of soil failure when the soil breaks into smaller pieces without disturbing the soil microstructure (Munkholm et al., 2002). Aggregate tensile strength is a common method of determination of aggregate mechanical strength. The differences in tensile strength of aggregates between sites and treatments can be related to differences in matric potential, mechanical stress application and textural differences.

It was widely studied that compaction leads to increase in strength of soil aggregates. Abid and Lal (2009) investigated the tensile strength of the soil ploughed with a chisel and the undisturbed soil. They found that lower values of tensile strength (175.3 kPa) were found in the no-tilled soil compared with the tilled one (281.3 kPa). Similar results described Munkholm et al. (2002). They determined the greatest tensile strength values in compacted soil but not in the non-compacted ones. This is also in agreement with our results, where the WG and CG sites had higher tensile strength values compared with the UG79 ones.

The differences in tensile strength between both sites were greater under drier conditions (40˚C) when the aggregates from LCh were stronger and more resistant to mechanical disturbance compared to SG irrespectively of the treatment. On the other hand if the soil water content is higher the soil aggregates become weaker. Our results showed that under wetter conditions (matric potential of -30 kPa) the tensile strength of aggregates did not differ significantly between both investigated sites. In addition, significant differences between treatments were observed only at LCh. Under wetter conditions the flattening and collapsing of the aggregates during the test decrease the inter-particle forces and result in less negative matric potential values. This is in agreement with the findings of Mosaddeghi et al. (2006).

The effect of freezing and thawing on changes in soil strength was studied widely (e.g. Oztas and Fayetorbay, 2003). It is well known that freezing and thawing can cause an increase in strength by pressing particles together. On the other hand freezing stress (expansion of water by 9%) causes a peeling off of the outer part of aggregates if the soil is originally strong (e.g. in plow pan just after plowing) and the stress is attenuated by the inner soil strength but the resistance to the atmosphere is nearly zero. Consequently such soil samples are weakened. In Inner Mongolia repeated freezing and thawing is one of the factors leading to soil structure recovery from grazing. The effectivity increases with the number of freeze-thaw cycles (Kværnø and Øygarden, 2006) and is even more pronounced when the water content in soil is higher prior to freezing (Oztas and Fayetorbay, 2003).

Our results confirmed these findings because we observed a decline in the tensile strength of aggregates after repeated freeze-thaw cycles. It is important to mention, that the decline in tensile strength was very clear even though the water content of the measured air dried samples was low (4-6%).

The reduction of water infiltration is controlled by physical, chemical and/or microbial processes leading to subcritical water repellency (Hallett et al., 2004). One of the most important factors affecting soil repellency is the organic matter content and type of organic carbon present in the soil (Urbanek et al., 2007). Our results showed that the LCh site was characterized by higher repellency index compared to SG, irrespective of the treatment and matric potential. At the LCh sites the values exceeded 1.95 which defines the beginning of repellency. Wiesmeier et al. (2009) investigated the spatial pattern of soil organic carbon at UG79 and at the continuously grazed sites in the topsoil of the LCh and SG steppe ecosystems in Inner Mongolia. They found that at the SG site the soil organic carbon contents were 28% lower at the ungrazed plots and at grazed ones 29% compared to the LCh site. Higher organic carbon content at the LCh than at the SG site can explain the differences in the repellency indices between the two investigated vegetation types and higher micro-stability of aggregates at the LCh site.

A very important factor that influences repellency of the soil is the moisture content. The water repellency is more pronounced in the dry soils and it vanishes when the soil becomes wet. Dekker and Ritsema (1996) investigated a degree of water repellency of peat soil samples collected from 20-25 cm depth and found that after drying at the temperature of 25˚C the soil was not completely dry and remained severely water repellent while after drying at 65˚C the completely dry soil exhibited extreme repellency. This is in agreement with our results where the repellency index was higher (except LCh WG) after drying at 40˚C compared with the aggregates drained to -30 kPa. Furthermore, under wetter conditions no differences in repellency indices between the grazed and UG79 treatments were detected for both investigated sites. On the other hand under drier conditions the higher repellency indices were found at the UG79 treatments. It was often investigated that grazing leads to reduction in plant cover and through that causes a decline in the amount of organic carbon (Dan et al., 2006). Therefore, the UG79 treatments, which are richer in organic carbon (Wiesmeier et al., 2009) are more repellent compared with the WG and CG ones and it must be also stated that continuous grazing also results in the regrowth of young organic material which consists of different organic material. It has also to be mentioned that Hallett et al. (2001) found a decline in soil repellency with an increase in disturbance and Bryant et al. (2007) found that increase in soil compaction causes a significant reduction in soil surface repellency due to a decreased soil roughness. Both, increase in disturbance and compaction and decrease in soil roughness result also from grazing and can be an additional reason for the measured decline of repellency index at our WG and CG treatments.

The mechanical behavior of the bulk soil depends on the properties of its individual aggregates as well as their architectural organization (Blanco-Canqui et al., 2005). The parameter – precompression stress – quantifies soil deformation and the highest load or the most intensive predrying that was previously applied to soil (Tobias and Tietje, 2007). We found, that in the first depth at the UG79 treatment the values of precompression stress at SG and LCh were low and very low, while at the WG and CG sites high and medium values were detected (DVWK, 1995). Our results also showed that the SG steppe is characterized by higher precompression stress values than the LCh site due to higher mechanical stresses in the past at the SG site. Many studies were done on the influence of animal trampling on soil compaction (e.g. Broersma et al., 2000) which causes an increase in soil mechanical strength. The obtained results of the precompression stress in the first depth of the grazed treatment reflected the ground contact pressure of one sheep hoof, which ranges between 80 kPa (Krümmelbein et al., 2006) and 124 kPa (Tollner et al., 1990). A slight increase in precompression stress due to grazing was also found by Peth and Horn (2006). Since, as it was reported by Greenwood and McKenzie (2001), grazing affects only the upper 15 cm of soil, the values in the second depth of the WG and CG treatments remained lower.

However, the question remains, why the values of the precompression stress at the UG79 treatment were smaller. Root growth, biological activity and a repeated wetting and drying as well as freezing and thawing all may indicate the long-term recovery process which leads to an improved soil structure as well as to a decline in mechanical strength. Thus, recovering soils are more sensitive in the beginning until a new dynamic aggregate and bulk soil strength equilibrium has been reached. Until now, i.e. after nearly 30 years soil recovery from grazing is still limited to the upper 10-15 cm soil depth as it was also found by Drewry (2006). It also explains higher values of precompression stress in the second investigated soil depth. Yong-Zhong et al. (2005) stated that the vegetation recovery can be quite fast after removal of grazing however the restoration of soil is a long-term process. Greenwood et al. (1998) found a decrease in bulk density and increase in unsaturated hydraulic conductivity at a pasture ungrazed for 20 years. Lesschen et al. (2008) stated that in semi-arid environment the recovery of soil properties can last at least 40 years. Since exclusion from grazing in 1979 was done, the recovery process at ungrazed treatments was more pronounced at the wetter LCh site (lower precompression stress) compared to the drier SG where longer time is needed for a more complete recovery of the soil.

One of the consequences of stress application, intensively studied in terms of the effect of agricultural machinery on the soil, is the formation of a platy soil structure (Sander et al., 2008). The structure of non-trampled soil is in general heterogeneous and is characterized by the occurrence of different sizes of aggregates and pores. Applied soil stresses as consequences of soil compaction and shear lead to the destruction of inter-aggregate pore spaces and, especially when applied repeatedly, the formation of a platy soil structure with horizontal fissures (Horn et al., 1995). Thus, such platy soil structure can also occur due to animal trampling. Martinez and Zinck (2004) found that the structure type was strongly affected by pasture establishment which caused occurrence of weak, fine to medium platy or transitional platy soil structure. Such findings can also explain our results of a significant anisotropy of the precompression stress in vertical direction at the SG CG. Furthermore, we can state that the strength is less pronounced when the samples are taken in the horizontal direction. During the test the plates could slightly move and therefore were less resistant to the applied stress compared with the samples taken in vertical direction. Therefore the anisotropy of the precompression stress values at this treatment and depth was significant and can also explain the structure reformation process and the direction dependent strength and/or weakness.

It is well known that the precompression stress values depend on the type of loading, the intensity of loading, time of load application and the number of compaction events which could be also confirmed by our data. Most of the stresses exerted by animal hooves in the field have a cyclic nature. In general animal trampling increases the soil strength (Krümmelbein et al., 2008). However, trampling changes also the mobility of particles which is the more pronounced the more the aggregates are destroyed and the higher the hydraulic gradients during wetting and drying which are needed to initiate the particle rearrangement. We found that at UG79 treatments the precompression stress of the soil which was loaded only once was higher than that after twenty loading cycles of each stress. This can indicate that at these sites the soil structure can resist the stress applied for a short time. Further loading can, however, lead to soil structure reformation due to rearrangement of soil particles and changes in soil hydraulic stresses which causes a soil weakening and a decline in precompression stress. This is in agreement with findings of Horn et al. (1994) who stated that in clay soils, while applying the stress for a very short time the precompression stress can be even doubled compared to the longer lasting compression. At SG CG the soil structure prior the mechanical application of stress was already changed (by grazing animals) thus, additional repeated loading led to further rearrangement of soil particles, a decrease in coarse pores and homogenization. As a consequence, increased water saturation weakened the soil because of the loss of capillary cohesion.

Air conductivity is one of the parameters used for quantification of soil functions which depends on the connectivity of soil pore network. The air conductivity values of the LCh UG79 were classified as medium while the SG UG79 had low air conductivity values. Trampling resulted in low air conductivity (WG and CG treatments). Finally, we can also define the effect of the recovery process on the preferred orientation of soil pores as it depends on the pore distribution before loading, the magnitude of the applied stresses and their direction (Cetin, 2004). Higher air conductivity values prior the test at LCh UG79 compared with SG UG79 can be explained with more connected pores of a given diameter (Mosaddeghi et al., 2007) at the LCh site which indicates better soil recovery from grazing at this site. This is also in agreement with our previous findings. On the other hand stresses exerted by sheep destroyed the pore network and decreased the air conductivity.

In well developed, aggregated soils no anisotropy in soil functions should be expected (Dörner and Horn, 2009) as it can be seen from the results of saturated hydraulic conductivity at LCh UG79. On the other hand, slightly higher values of saturated hydraulic conductivity in horizontal direction at the SG UG79 underline that the recovery process from grazing is still not finalized at this site.

However, it must be stated that if grazing is done under wet conditions and the soil is already weakened due to hydraulic stresses, then animal trampling leads to a pronounced deterioration and homogenization caused by puddling and results in a complete loss of the soil strength and a higher swelling and shrinkage potential. Consequently, the initiation of a new crack generation again can be derived by the occurrence of cracks and an increased saturated hydraulic conductivity in vertical direction. Thus, also the higher hydraulic conductivity values in the vertical direction at the LCh WG site can be explained by secondary generation of cracks and is also in agreement with other studies (Horn, 1986; Proffitt et al., 1995).

CONCLUSIONS

Soil structure formation and deterioration in Inner Mongolia, China are intensively affected by external as well as by internal soil processes and affect physical soil properties and functions.

1. Animal trampling led to changes in soil mechanical and hydraulic properties on different scales (from disturbed soil to the structured bulk soil and single aggregate). An intensive grazing in Inner Mongolia increased tensile strength of aggregates and precompression stress of bulk soil. Furthermore, the anisotropy of precompression stress at the SG site may indicate the formation of platy soil structure caused by animal trampling at this site. Decline in air conductivity and saturated hydraulic conductivity at the WG and CG sites may also indicate the destruction of pore network due to the stresses exerted by trampling animals. Moreover, the cyclically applied stresses (exerted by animals) lead to much stronger rearrangement of soil particles and/or soil homogenization compared with the static stresses which led to decrease in precompression stress values.
2. Soil formation and reformation are important for the alterations of moisture conditions. Under drier conditions the soil aggregates became stronger and more repellent while under wetter conditions as well as after repeated freezing and thawing processes soil aggregates were weaker. Furthermore, an intensive grazing under wet conditions like at LCh site, leads to a complete loss of soil strength and homogenization through soil puddling.
3. Soil mechanical and hydraulic properties depend on vegetation type. In general the LCh was characterized by higher tensile strength and repellency index, lower precompression stress, higher air conductivity and lower saturated hydraulic conductivity. The recovery processes of the soil have been observed mostly in the surface soil horizons and at the LCh UG79 site they were more intensive (lower precompression stress, higher air conductivity and isotropy of saturated hydraulic conductivity) than at SG UG79 site where more time is needed for a full recovery of the soil.

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GRAZING EFFECTS ON COMPRESSIBILITY OF KASTANOZEMS IN INNER MONGOLIAN STEPPE ECOSYSTEM

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ABSTRACT

In Inner Mongolia animal trampling is one of the main factors causing soil degradation manifested by altered mechanical strength or changes in water and gas fluxes. Soil samples were collected at two depths (4-8 and 18-22 cm) on the *Stipa grandis* steppe ecosystem in Inner Mongolia from two treatments characterized by different grazing intensities: ungrazed since 1979 (UG79) and continuously grazed (CG). The following mechanical soil properties were determined under static and repeated loading conditions: precompression stress, P_c; coefficient of cyclic compressibility, c_n and compression index, C_c. Air conductivity measurements were used to quantify the changes in soil functions due to application of repeated loading. The CG site showed significantly higher precompression stress values (111 kPa) than the UG79 (64 kPa) in the first soil depth. The highest c_n values were found in the topsoil of the UG79 site, while the CG site had significantly lower values of c_n. Repeated loading caused higher soil deformation compared to the static loading test. It was also found that the strain of soil samples from the UG79 site was higher than the CG site. We found a good fit between c_n and precompression stress. The C_c values of the cyclically loaded samples were significantly lower at the CG site than the statically loaded ones. The air conductivity of the UG79 site remained constant for a wider stress range of repeatedly applied stress compared with the CG site, which reflects higher stability of the soil pore network at the UG79 site.

Keywords: *soil structure; sheep grazing; precompression stress; cyclic loading; coefficient of cyclic compressibility; air conductivity*

INTRODUCTION

Animal trampling is regarded as one of the main factors leading to vegetation and soil degradation. Through animal hoof action, grazing results in a decline of soil physical properties such as infiltration rate, continuity of soil pores, air and hydraulic conductivities, and soil penetration resistance (Horn, 1985). Furthermore, frequent animal trampling leads to the deterioration of soil structure by soil deformation and soil compaction. It also can lead to environmental damage such as erosion and desertification (Hole, 1981). Although the negative influence of grazing on soil physical properties has been often described, the aspect of changes in the soil mechanical strength and compressibility due to animal trampling has been widely ignored. The pressures exerted by grazing animals on the soil are comparable to those of agricultural machinery but with a smaller contact area. Even though the animals' hoof area restricts the soil deformation mostly to the upper 15-cm soil layer (Greenwood and McKenzie, 2001), the cyclic loading and unloading as well as shearing enhance the deformation processes. Soil compressibility defines the sensitivity of the pore system to mechanical stress application; thus it defines the susceptibility of the soil to compaction (Smith et al., 1997).

One of the main parameters commonly used to quantify soil strength is the precompression stress (Horn, 1993). The precompression stress quantifies the stresses to which the soil was exposed in the past, irrespective of its origin. It is understood that soils react elastically (with a reversible deformation) if the applied stresses do not exceed the precompression stress value, while stresses higher than the precompression stress value result in a further plastic and irreversible deformation (Horn et al., 1995). This is mostly true if stresses are applied statically. The precompression stress approach, however, has not been tested for conditions when the stress is applied repeatedly and when the hydraulic boundary conditions are still not in equilibrium. Under such conditions, a gradient-dependent water flux within the soil can result in a further weakening of the soil structure (Krümmelbein et al., 2009). This weakening appears to be created by the pumping effect of water, which is caused by the repeated changes in soil matric potential during loading-unloading events. Consequently, the shear resistance between aggregates and particles decreases and the mobility of soil particles increases. This results in increased soil deformation and leads to a more intense deterioration of pore functions and can result in a complete homogenization, as can be also seen in the headland of arable land. O'Sullivan and Robertson (1996) showed that repeated application of the same load caused a small cumulative deformation until the equilibrated soil strength was finally reached, which was attributed to the time dependency of soil settlement. Other interactions between strength, stress, and soil strain have to be considered, however. It has been reported that a higher loading frequency with a lower load can lead to soil compaction having the same intensity as when using lower loading frequency with a higher load (Alakukku et al., 2003). The more often soils are loaded, the higher is their deformation, leading to destruction of the existing soil structure; pronounced changes in pore distribution, orientation, and continuity; and changes in soil functions.

These interactions are especially true for grassland ecosystems because most of the stresses exerted on the soil by animal hooves have a cyclic nature. In Inner Mongolia, overgrazing is one of the main factors leading to the deterioration of grasslands (Yu et al., 2004) and to increased air pollution over hundreds of square kilometers due to wind erosion. Additionally, the semiarid climate conditions in Inner Mongolia make soil structure degradation more common. Not much information about the effects of animal trampling on the mechanical compressibility of semiarid grassland soils is available, however. The aim of this study, therefore, was to investigate the consequences of grazing on soil compressibility and pore functions of a steppe ecosystem in Inner Mongolia, China. We hypothesized that grazing frequency weakens the soil structure and results in more pronounced structure deterioration and, as a consequence, the soil strength and its anisotropy undergo severe changes. Thus, these changes in soil strength and pore functions may be also linked to the long-term stability and resistance of the soil to wind erosion hazards, as was pointed out by Steffens et al. (2009).

MATERIALS AND METHODS

Study area

The experimental area was situated at the Xilin River catchment in Inner Mongolia, P.R. China, around 450 km North of Beijing, close to the Inner Mongolian Grassland Ecosystem Research Station (IMGERS, Chinese Academy of Sciences; 43° 38' N, 116° 42' E, 1270 m above sea level). The study area is located around 30 km southwest of IMGERS and the dominant plant species is *Stipa grandis* (P.A. Smirn.). The area is characterized by a dry and cold middle latitude steppe climate in the temperate zone. The mean annual precipitation is around 340 mm and most of it falls during the summer months. The minimum and maximum annual temperatures are – 40°C (January) and 33°C (July); the mean annual temperature is 0.7°C. The frost-free period is shorter than 100 d. The typical growing season lasts for approximately 150 d, from the beginning of April until late September (Bai et al., 2004). These grassland soils were developed from fine–sand loess sediments. The soils at the investigated research sites were classified as Kastanozems (based on the IUSS Working Group WRB, 2007) with secondary carbonates within 100 cm of the soil surface.

Grazing experiments

For centuries the investigated area was used only for grazing, which was practiced in a nomadic way. There was no agriculture and no fertilizer was applied. In the 20th century, due to political changes, an increase in grazing intensity was observed. We investigated two treatments: ungrazed since 1979 (UG79) and continuously grazed (CG). Until 1979, the whole area was grazed at a low intensity. In 1979, the Institute of Botany of the Chinese Academy of Sciences established the UG79 treatment by fencing and excluding an area of about 23 ha of the *Stipa grandis* steppe from grazing. Since then, no grazing has taken place at this site. The remaining 19-ha area (CG) was continuously grazed. Since 1995, this treatment has been grazed all year by 200 animals for 2 to 3 h d^{-1}. The grazed treatment is not fenced; therefore, the grazing intensity can vary in different areas of this site within a year. The herd consists of sheep (three-quarters of the herd) and goats (one-quarter of the herd).

Sample collection and preparation

Soil samples were collected in the summer of 2007 and 2008 from the UG79 and CG treatments of the *Stipa grandis* steppe ecosystem. Because soil physical properties can vary spatially within the site, we collected soil samples from three replicate locations (approximately 60 cm deep), situated at a distance of 15 m from each other. Disturbed soil samples were collected from all locations for a determination of the particle size distribution and soil organic C content (two samples per depth of each profile). Undisturbed soil samples were also taken to measure soil mechanical properties (static loading and repeated loading) at two different depths: 4 to 8 cm and 18 to 22 cm. Five soil samples for static loading tests and five samples for repeated loading tests were collected per soil depth from each soil profile using 236-cm^3 stainless steel cylinders (30-mm height and 100-mm diameter). An additional five undisturbed samples were taken per site from the first soil depth to determine the effect of repeated loading on air conductivity. After collection, the samples were carefully transported to the laboratory, where they were stored in a cool room until analysis.

General soil physical and chemical properties (bulk density, organic C content, and soil texture) were determined according to Schlichting et al. (1995). The bulk density was determined by the oven-drying method. The total C content was measured coulometrically via dry combustion in a stream of O_2 and spreading CO_2 through a suspension of $Ba(OH)_2$ with Ströhlein gas analyses device. The inorganic C was measured volumetrically according to Scheibler's method. The soil texture was measured according to the method introduced by Atterberg (1912). To perform static and repeated loading tests, undisturbed soil samples were saturated and afterwards equilibrated to a standard matric potential of -30 kPa using ceramic porous plates. This is the highest matric potential that can be expected under these climatic conditions according to Zhao et al. (2010) and, therefore, defines the weakest soil conditions. Thereafter, one set of samples was exposed to static loading tests performed using a standard oedometer device, which measures the rate and amount of consolidation of a soil specimen under pressure. Another set of samples was tested in repeated (cyclic) loading tests performed using a standard multistep-oedometer device (described in details by Peng et al., 2004). Both tests were performed under confined, drained conditions. During both tests, the settlement and matric potential changes were recorded using potentiometric displacement transducers and micro-tensiometers, respectively.

To determine the air conductivity, the soil samples were saturated and also drained to -30 kPa using ceramic porous plates. The air conductivity was measured using an air permeameter as described by Vossbrink and Horn (2004).

Soil mechanical tests

Static loading

The static loading test (SL) included the following stresses: 10, 20, 30, 40, 50, 70, 100, 120, 150, 200, 300 and 400 kPa. Each stress was applied for ten min. After the last load, the soil was left unloaded for 10 min. The precompression stress (P_c) was determined according to Casagrande (1936). Soil strain was calculated using the ratio of soil settlement (mm) at the end of an applied load to the initial height of the soil core (30 mm).

Repeated loading tests

The cyclic loading imitates conditions (loading and unloading) similar to the trampling of animals. We performed two different types of repeated loading tests: pure cyclic loading and stepwise cyclic loading.

Pure cyclic loading

This kind of test simulates the effect of repeated loading caused by an application of a stress lower than the precompression stress on the compressibility of the soil. We applied 100 cycles with a constant external stress of 40 kPa, whereby each cycle consisted of 30 s loading and 30 s unloading (***Fig. 3.2.1.***). Such a test is called pure cyclic loading (PCL).

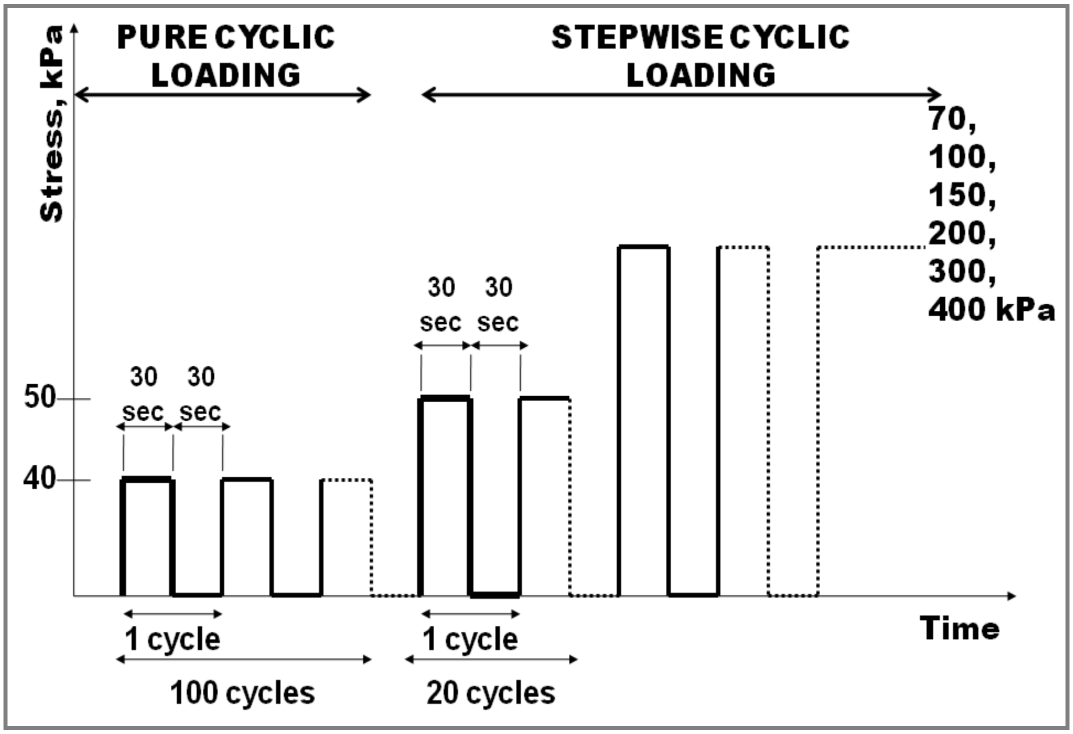

Figure 3.2.1. Schematic graph showing the stress path during the pure cyclic and stepwise cyclic loading tests

The coefficient of cyclic compressibility (c_n) was calculated according to the method introduced by Peth and Horn (2006) and refers to the slope of the linear regression function obtained by plotting the logarithm of number of loading cycles vs. the void ratio of soil samples during unloading.

Stepwise cyclic loading

Immediately after the PCL, the stresses were increased to 50 kPa followed by six stresses: 70, 100, 150, 200, 300, and 400 kPa, which were applied in 20 cycles (each cycle consisted of 30 s of loading and 30 s of unloading), and resulted in a total time of 10 min of loading and 10 min of unloading. This kind of repeated loading test is called stepwise cyclic loading (SCL) and simulates the effect of animal trampling on soil under in situ conditions when repeated loads of approximately 80 to 124 kPa (the stress exerted by one sheep hoof) are applied. The total time of loading during a cyclic application of one stress was equal to that applied during the static loading test. The precompression stress for the SCL test (P_c') was calculated from the strain of the last (20th) cycle of each stress applied. At this stage, i.e., after 20 cycles, the samples had mostly reached a state of equilibrium of strain. From the stress-strain relationship, we derived the compression index (C_c), which defines the slope of the virgin compression curve, and we compared the results of the statically loaded samples to the C_c results of the first and the 20th cycles of the samples loaded during the SCL tests.

Air conductivity

The changes in air conductivity (k_a) of the soil due to cyclic loading were measured before the test at -30 kPa matric potential and after each load of the cyclic loading tests (with loads of 40, 50, 70, 100, 150, 200, 300, and 400 kPa). The ratios $k_{a(stressed)}/k_{a(initial)}$ were calculated for each load applied.

Statistical analyses

Statistical analyses were done using the R 2.5.1 software (Hornik, 2009). The normal distribution was tested using the Shapiro-Wilk test of normality. To determine the statistical differences between samples, Wilcoxon and t-tests were performed. The results were classified as statistically significant at $P<0.05$. For a graphical visualization of the results of c_n and C_c, box plots were chosen. In each box plot, the information about the median value (the black line across each box), the lower and upper hinges (defined as the 25th and the 75th percentiles), and the minimum and maximum values as well as outliers (displayed as diamonds) were shown. The notches indicate the 95% confidence interval of differences between medians (for further information, see McGill et al., 1978). The box plots can be used not only for presenting normally distributed data but also as an appropriate method of presenting data that are not-normally distributed, for which no additional transformation into logarithms is needed.

RESULTS AND DISCUSSION

Main soil physical and chemical parameters

The mean values of the main soil characteristics from three replicate profiles of the investigated sites are presented in ***Table 3.2.1***. The soil textural class was defined as sandy loam (*FAO and USDA*). In the topsoil of the UG79 site, the organic C content was slightly higher and the bulk density was lower compared to the CG site.

Table 3.2.1. Mean values of bulk density, organic carbon content and particle size distribution of two investigated treatments (ungrazed since 1979, UG79, and continuously grazed, CG) of the *Stipa grandis* steppe ecosystem for two depths: 4 to 8 cm and 18 to 22 cm; standard deviation is shown in brackets

Site	Depth (cm)	Bulk density (g cm^{-3})	Organic C (%)	Sand (%)	Silt (%)	Clay (%)
UG79	**4-8**	1.19 (± 0.08)	1.76 (± 0.34)	62.3 (± 2.6)	25.1 (± 1.9)	12.6 (± 1.3)
	18-22	1.25 (± 0.06)	1.27 (± 0.01)	60.0 (± 3.2)	26.0 (± 2.4)	14.0 (± 0.9)
CG	**4-8**	1.28 (± 0.07)	1.43 (± 0.07)	65.6 (± 1.9)	21.4 (± 1.4)	13.1 (± 0.5)
	18-22	1.26 (± 0.08)	1.22 (± 0.11)	62.3 (± 3.0)	24.1 (± 3.0)	13.6 (± 0.1)

Time settlement curves for various loading conditions

It is well known that the type of loading, load intensity, time of loading, and number of compaction events affect settlement, which is of great importance for the prediction of soil mechanical strength. Soil responds differently depending on the kind of the applied stress. Soil deformation due to the application of static loads has been widely studied (e.g., Stone and Ekwue, 1996; Zhang et al., 2005), while the effect of cyclic loading has rarely been determined (Krümmelbein et al., 2008). Soil deformation resulting from the static loading differed from that caused by repeated loading (***Fig. 3.2.2.***). The soil deformation during the static loading test increased with applied stress. In the beginning of the application of each stress, an intensive settlement could be observed, while as the time of loading increased, the incremental strain decreased until it reached a constant value.

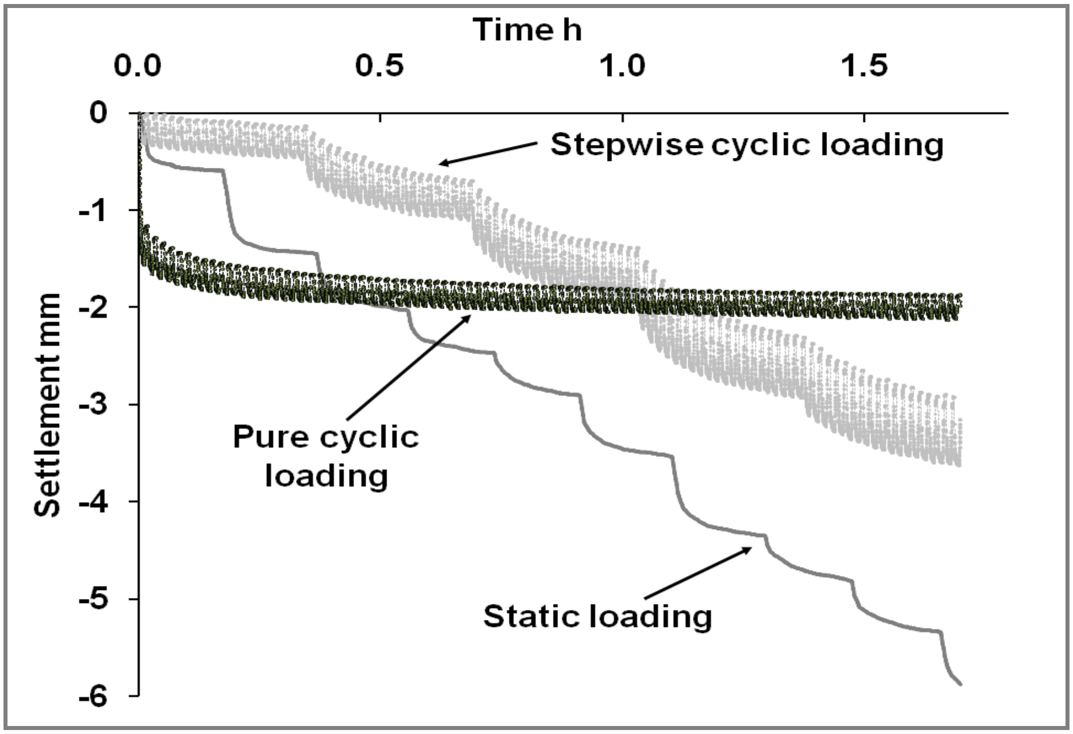

Figure 3.2.2. Examples of time-displacement curves during static, pure cyclic, and stepwise cyclic loading tests

The changes in soil settlement during a PCL test depended on the frequency of applied stresses. Although the applied stress was lower than the precompression stress, additional incremental soil settlement was detected. The highest proportion of the total settlement was obtained during the first loading cycle, and it decreased as the number of cycles increased. These results are in agreement with the findings of Peth and Horn (2006), who determined that much stronger settlement of the homogenized samples after the first loading-unloading event could be related to saturation and desaturation of samples during preparation for the test, followed by rearrangement of soil particles and changes in the spatial distribution of soil water. Even after 100 cycles, however, the stress-strain relation did not reach a full equilibrium, although the incremental soil settlement became negligibly small. Our results are in agreement with those of O'Sullivan and Robertson (1996), who stated that repeated application of the same load causes successively smaller increases in permanent deformation until the moment when the soil cannot compact any more. During the PCL test, the soil reacted with an elastic rebound during unloading.

The settlement paths during SCL were comparable to those obtained in the SL and PCL tests. The alteration of the settlement during SCL depended on the applied load, the number of loading-unloading events, and the stress situation. It was found that the higher the load, the higher was the incremental soil deformation, which is in agreement with the findings of Wiermann et al. (1999), who investigated the effect of dynamic loads on soil displacement. They found that the vertical displacement increased significantly from 16.1 mm when the dynamic load was 13.2 kN to 70.0 mm when the dynamic load was 25.3 kN. During unloading, a decline in settlement was observed, which indicated an elastic behavior of the soil. The rebound increased as the applied stress increased. Zhang et al. (2005) stated that fluctuations of settlement and matric potential during cyclic loading determine resistance (to loading) and resilience (to unloading) of the soil. Furthermore, they found an increase in height of rebound with applied stress and stated that the rebound can be used to quantify the soil mechanical resilience, i.e., the recovery of the soil pore structure after mechanical disturbance. This is in agreement with our results. During loading, we observed a comparable tendency in settlement change as for PCL. The settlement during the stepwise loading increased from the first to the 20th loading cycle of each load.

Compressibility of soil under static loading

The precompression stress differed between the CG and UG79 treatments (***Table 3.2.2.***). Animal trampling affected the first soil depth, resulting in significantly higher P_c values at the CG site (111 kPa) compared with the UG79 site (64 kPa). The P_c values were classified as medium for the UG79 treatment according to German Association of Hydrology and Engineering (1995), while for the CG treatment the P_c values were classified as high (in the first layer) and decreased to medium at the second depth.

Table 3.2.2. The precompression stress values of the treatments (ungrazed since 1979, UG79, and continuously grazed, CG) obtained from the static loading test at a given matric potential of -30 kPa. A symbol * defines statistically significant differences between two sites; standard deviation is shown in brackets; n=15

Site	Detph (cm)	Precompression stress, P_c (kPa)
UG79	**4-8**	*64 (± 22)
	18-22	79 (± 29)
CG	**4-8**	*111 (±32)
	18-22	89 (± 41)

The P_c values in the topsoil of the CG treatment reflected the ground contact pressure of one sheep hoof, which ranges between 80 kPa (Krümmelbein et al., 2006) and 124 kPa

(Tollner et al., 1990). Greenwood and McKenzie (2001) stated that grazing affects mostly the upper 5 to 15 cm of the topsoil and fades with depth, which is in agreement with our findings. We have to consider additional effects, however: (i) Horn (1985) stated that the precompression stress of mountainous forest soil and pasture increased with trampling, but after exceeding a maximum value, it decreased again because more intense animal trampling, in combination with a surplus of soil water that cannot be drained off, resulted in a complete homogenization due to puddling; (ii) at the UG79 site, which was not stressed within the last 30 yr, the higher values of precompression stress were found in the lower soil horizon. Such a finding can be explained by a recovery of the soil structure from animal trampling, which results in a certain loosening of the soil. Such recovery, however, especially in semiarid environments, is expected to be very slow, taking 40 yr or more, and is limited only to the upper soil horizon (Lesschen et al., 2008).

We found a more pronounced (although not significantly) strain of the statically loaded samples taken from the UG79 site compared with the CG site (***Fig. 3.2.3.***).

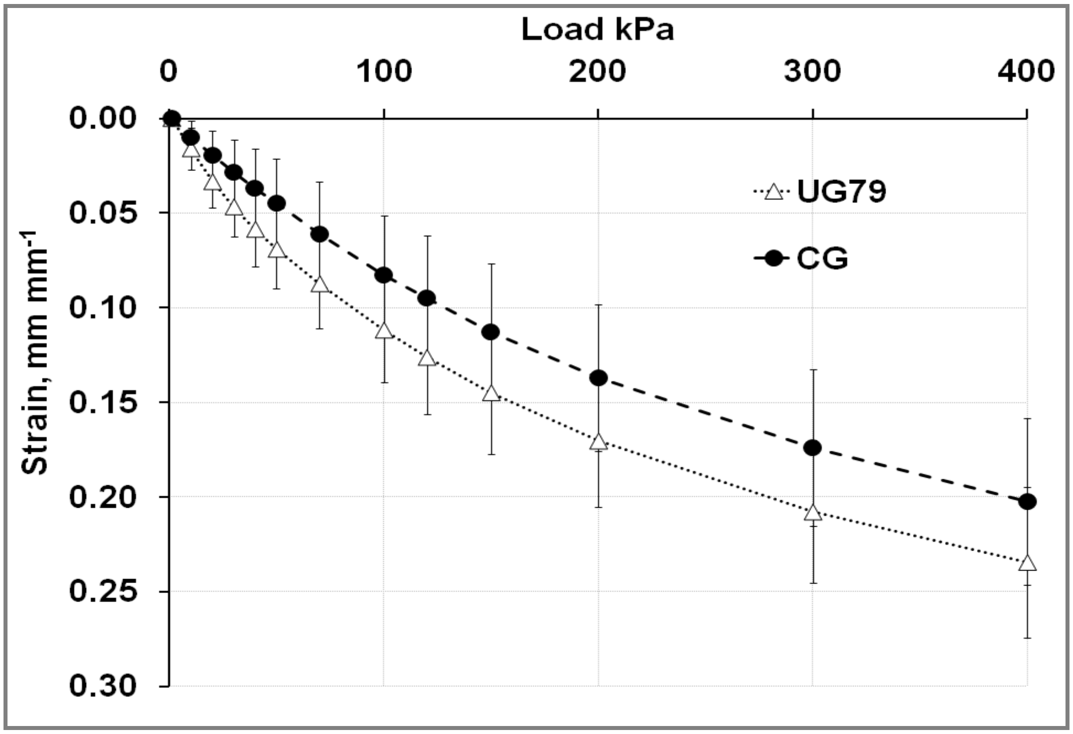

Figure 3.2.3. Displacement curves of ungrazed since 1979 (UG79) and continuously grazed (CG) treatments during static loading tests for the depth of 4 to 8 cm; error bars show standard deviation (n=15). The initial mean values of the void ratio were 1.22 (± 0.16 cm^3 cm^{-3}) and 1.06 (± 0.11 cm^3 cm^{-3}), while after 400 kPa the void ratio values declined to 0.69 (± 0.08 cm^3 cm^{-3}) and 0.64 (± 0.08 cm^3 cm^{-3}) at the UG79 and CG, respectively.

Due to animal trampling, these defined changes in strength can also be partly derived from an increase in bulk density, a decrease in the organic matter content, and formation of coarse pores in a platy soil structure if the puddling effect is not very pronounced for various reasons. Consequently, under these intermediate conditions, these soils are more resistant to additional soil deformation (lower strain) as long as the applied stress does not exceed the internal soil strength. It must be emphasized, however, that a trampling-induced soil strength increase is limited to the former applied stress. In combination with poor aeration and hydraulic conductivity, the trampled sites are characterized by a higher susceptibility to degradation, runoff, and sensitivity to wind erosion.

Compressibility of soil under pure cyclic loading

The coefficient of cyclic compressibility (c_n) differed between sites and depths. The highest median value of c_n was found in the first depth, 4 to 8 cm, of the UG79 site (***Fig. 3.2.4.***) and it was significantly higher at this depth than that at the CG site.

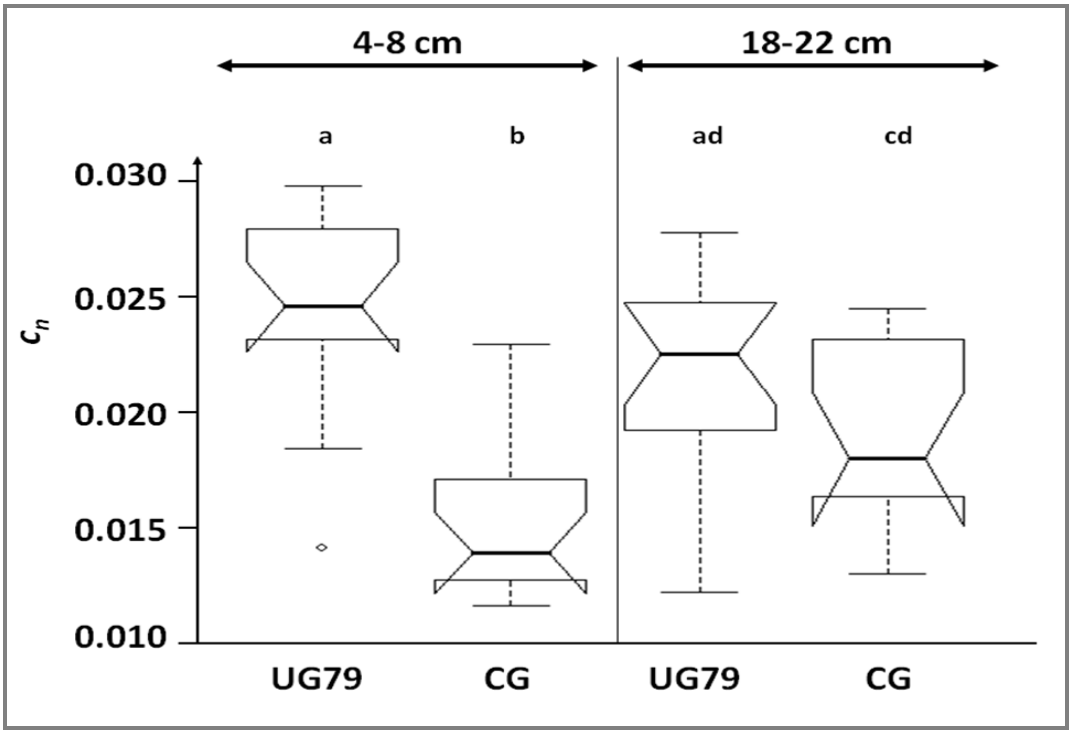

Figure 3.2.4. Coefficients of cyclic compressibility (c_n) of two treatments (ungrazed since 1979, UG79, and continuously grazed, CG) and two depths (4-8 cm and 18-22 cm). Different lowercase letters indicate statistically significant differences between the sites; the outlier is displayed as a diamond (n=15).

These c_n values show the varying sensitivity of the two sites to soil deformation. Krümmelbein et al. (2006) found that the grazed site was less susceptible to changes in pore volume resulting from repeated loading, which is also in agreement with findings of Stone and Ekwue (1996), who stated that soils that experience higher volumetric strains are subjected to greater compression and, therefore, greater reduction in volume.

The difference in c_n between sites declined in the second soil depth. Furthermore, the compressibility of the soil changed between depths depending on the different land uses. At the CG site, c_n was significantly lower in the topsoil than the subsoil. The greater differences between the c_n values in the topsoil of the two sites compared with the subsoil were to be expected, because animal trampling affects only the upper soil layer. This was also confirmed by Ferrero (1991) and explains the higher c_n values (= more rigid conditions) in the deeper soil horizon at the CG site and, therefore, less difference between the two sites at this depth.

Soil compressibility under stepwise cyclic loading

It must be pointed out that, in the past, soil strength was mostly related to static loading conditions. Because soil deformation during static loading is restricted only to a stress-dependent drainage in combination with soil settlement, however, it only gives a short-term insight into the process under in situ conditions. If we also consider the loading-unloading-dependent drainage and its frequency, we get better insight in the re-watering of the stressed samples and the coinciding weakening of the soil system if the overburden-dependent-water release could not be drained off immediately. The comparison of the stress-strain paths for various stress conditions showed differences between the samples from the SL and SCL tests. Although the strain differences between the two tests were not statistically significant, some trends for variously loaded soil samples could be detected. In principle, it could be proven that repeated loading caused higher soil deformation than static loading (***Fig. 3.2.5.***) and confirmed also the findings of Martinez and Zinck (2004). They stated that animal trampling exerts a short-term pressure on the soil, which can be two to four times the pressure resulting from static loads. The higher the applied stress, the smaller were the differences in strain between samples loaded statically and cyclically. It could be seen that during application of 40-kPa stress, the strain of cyclically loaded samples was 50% higher than the statically loaded samples; at 100 kPa, the difference in strain declined to 25% and it faded after the last loading.

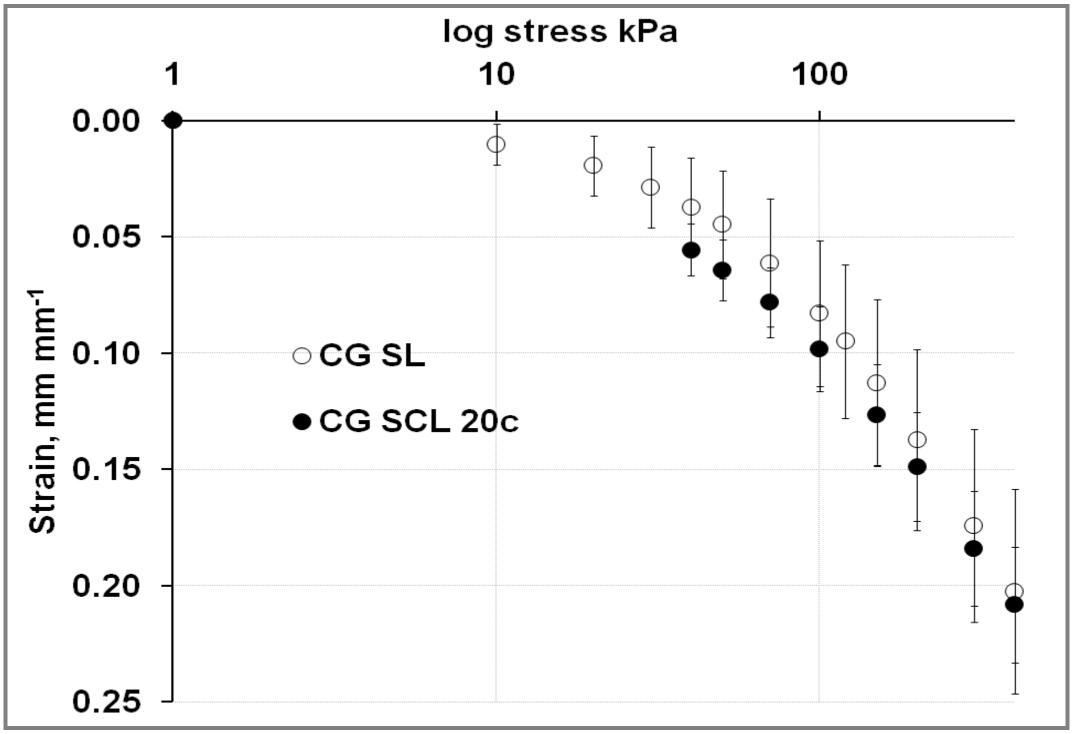

Figure 3.2.5. The stress-strain paths of statically and cyclically loaded samples for the continuously grazed (CG) treatment for the depth of 4 to 8 cm; SL indicates the strain obtained for each load from the static loading tests; SCL 20c indicates the strain obtained for each load from the 20th cycle of the stepwise cyclic loading (SCL) tests; error bars show standard deviation (n=15). The initial mean values of the void ratio were 1.06 (± 0.11 cm^3 cm^{-3}) and 0.97 (± 0.11 cm^3 cm^{-3}), while after 400 kPa the void ratio values declined to 0.64 (± 0.08 cm^3 cm^{-3}) and 0.61 (± 0.08 cm^3 cm^{-3}) in statically and cyclically loaded samples, respectively.

We found a less negative matric potential during loading compared with the conditions when the stress was released. In addition, the differences in matric potential between loaded and unloaded samples increased with increasing applied stress (***Table 3.2.3.***).

Table 3.2.3. Examples of changes in matric potential (in hPa) during the first loading – unloading event of the pure cyclic loading (PCL) and three loads (100, 200, and 400 kPa) of stepwise cyclic loading (SCL) for the ungrazed since 1979 (UG79) and continuously grazed (CG) sites; the range of results from the minimum to the maximum are given in parentheses; depth = 4 to 8 cm; n=15.

Site	PCL	SCL		
		100 kPa	200 kPa	400 kPa
UG79	2.2 (0.1 – 11.0)	3.3 (0.3 – 14.3)	5.5 (0.5 – 24.0)	10.2 (1.4 – 41.9)
CG	3.9 (0.4 – 16.6)	6.7 (0.4 – 26.9)	9.8 (1.3 – 37.0)	14.9 (1.5 – 53.4)

Horn et al. (1995) stated that repeated loading induced a denser rearrangement of the soil aggregates, which could be also attributed to a certain weakening of the aggregate edges or outer skins due to partial swelling. This interaction was described by Krümmelbein et al. (2008). They explained the higher sensitivity to compression as a “water pumping effect", which was quantified by the stress-dependent changes in the pore water pressure values within the samples during loading and unloading. Thus, our results are also in agreement with their findings and emphasize that the combination of mechanical and hydraulic processes is essential to understand the complex stress-strain paths more in detail.

The results of the correlation between the c_n values and the precompression stress (P_c') calculated for the SCL showed a linear dependency of the two parameters (***Fig. 3.2.6.***). The P_c' varied between 50 and 95 kPa. The UG79 treatment was characterized by lower P_c' values and higher c_n values. The opposite was true for the CG treatment, which may be correlated with the hydraulic and stress-dependent fluxes. About 64% of the P_c' results can be explained by the c_n values.

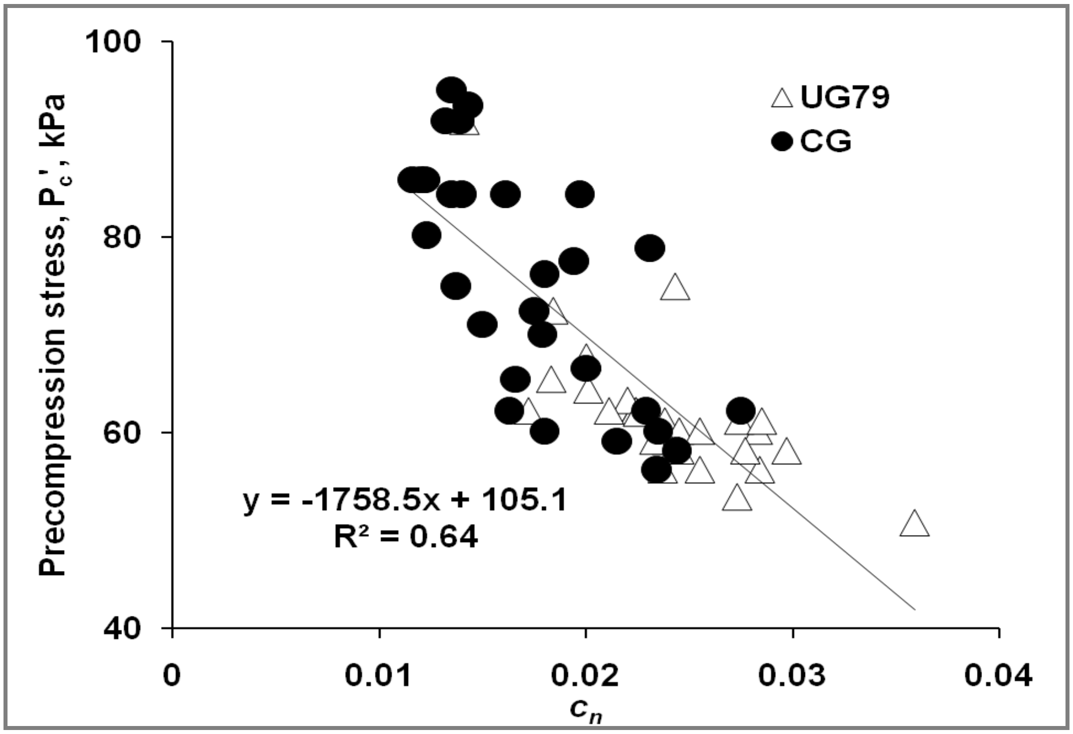

Figure 3.2.6. Linear regression of the coefficient of cyclic compressibility (c_n) and precompression stress determined using the 20th loading cycle (P_c') for two treatments, ungrazed since 1979 (UG79) and continuously grazed (CG), for both investigated soil layers, 4 to 8 cm and 18 to 22 cm (n=30).

Those horizons that have a more rigid soil structure are characterized by smaller c_n values and vice versa. Our findings also proved that the UG79 site has to be defined as less rigid, because, during the process of soil recovery, the rearrangement of soil particles and the formation of new and more continuous pores coincided with a stage of increased intermediate sensitivity until the final stage of the smallest entropy will be reached. In this context, the term "rigidity" defines various conditions. First, with respect to soil engineering, it can define a completely compacted soil (***Fig. 3.2.7.***). Second, it can define a soil with vertical tubes (pores) within it. Finally, rigidity can define a structured soil with strong aggregates that already has reached the smallest degree of entropy and the highest permeability and accessibility of particle surfaces.

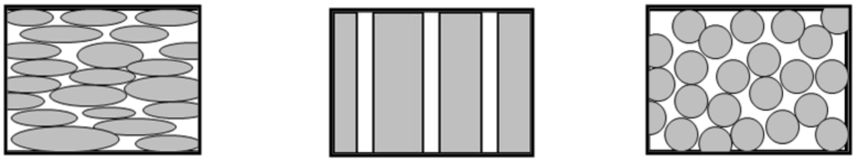

Figure 3.2.7. Schematic two-dimentional graphs showing the rigidity of compacted soil (left); the soil with vertical tubes (middle), and the soil with strong aggregates (right).

The often described C_c value (defined as the slope of the virgin compression curve) can be primarily related to texture-dependent changes within samples. If we also consider the interaction between hydraulic and mechanical stress processes, however, it can give further information for a given texture about differences in the slopes of the virgin compression curves of samples loaded statically and cyclically. In our experiments, the C_c values at the CG site were always smaller when cyclically loaded (***Fig. 3.2.8.***). Thus, we must enlarge this discussion not only to the textural dependencies, but the differences in the slopes of the virgin compression curves, which also depend on, e.g., the amount and size of the broken aggregates, the clay content, etc. At the CG site, significantly lower C_c values obtained from the SCL tests than the SL tests indicated that at this site the repeated loading caused higher soil structure deformation and rearrangement of soil particles, as shown by a lower slope of the virgin compression curve. This agrees with the studies of Smith et al. (1997), who found lower C_c values for relatively incompressible soils. It is worthwhile to mention that the differences in the C_c values between the UG79 and CG sites can be found only for the SCL test.

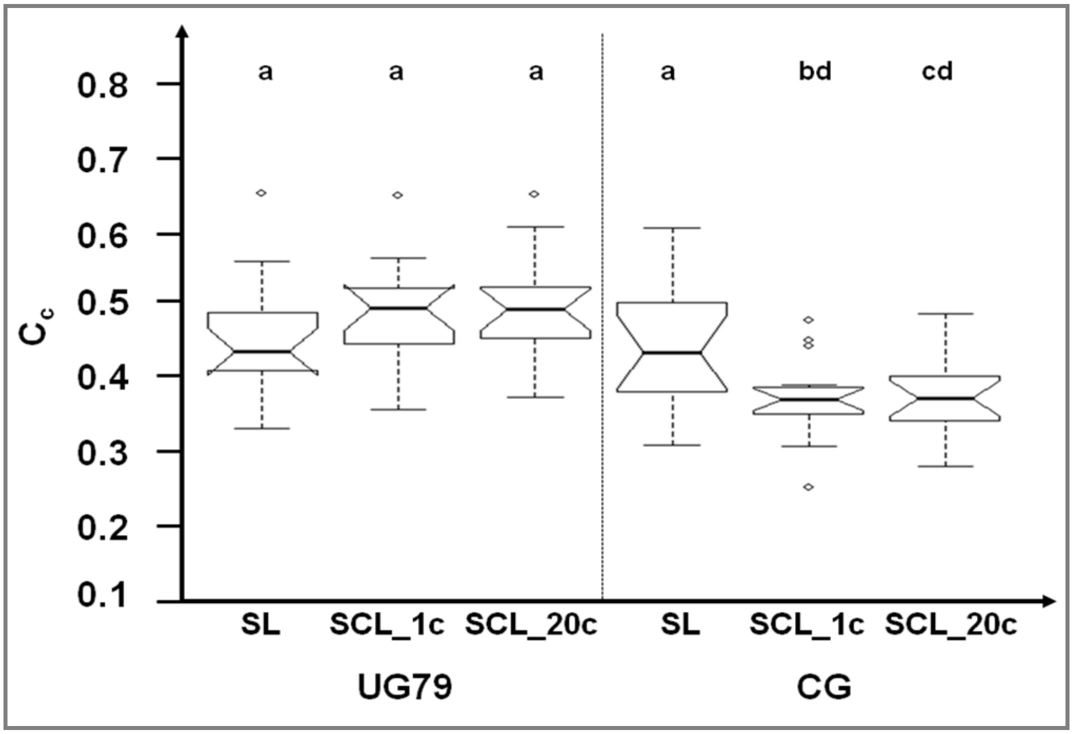

Figure 3.2.8. Compression index (C_c) of variously loaded samples for two investigated treatments (ungrazed since 1979, UG79, and continuously grazed, CG) at the 4- to 8-cm depth; SL indicates the compression index of statically loaded samples, SCL_1c and SCL_20c indicate the compression indices obtained from settlement of the first and the 20th cycles of the stepwise cyclic loading test. Different lowercase letters indicate statistically significant differences between sites; the outliers are displayed as diamonds (n=15).

Changes in air conductivity due to repeated loading

The air conductivity of soil depends on the connectivity of the pore network and is often used to define and to quantify soil functions. The air conductivity, k_a, decreased with increased stresses applied (***Fig. 3.2.9.***). Before the test, the UG79 treatment was characterized by a slightly (however not significantly) higher k_a (median value of 0.0012 cm s^{-1}) compared with the CG treatment (median value of 0.0010 cm s^{-1}). The air conductivity before load application was classified as low (according to the German Association of Hydrology and Engineering, 1997) for both treatments. After the first load (40 kPa), the air conductivity at the UG79 site decreased only slightly, and the following loads led to a further, stepwise decline in air conductivity. At the CG site, the air conductivity declined strongly after the first load. Further loading did not lead to more pronounced changes in air conductivity at this site because it had already reached the final and most compacted stage.

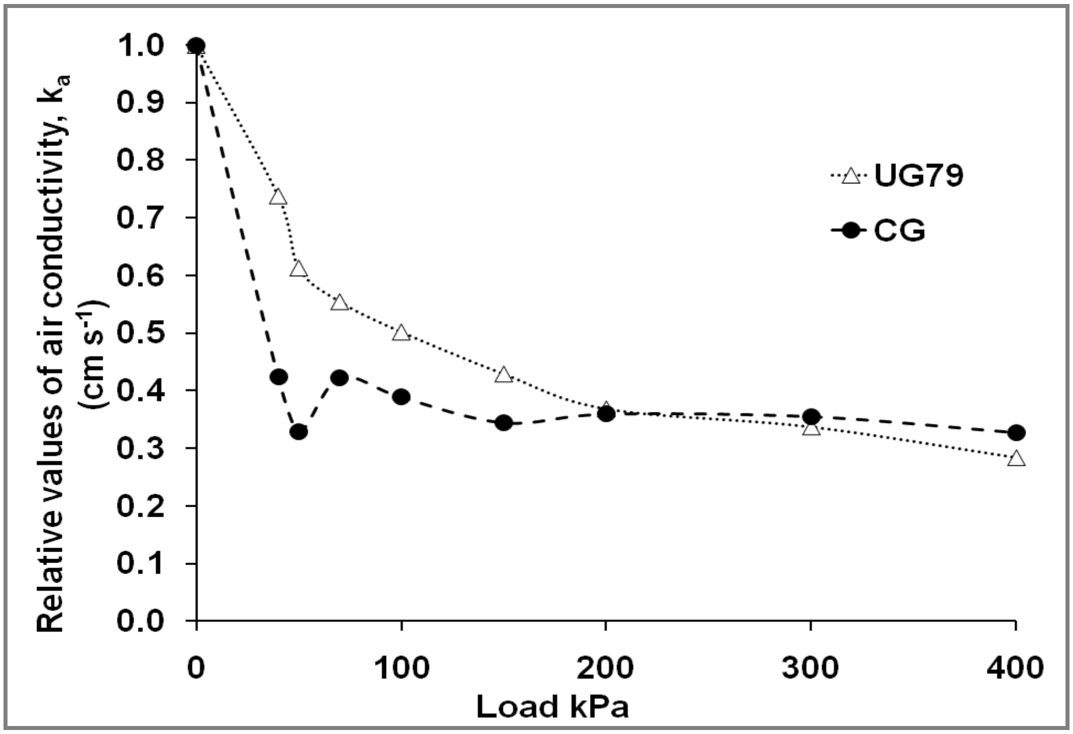

Figure 3.2.9. Relative changes in air conductivity values after each load application for ungrazed since 1979 (UG79) and continuously grazed (CG) treatments related to initial values; 1.0 indicates the air conductivity values of each treatment determined before the tests (0 kPa) (n=5).

If we, furthermore, assume that the transport of air in the soil profile occurs mostly within the interaggregate macropore system, such stress-dependent decline in the air conductivity emphasizes the incomplete recovery process. At the UG79 site, the soil recovery process led to an increase in the number macropores and the air conductivity, which, in addition, slightly increased the strength between the aggregates and the coarser interaggregate pores. This interaction was also described by Drewry (2006). Compressing the soil samples from the UG79 site led to the rearrangement of soil aggregates and their closer configuration, but the conductivity of air was still possible. Only after a higher frequency of loading or higher stresses applied can we expect a collapse in aggregates, as can be seen in *Fig. 3.2.9*. Thus, these soils are more resistant to applied stresses and maintain their functions for a longer time, which is in agreement with Zinck (2009). At the CG site, however, animal trampling caused a decrease in the number of coarse pores, and, in addition also connected pores, leading to a decline in air and water flux and resulting in an increase in the number of contact points between the particles. The latter coincides with an increase in mechanical strength but also with a weakening of the pore system, which is in agreement with other studies (Horn, 1985; Martinez and Zinck, 2004).

It is important to mention that even though the UG79 site was characterized by higher c_n and C_c values (higher mechanical compressibility), the results of air conductivity changes caused by cyclic loading show that, when considering the changes in soil functions, the UG79 site remained more stable or less sensitive to soil deformation. We finally have to state, however, that even after >30 yr without grazing, these sites still have not reached a new and more complete, rigid, final pore structure status, which emphasizes the long-term irreversibility of soil regeneration after a given mechanical treatment.

CONCLUSIONS

From our investigations, we can conclude that grazing influences soil's mechanical stability and compressibility. At the CG site, animal trampling led to an increase in the mechanical stability of the soil because the precompression stress values increased. The soil compressibility changed even when stresses were applied that were lower than the precompression stress value, due to the "pumping" effect of water related to the changes in pore water pressure during repeated loading-unloading events. Irrespective of an increased mechanical strength at the CG site, animal trampling had a negative effect on air conductivity. The changes in soil mechanical properties due to grazing must be considered when talking about soil degradation in Inner Mongolia and should be taken into account when considering further environmental changes in this semiarid steppe area. To prevent further environmental damages as well as to improve the existing soil conditions, it is recommended that the number of animals in a herd be decreased and rotational grazing introduced. Excluding some areas from grazing for a longer time would allow partial recovery of the soil structure.

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INFLUENCE OF GRAZING ON SOIL WATER AND GAS FLUXES OF TWO INNER MONGOLIAN STEPPE ECOSYSTEMS

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ABSTRACT

Intensive overgrazing, practiced for the last decades in Inner Mongolia, has led to serious grassland degradation and deterioration of soil structure. As a consequence, the soil gas and water fluxes and therefore soil functions were affected by grazing. We investigated two steppe ecosystems characterized by two plant communities: *Stipa grandis* (SG) and *Leymus chinensis* (LCh) and different grazing intensities: ungrazed since 1979 (UG79), continuously grazed (CG, at the SG site) and winter grazed (WG, at the LCh site). The undisturbed soil samples, for determination of saturated (k_s) and unsaturated (k_u) hydraulic conductivities and air conductivities (k_a), were collected in vertical and horizontal direction from two soil horizons. The coefficients of anisotropy were calculated as ratios of the values obtained for the samples taken in horizontal direction to the values of the vertical samples. The results indicated a good recovery of soil structure at the sites ungrazed for more than 30 years. Furthermore, the recovery was more pronounced at the LCh site compared with the SG site. The results suggested that grazing causes significant changes in anisotropy of soil functions related to rearrangement of aggregates and creation of a platy soil structure. The results of the coefficients of anisotropy of hydraulic conductivity showed that they depend on the matric potential for both treatments.

Keywords: *soils functions; hydraulic conductivity; air conductivity; anisotropy*

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INTRODUCTION

An Inner Mongolian grassland ecosystem is one of the main, most important natural, renewable resources of the arid and semiarid regions of China (Chen et al., 2005). However, an intensive grazing practiced in this country for the last few decades has become a major problem leading to a serious decline in grassland productivity, its degradation and desertification. Numerous studies have shown that an intensified grazing in Inner Mongolia has consequences for plant growth (e.g., decline in the vegetation cover, height, standing biomass and belowground biomass production); it causes soil loss due to water and wind erosion, intensification of desertification processes as well as a decline in soil chemical and physical properties (Li et al., 2000; Zhao et al., 2005; Kurz et al., 2006; Gao et al., 2008; Hoffmann et al., 2008a; Steffens et al., 2008).

A negative influence of grazing on soil physical properties is related to the hoof action of the grazing animals which – due to exerted mechanical stresses – can result in either a denser configuration of aggregates and a reduction in coarse inter-aggregate pores, or a platy soil structure, followed by a total soil homogenization. The latter may be also starting point for the reformation of new structure elements and altered soil functions. However, in order to characterize the effect of grazing on soil functions, it requires more than only investigating the capacity parameters of the soil, such as bulk density, pore size distribution or grain size distribution, because of a too weak correlation to the soil-structure-dependent properties. Such parameters also do not regard the arrangement of soil particles in a given soil volume (Horn et al., 1994). Therefore, it is necessary to apply intensity parameters (such as saturated and unsaturated hydraulic conductivity or air permeability) which are fundamental for understanding the soil functions, as these parameters include the dynamic aspects over time and space and quantify the soil functions under a given management (Horn and Kutilek, 2009).

It was stated by Dörner and Horn (2009) that in well developed aggregated soils, isotropy of soil functions should be dominant. Animal trampling can change the direction-dependent behavior of soil properties. Krümmelbein et al. (2006) reported that high pressures exerted by animal hooves can lead to soil compaction and to the formation of a platy soil structure which results in an anisotropy of physical soil functions. Martínez and Zinck (2004) obtained similar results. Intensive grazing, especially under wetter soil moisture conditions can also lead to a complete soil homogenization and destruction of the continuity of the soil pore network (Horn, 1986) while long-term exclusion from grazing is accompanied by soil recovery processes due to repeated swelling and shrinkage processes, freezing and thawing or biological activity of the soil organisms. Thus, soil structure formation and its alteration due to external processes also include tensorial effects which must be analyzed in order to fully understand landscape properties and functions. Studying a direction-dependent soil behavior can provide additional information about soil functions, degree of soil degradation and recovery as well as it allows to indentify the risk of erosion or to evaluate the possibility of plant growth.

In our studies we focused on the effect of grazing and exclusion from grazing on direction-dependent soil functions (i.e., gas and water fluxes) in Inner Mongolian steppe ecosystem. We investigated two different steppe communities: *Stipa grandis* and *Leymus chinensis*, which are dominant steppe ecosystems occurring in the investigated region of the Xilin River Basin.

The objective of these studies was to address the following research questions:

1) How far does grazing affect these soil functions under different vegetation types?
2) How far can the soil recover after 30 years of exclusion from grazing, under two different vegetation types?
3) How much can the anisotropy of soil functions change under different moisture conditions?

MATERIALS AND METHODS

Site description

The investigations were carried out in Inner Mongolia, P.R. China, at the Xilin River Basin, close to Inner Mongolia Grassland Ecosystem Research Station (IMGERS, Institute of Botany, Chinese Academy of Sciences; 43°38' N, 116°42’ E), situated around 450 km North from Beijing. The investigated area is located in a semiarid steppe ecosystem at the altitude of around 1270 m above sea level. The climate in this region is characterized as dry and cold temperate with the mean annual temperature of +0.7 °C and the maximum and minimum annual temperatures of +33 °C and -40 °C, respectively. The mean annual precipitation is around 340 mm and the growing season lasts about 150 days, from the beginning of April until the end of September. We investigated two different steppe ecosystems, characterized by domination of the two plant species: *S. grandis* (SG) and *L. chinensis* (LCh). The two studied vegetation types are dominant at the Xilin River Basin and they account for approximately 60% of the whole catchment (Chen et al., 2005). The SG and LCh sites are situated at a distance of approximately 30 and 8 km south-west from the IMGERS. The LCh site is characterized by relatively higher annual precipitation (~408 mm) than the SG (~361 mm). The soils in this area were derived from fine-sand aeolian sediments and were classified according to the World Reference Base for Soil Resources (IUSS Working Group WRB, 2006) as Calcic Chernozems and Kastanozems at the LCh and SG, respectively. In the topsoil of the SG site a visible platy soil structure was defined under in situ conditions, which, because of the texture, is not completely strong.

We investigated two treatments, characterized by different grazing intensities: ungrazed since 1979 (UG79) and grazed (continuously grazed, CG, at SG and winter grazed, WG, at LCh). At SG site, until 1979 the whole area was grazed with a low grazing intensity. In 1979 an area of 23 ha was fenced and excluded from grazing and since that time no grazing has been done at this treatment. At the remaining 19 ha area grazing has been continued, and since 1995 grazing by 200 animals takes place every day for 2-3 hours. The grazed area is not fenced; therefore the grazing intensity at this treatment varies during the year. The herd at SG CG treatment consists of 75% of sheep and 25% of goats.

In 1979 the area of around 24 ha of the *L. chinensis* steppe ecosystem was fenced and excluded from grazing. The remaining area was grazed until 1979 with a low grazing intensity and after 1979 the grazing intensity was increased to a moderate level. In 1999 an area of 34 ha was fenced and grazed only during the winter time with a grazing intensity of 0.5 sheep units/ha (1 sheep unit equals one sheep with one lamb). The herd at this treatment consists of 70-90% of sheep and 10-30% of goats.

Sampling design

The soil samples were collected in the summer of 2004-2006 (from the LCh site) and 2007-2008 (from the SG site). We collected undisturbed soil samples from three replicate soil profiles (approximately 60 cm deep) per each treatment, situated from each other at a distance of approximately 15 m. The undisturbed soil samples were taken from the first two soil horizons of each profile.

For determination of the saturated hydraulic conductivity (k_s) we collected seven replicate samples using 100 cm^3 stainless steel cylinders (40 mm height and 56 mm diameter). The soil samples were collected in vertical direction from each profile of the LCh and SG sites and from two depths (4-8 and 18-22 cm). In addition, in order to determine if k_s presents a direction-dependent behavior, seven soil samples in horizontal direction were taken from two investigated soil horizons of each profile. The unsaturated hydraulic conductivity (k_u) was measured on three samples (470 cm^3) collected from each profile of LCh and SG sites, from two horizons (2-11 cm and 12-22 cm) and in two directions (vertical and horizontal). In order to determine the air conductivity (k_a), we collected 15 samples from each soil profile of the SG site, using 236 cm^3 stainless steel cylinders (30 mm height and 100 mm diameter). The soil samples were taken from two depths (4-8 and 18-22 cm) and in two directions (vertical and horizontal).

Measurements

Hydraulic properties

The saturated hydraulic conductivity was measured using falling-head method as described by Hartge and Horn (2009). The unsaturated hydraulic conductivity was determined using the method described by Plagge (1991) by measuring the soil water content and the matric potential at two positions within the soil sample over time.

Air conductivity

The air conductivity was determined at a pre-drying intensity of -300 hPa using an air permeameter (described by Peth, 2004). The defined matric potential is the highest which may be expected under semiarid climatic conditions after the summer rainfall and defines the weakest soil stability state.

Calculations

Hydraulic properties

The saturated hydraulic conductivity (k_s) for an unsteady flow conditions was calculated using Darcy's law as follows (Eq. [1]):

$$k_s = \frac{al}{tA} \ln \frac{h_0}{h_1} \qquad [1]$$

where: k_s is the saturated hydraulic conductivity (cm s^{-1}); a is the area of the hydraulic head (cm^2); l is the height of the hydraulic head (cm); A is the cross-sectional area of the cylinder (cm^2); h_0, h_1 is the height of the hydraulic head in the beginning and in the end of the measurement (cm); t is the time of discharge of the quantity of water between h_0 and h_1 (s).

The obtained results of unsaturated hydraulic conductivity varied in the range of matric potentials from approximately -40 hPa to -1000 hPa. In order to characterize the relation between the hydraulic conductivity (k) and matric potential (ψ, shown in figures as pF values), the measured values of unsaturated hydraulic conductivity (k_u), obtained from all cylinders of each site, were fitted to the model (Eq. [2]) proposed by van Genuchten et al. (1991).

$$k_u(\Psi) = k_s \frac{\left[1-(\alpha\cdot|\Psi|)^{m\cdot n}\cdot\left(1+(\alpha\cdot|\Psi|)^n\right)^{-m}\right]^2}{\left[1+(\alpha|\Psi|)^n\right]^{m\cdot l}} \qquad [2]$$

where: k_u is the unsaturated hydraulic conductivity (cm s^{-1}); k_s is the saturated hydraulic conductivity (cm s^{-1}); ψ is the matric potential (hPa); α (cm^{-1}), *n, m, l* are the van Genuchten empirical shape parameters. The parameter *m* was calculated with the restriction $m=1-1/n$. The inverse of α is described as the air entry value of bubbling pressure and the *l* is a pore connectivity parameter, usually set to 0.5.

In order to get a better fit of the measured values to the model, in a process of deriving the k(ψ) curves we used the measured median values of k_s and excluded them from the modeling process (so that the values of k_s were not changed during the modeling). We used the median values of k_s, because they did not significantly differ from the geometric means (usually used) obtained for each set of samples. The k (ψ) curves were drawn using the median values of the saturated hydraulic conductivity (k_s) and modeled values of unsaturated hydraulic conductivities (k_u) obtained for different matric potential values.

The anisotropy coefficient of k_s was calculated as the ratio of the median values measured in horizontal direction to values measured in vertical direction. The anisotropy coefficients of the unsaturated hydraulic conductivities were calculated for different matric potentials using the ratio of the predicted for the horizontal direction values of k_u to the values obtained for the samples taken in vertical direction.

Air conductivity and air-filled porosity

The anisotropy coefficient of the air conductivity was calculated as the ratio of the median values of the samples taken in horizontal direction to the values of the samples taken in vertical direction. The air permeability k_{ap} (μm^2) was calculated from the air conductivity k_a ($m\ s^{-1}$) as follows (Eq. [3]):

$$k_{ap} = \frac{k_a \eta_a}{\rho_a g} \qquad [3]$$

where: k_{ap} is the air permeability (μm^2); k_a is the air conductivity ($m\ s^{-1}$); η_a is the air viscosity (Pa s); ρ_a is the air density ($kg\ m^{-3}$); g is the gravitational acceleration ($m\ s^{-2}$). The air-filled porosity (ε_a) was calculated as the difference between total porosity and the volumetric water content at the matric potential of -300 hPa.

Pore-continuity indices

The relationship between air permeability (k_{ap}) and air-filled porosity (ε_a) was used for calculation of two indices (C_2 and C_3) of pore continuity (Eqs. [4] and [5]) as proposed by Groenevelt et al. (1984) and modified according to Ball et al. (1988):

$$C_2 = \frac{k_{ap}}{\varepsilon_a} \qquad [4]$$

$$C_3 = \frac{k_{ap}}{\varepsilon_a^{\ 2}} \qquad [5]$$

where: C_2, C_3 are the indices of pore continuity (μm^2); k_{ap} is the air permeability (μm^2) and ε_a is the air-filled porosity ($cm^3\ cm^{-3}$).

The median values of the pore-continuity indices were calculated. The indices of pore continuity (C_2 and C_3) describe how far the air permeability is influenced by the air-filled porosity as well as by the geometrical aspects of air-filled pore space (Groenevelt et al., 1984). The C_2 index is often used to describe the direct interrelation between air permeability and air-filled porosity. However it does not consider the geometrical aspects of the air-filled pores which conduct the air. The C_3 index was therefore derived based on the Hagen-Poiseuille's law and is characterized by lower sensitivity to the pore-size distribution (Dörner and Horn, 2006). Furthermore, Groenevelt et al. (1984) underlined that soils with similar values of C_2 should be characterized by similar pore-size distribution and continuity. Furthermore, how far do the management-induced changes in the pore functioning improve the site can be evaluated from the C_3 index. The pore-continuity indices were determined for two soil horizons of SG site, in vertical and horizontal direction. In addition, in order to classify the C_2 and C_3 indices, the values of air conductivity which according to DVWK (1997) define the thresholds of different classes were recalculated to air permeability values which were used to calculate the pore-continuity indices. The obtained C_2 and C_3 values were then plotted versus chosen values of ε_a (varying from 0.1 $cm^3\ cm^{-3}$ to 0.4 $cm^3\ cm^{-3}$) and ε_a^2, respectively.

Statistical analyses

The statistical analyses were done using the R 2.5.1 software (Venables et al., 2009). The normal distribution of the data was tested using Shapiro-Wilk test of normality. The statistically significant differences between results were tested using Wilcoxon test. The results were classified as statistically significant at a level of significance of $p<0.05$. For graphical visualization of results of air conductivity, air-filled porosity and pore continuity indices the box plots were chosen. The box plots can be used not only for presenting normally distributed data but are an appropriate method of presenting not-normally distributed data for which no additional transformation into logarithms is needed. Each box plot contains the information about the median value (black line across the box), lower and upper hinges (defined as the 25th and 75th percentiles), minimum and maximum values and outliers (displayed as diamonds). In addition, the notches presented in each box plot showed the 95% confidence interval of differences between medians (for further information see: McGill et al., 1978). In order to determine the statistically significant differences between the k (ψ) curves the 95 % confidence intervals were calculated.

RESULTS

Hydraulic properties

Comparison of the effect of soil management on k(ψ) curves

The results of hydraulic conductivity (k) obtained for the first soil horizon showed differences depending on matric potential, vegetation type and treatment (***Fig. 3.3.1.***). The hydraulic conductivity decreased as the matric potential became more negative. At the SG site the unsaturated hydraulic conductivity of the samples taken in vertical direction from the UG79 treatment was significantly higher compared to the CG treatment at matric potentials lower than pF 2.2, while the opposite was found at the matric potential values higher than pF 2.5. Between the horizontally oriented samples collected from the SG UG79 and SG CG treatments no statistically significant differences in hydraulic conductivity were found for matric potentials smaller than pF 1.5. However, at the LCh site, significantly lower k_u values were found in horizontally oriented samples taken from the

UG79 compared with the WG treatment if the matric potentials were less negative than pF<2.5.

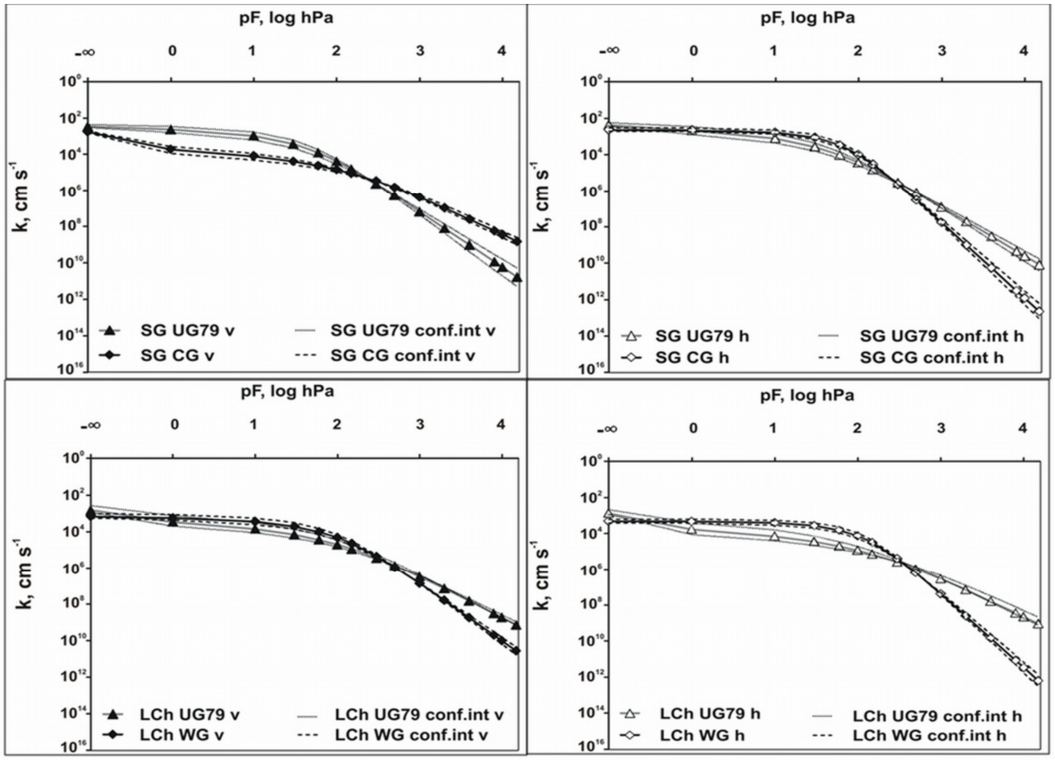

Figure 3.3.1. Hydraulic conductivity (k) for different matric potential values (pF) drawn for samples taken in vertical (v) and horizontal (h) direction from the *Stipa grandis* (SG) and *Leymus chinensis* (LCh) sites, from treatments: ungrazed since 1979 (UG79), continuously grazed (CG) and winter grazed (WG); depth: 2-11 cm; n=9; the scatter lines indicate the lower and upper 95% confidence intervals (conf. int)

Comparison of the k(ψ) ratios depending on management, sampling direction and depth

In order to compare the flux properties within the soils in two directions, the k (ψ) curves were drawn separately for each site, treatment and horizon. The results showed that at less negative matric potentials (pF<2.5), in the first depth of the SG CG site (***Fig. 3.3.2.***) significantly higher conductivities in horizontal direction compared to the vertical one were found while at LCh WG site (***Fig. 3.3.3.***) no statistically significant differences between vertical and horizontal conductivities were detected.

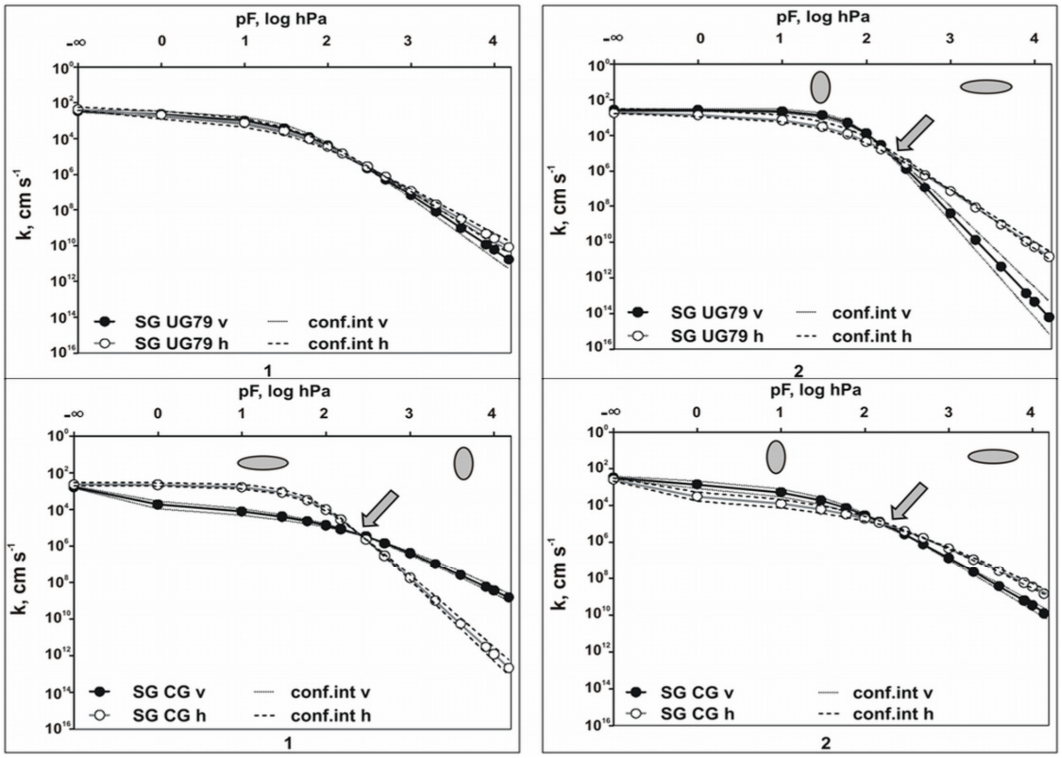

Figure 3.3.2. Hydraulic conductivity (k) for different matric potential values (pF) drawn for samples taken in vertical (v) and horizontal (h) direction from the *Stipa grandis* (SG) site, from two treatments: ungrazed since 1979 (UG79) and continuously grazed (CG); and two horizons: 2-11 cm (1) and 12-22 cm (2); n=9; the scatter lines indicate the lower and upper 95% confidence intervals (conf. int); the arrows indicate the cross-over matric potential values (= isotropic conditions); the shape of the ellipses indicates the dominant direction of the water flow at matric potentials before and after cross-over value (e.g., higher horizontal axis of the ellipse than vertical one indicates the higher water flow in horizontal direction)

In the second soil horizon of the SG site and LCh UG79 treatment significantly higher k_u values in vertical direction were found at the less negative matric potentials while the LCh WG site had significantly higher k_u in horizontal direction.

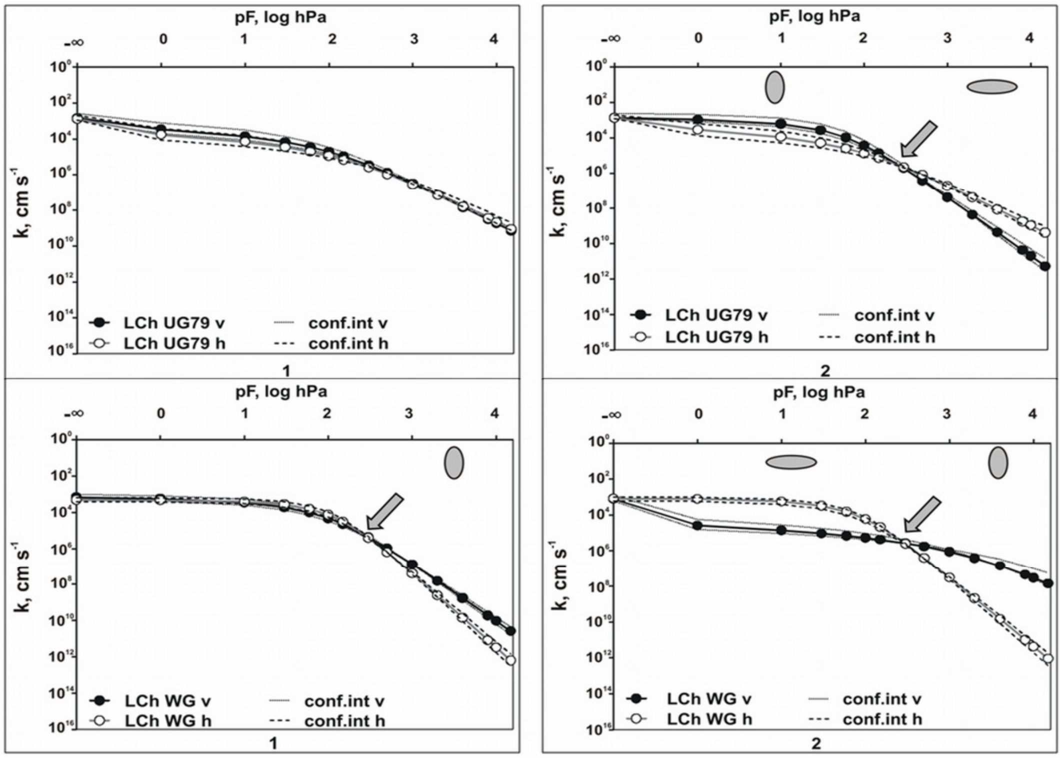

Figure 3.3.3. Hydraulic conductivity (k) for different matric potential values (pF) drawn for samples taken in vertical (v) and horizontal (h) direction from the *Leymus chinensis* (LCh) site, from two treatments: ungrazed since 1979 (UG79) and winter grazed (WG); and two horizons: 2-11 cm (1) and 12-22 cm (2); n=9; the scatter lines indicate the lower and upper 95% confidence intervals (conf. int); the arrows indicate the cross-over matric potential values (= isotropic conditions); the shape of the ellipses indicates the dominant direction of the water flow at matric potentials before and after cross-over value (e.g., higher horizontal axis of the ellipse than vertical one indicates the higher water flow in horizontal direction)

The coefficients of anisotropy calculated for different sites, treatments and depths varied depending on the matric potential (***Table 3.3.1.***). Between the matric potential of -150 and -300 hPa the shift of the anisotropy (i.e., the change from the anisotropy in horizontal direction to anisotropy in vertical direction and vice versa) could be observed at almost all investigated sites and horizons (except for the first horizon of the LCh UG79). Another shift in anisotropy was detected at the conditions close to saturation i.e. between the matric potentials 0 and -1 hPa in the first soil horizon of SG UG79 site. The differences in coefficients of anisotropy between ungrazed and grazed treatments were at SG site more pronounced in the first depth while at LCh site the more pronounced differences were found in the second horizon.

Table 3.3.1. Coefficients of anisotropy of saturated (matric potential = 0 hPa) and unsaturated (matric potentials from -1 hPa to -1000 hPa) hydraulic conductivities of two investigated sites: *Stipa grandis* (SG) and *Leymus chinensis* (LCh) and different treatments: ungrazed since 1979 (UG79), continuously grazed (CG) and winter grazed (WG) for different matric potentials; depths: 2-11 cm and 12-22 cm; n=9

Matric potential (-hPa)	Site and depth (cm)							
	SG UG79		SG CG		LCh UG79		LCh WG	
	2-11	12-22	2-11	12-22	2-11	12-22	2-11	12-22
0	1.20	0.70	1.30	0.80	0.90	1.00	0.70	1.10
1	0.88	0.52	11.63	0.22	0.51	0.27	0.84	29.40
10	0.74	0.32	20.66	0.24	0.50	0.19	1.11	40.37
30	0.71	0.23	21.06	0.33	0.52	0.19	1.39	34.51
60	0.77	0.23	13.94	0.47	0.56	0.25	1.57	21.54
100	0.86	0.34	7.06	0.66	0.59	0.36	1.58	10.90
150	0.97	0.60	3.29	0.90	0.63	0.52	1.43	5.02
300	1.23	2.02	0.68	1.53	0.72	1.14	0.93	0.92
500	1.47	5.22	0.20	2.19	0.79	2.07	0.60	0.22
1000	1.90	18.73	0.04	3.37	0.89	4.56	0.31	0.03

Air conductivity and air-filled porosity

In the top 10 cm the SG UG79 site had significantly higher k_a values in horizontal direction compared with the SG CG site; additionally a significant anisotropy of k_a in horizontal direction was found at the SG UG79 site. At the SG CG site the air conductivity showed similar values in both directions (***Fig. 3.3.4., left***). In the second depth both SG UG79 and SG CG sites were characterized by a significant anisotropy of k_a in horizontal direction.

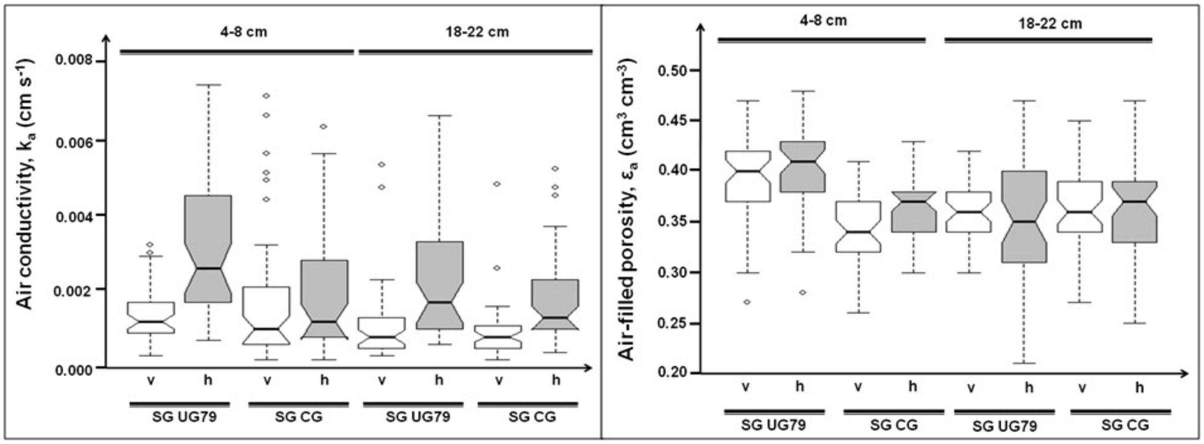

Figure 3.3.4. Air conductivity (k_a, left) and air-filled porosity (ε_a, right) of ungrazed since 1979 (UG79) and continuously grazed (CG) treatments of the *Stipa grandis* (SG) site determined for different directions: vertical (v) and horizontal (h); depths: 4-8 cm and 18-22 cm; n=45; matric potential = -300 hPa

In the first soil horizon, significantly higher values of air-filled porosity were found in horizontally oriented samples of SG CG compared to the vertical ones because of a higher variation and uneven distribution of pores in samples taken in vertical and horizontal direction. In this horizon the SG UG79 site was characterized by significantly higher air-filled porosity than the SG CG site (***Fig. 3.3.4, right***).

Pore-continuity indices

The pore continuity indices obtained for the SG site differed depending on the treatment, depth and direction. It was found that at all treatments the values of C_3 were significantly higher compared to the values of C_2. Irrespective of the treatment under *S. grandis* (UG79 and CG) the higher values of the indices of pore continuity (C_2 and C_3) were found in the samples taken in the horizontal direction (***Fig. 3.3.5.***). Except for the topsoil (4-8 cm) of the SG CG site the differences between the values of the pore continuity indices of the samples collected in vertical and horizontal direction were statistically significant.

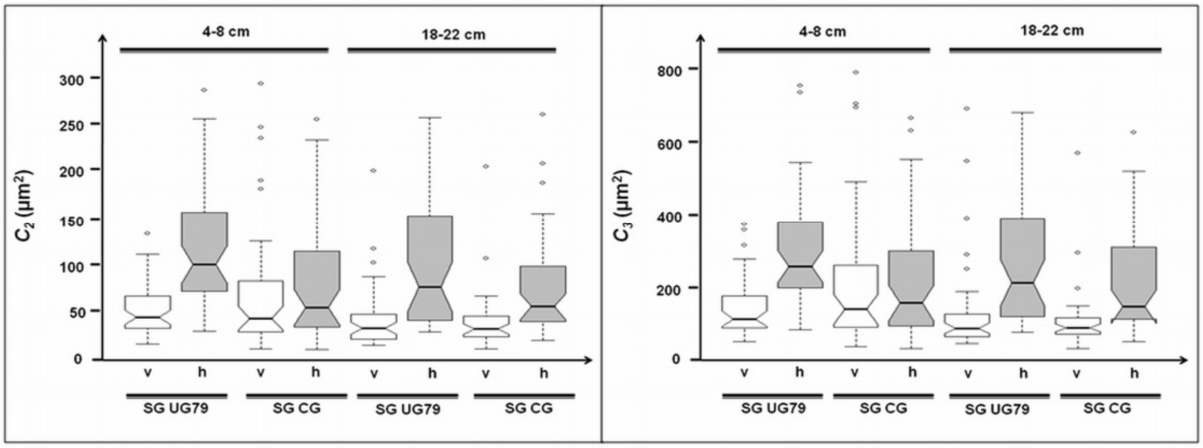

Figure 3.3.5. Pore continuity indices (C_2 and C_3) of the ungrazed since 1979 (UG79) and continuously grazed (CG) treatments of the *Stipa grandis* (SG) site calculated for different directions: vertical (v) and horizontal (h); depths: 4-8 cm and 18-22 cm; n=45; matric potential = -300 hPa

Classification of the pore-continuity indices

According to the German soil mapping instructions, the relation between C_2 or C_3 and the air-filled porosity can be subdivided into various classes (shown in ***Fig. 3.3.6.*** and ***3.3.7.***). It can be seen that with an increase of air-filled porosity the indices of pore continuity decline. In addition, the application of such scheme to differentiate between the two treatments, directions and depths gives an insight in the processes which depend on these external effects.

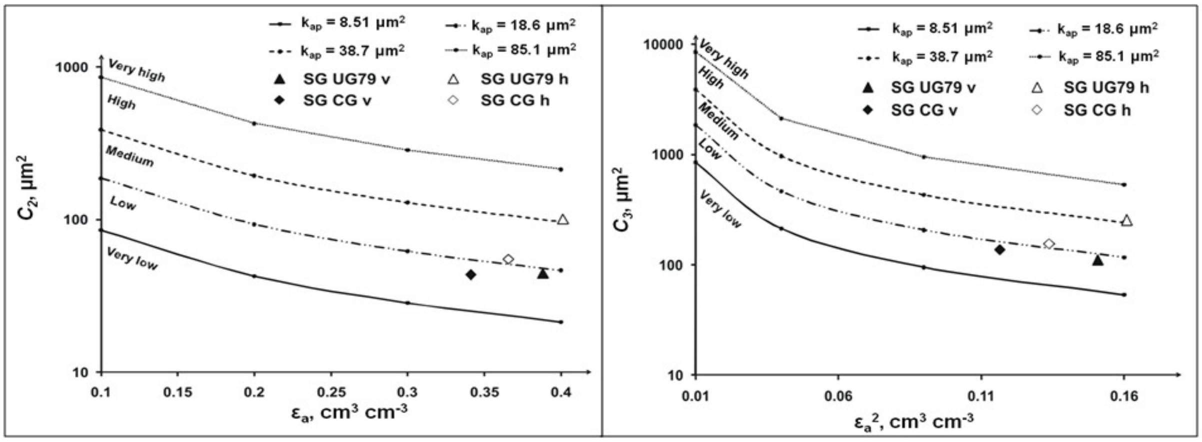

Figure 3.3.6. Relation between pore continuity indices (C_2 – left, and C_3 – right) and air-filled porosity (ε_a – left) and squared air-filled porosity (ε_a^2) calculated for the ungrazed since 1979 (UG79) and continuously grazed (CG) treatments of the *Stipa grandis* (SG) site for different directions: vertical (v) and horizontal (h); depth: 4-8 cm; matric potential = -300 hPa; the isolines indicate the threshold values of air permeability for different classes

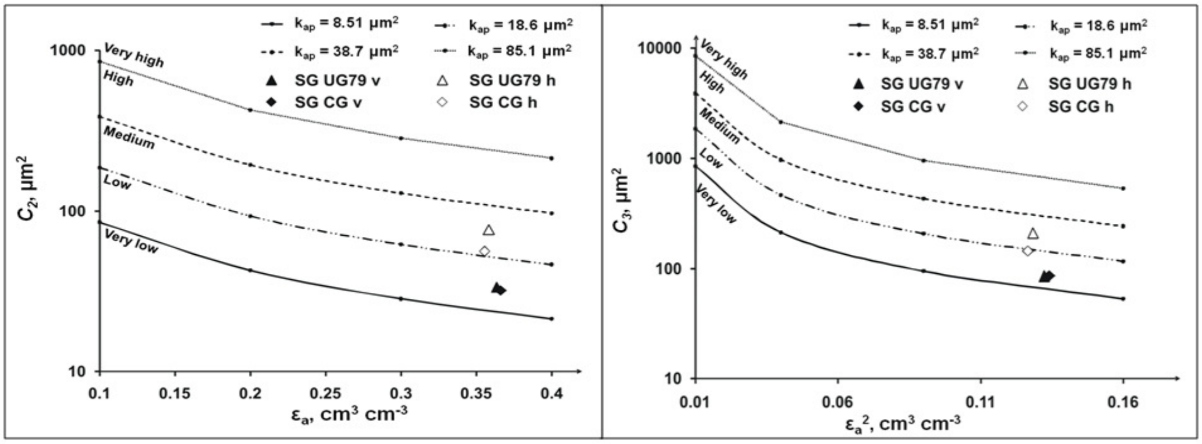

Figure 3.3.7. Relation between pore continuity indices (C_2 – left, and C_3 – right) and air-filled porosity (ε_a – left) and squared air-filled porosity (ε_a^2) calculated for the ungrazed since 1979 (UG79) and continuously grazed (CG) treatments of the *Stipa grandis* (SG) site for different directions: vertical (v) and horizontal (h); depth: 18-22 cm; matric potential = -300 hPa; the isolines indicate the threshold values of air permeability for different classes

In the first soil horizon the C_2 and C_3 values calculated for the vertically oriented samples of SG UG79 and SG CG sites were classified as low while the values obtained for horizontal direction were classified as medium at SG CG site and high at SG UG79 site (***Fig. 3.3.6.***). The pore-continuity indices of vertical samples did not differ significantly between both treatments while the significantly higher values of indices of pore continuity were found in horizontal samples taken from SG UG79 site compared to the SG

CG site. In the second soil horizon the pore-continuity indices calculated for vertical samples were at both treatments classified as low (***Figure 3.3.7.***). The values of C_2 of horizontally oriented samples were classified as medium while the values of C_3 were classified as low at SG CG site and as medium at SG UG79 site. No statistically significant differences between the pore-continuity indices of two treatments were found in the second horizon which was true for both directions.

DISCUSSION

Effect of soil management on soil resilience

Water and air fluxes in soil depend on the continuity of pore network and are good indicators of changes in soil structure. In structured soils under saturated or close to saturated conditions, the coarse inter-aggregate pore network affects the rapid downward movement of water in soil (Beven and Germann, 1982). Water redistribution under unsaturated conditions, however, primarily occurs through the smaller, and less mobile intra-aggregate pore system (Carminati et al., 2008; Leeds-Harrison et al., 1994) and is retarded because of the flux resistances between coarser and finer pores. However, the quantification of the flow processes including the tensorial interaction is until now seldom analyzed and most of the statements regarding this subject are based on numerous assumptions. Until now, the research on the iso- or anisotropy of water flow in soils was concentrated on the investigation of the hydraulic conductivity under saturated conditions while the direction-dependent water flow under unsaturated conditions is rarely studied (Dörner, 2005; Tigges, 2000). In addition, until now the studies on the anisotropy of unsaturated hydraulic conductivity were based on the assumption that the anisotropy of unsaturated porous media is the same as at saturation (Zhang et al., 2007).

Our results also showed that the flow of air and water through the soil as well as its anisotropy can vary depending on time, land use as well as matric potential. Repeated wetting and drying, swelling and shrinkage, freezing and thawing processes or biological activity play the key role in soil structure reformation coinciding with a natural soil recovery from deterioration and accompanied by creation of soil pores (Dexter, 1988; Horn and Smucker, 2005). It has been proven, that exclusion from grazing leads to increase in the amount of macropores and infiltration (Castellano and Valone, 2007; Drewry and Paton, 2000). Greenwood et al. (1998) found a significant increase in unsaturated hydraulic conductivity at 1.5 and 0.5 cm tensions (which correspond to the 2.0 mm and 6.0

mm equivalent cylindrical pore diameters) after exclusion from grazing for 2.5 years. Hoshino et al. (2009) found that at water content higher than 0.35 cm^3 cm^{-3} the unsaturated hydraulic conductivity at the treatment excluded from grazing was greater than that of the grazed treatment. This is in agreement with our results. We found the higher k_u values in vertical direction at the SG UG79 site compared to the SG CG site at the matric potentials lower than pF 2.2 (the diameter of pores > 0.02 mm). In addition, our results pointed out not only the recovery of the amount of pores at the ungrazed treatments but also of related soil functions. In well-recovered (i.e. well aggregated) soil no anisotropy in soil functions should be detected (Dörner and Horn, 2009) which is in agreement with our data for the first horizon of the ungrazed treatments of the SG and LCh sites, where no statistically significant differences in the hydraulic conductivities between the vertically and horizontally oriented samples were found. Furthermore, the recovery of the soil pore network in the first horizon was more pronounced at the LCh site as it can be seen from the lower values of the coefficients of anisotropy compared to the SG site.

The coefficients of anisotropy of hydraulic conductivity change at different matric potentials, which is until now not well described in the literature and it requires detailed analyses of samples collected in both directions. In order to explain the matric-potential- and the treatment-affected dependency, we have to consider not only the general crack formation processes but also the interactions between animal trampling, climatic conditions and their consequences on the various generations of aggregates concerning their hydraulic and gaseous flux regimes. Under saturated conditions (matric potential = 0 hPa) the SG UG79 site was characterized by anisotropy in horizontal direction which can be related to the high amount of plant rhizomes at this site. According to Brix (1987) such rhizomes create macropores, mostly of tubular shape which after decay leave horizontally-oriented channels, filled with loosely packed organic material. Because the rhizomes very often have diameters greater than 3 mm, the water fluxes in these pores are affected only by the matric potential values close to saturation (i.e. less negative than -1 hPa). If, however, the soil dries out more intense, the intensity and kind of anisotropy changes again and shows the same kind of ratio only at more negative matric potential values. Thus, we cannot assume constant anisotropy ratios but they depend on soil management and management history.

Finally we want to draw attention to the functioning of the pores i.e. their continuity concerning the mass movement of water or gas. Air permeability is influenced by the magnitude of air-filled porosity as well as pore-size distribution, shape, pore continuity or tortuosity of air-filled pores (Tamari, 1994). The obtained results of the air conductivity for the SG site at a given matric potential of -300 hPa, underline once again the anisotropic alignment of pores and their functions. It could be seen, that results of air conductivity had similar trends as hydraulic conductivity, however it can be stated that the differences in air conductivity between the treatments can be strongly influenced by existence of blocked porosity and rearrangement of particles of vertically and horizontally oriented samples (Ball et al., 1988; Dörner and Horn, 2009). In order to determine if the differences in k_{ap} resulted only from the differences in air-filled porosity or geometrical aspects of air-filled space, the k_{ap} should be related to the flux-controlling pore diameter (according to Hagen-Poiseuille's law). Groenevelt et al. (1984) calculated the C_3 values for different treatments and points of time. They found that the conductivity, or pore continuity, mostly does not differ, irrespective of the management. We calculated the C_3 values only for one matric potential and could prove significant differences depending on management, especially in the top soil layer and partly in subsoil. In general the continuity of pores was better in horizontal direction compared to the vertical one, which was true for SG UG79 and SG CG sites. If we finally classify our data according to the German soil mapping instructions we find that our results of C_2 and C_3 are mostly classified as low and medium. The structure reformation and the improved pore continuity seem to coincide, even if due to the expected scattering of data a clearer picture would request more detailed analyses at various matric potential values.

Grazing effects on anisotropy of soil physical functions

Animal trampling causes a decline in the hydraulic conductivity, mostly related to destruction of the macropores and changes of soil functions (Pietola et al., 2005). However, the consequences for the kind and degree of anisotropy were not analyzed in those days. More information can be found about the recovery time and intensity under various land use systems. Zimmermann and Elsenbeer (2008) studied the effect of soil disturbances on the variation of saturated hydraulic conductivity and its recovery over the time. They found that saturated hydraulic conductivity as a very sensitive indicator of soil disturbance decreases due to grazing, which is in agreement with our studies. Moreover, grazing can lead to significant formation of platy soil structure through compaction coinciding with the rearrangement and reorganization of the particles and formation horizontally oriented pores (Martinez and Zinck, 2004). Such rearrangement of particles and formation of new structure units can be characterized by the matric-potential-dependent changes in the isotropy or anisotropy of soil flux parameters. While often the isotropy is assumed to dominate, this is indeed mostly unrealistic and theoretically limited to the densest configuration of equally shaped spheres. Anisotropy, however, can vary in both directions: while prisms are characterized by the (first) crack formation in vertical direction, they also show a more pronounced vertical anisotropy of hydraulic conductivity near saturation, while platy structure is defined by a horizontal anisotropy. Polyhedral or subangular blocky structure as results of shear induced crack formation and derived from the prisms are assumed to show a more close to isotropy behavior but the previous structure properties are still to be found. Finally, crumbs can be classified as macroscopic homogenous, which should result in close to isotropy conditions especially within the finer pore system (Dörner and Horn, 2006). However, we must point out that the kind and intensity of anisotropy changes as soon as the structural shrinkage range is exceeded and the proportional shrinkage range (according to Peng and Horn, 2005) is reached. Under those conditions the rearrangement of aggregates (via changes in inter-aggregate macropores) and of particles results in a predominantly vertical new crack formation. A significant anisotropy of k_u in horizontal direction in the first horizon of the SG CG site can confirm the creation of a platy soil structure at this site and is also in agreement with findings of Krümmelbein et al. (2006). Furthermore, in this horizon the horizontal water flux under unsaturated conditions found at less negative matric potentials was higher at grazed treatments compared to UG79 ones which underlines the differences in soil structure between the treatments. On the other hand grazing, especially under wetter conditions can cause soil puddling, weakening and homogenization coinciding with more intense shrinkage, the reformation of new vertically oriented macropores. These macropores may be even less rigid due to the release of soil organic carbon followed by further destabilization of soil aggregates (Horn, 1986; Pietola et al., 2005; Wiesmeier et al., 2009). In such weaker system the stress distribution can reach the deeper soil horizons and form additional horizontal cracks. Pietola et al. (2005) found that trampling at wetter conditions has led to complete loss of strength and cohesion at the soil surface (0-5 cm) and on the other hand an increase in air permeability and saturated hydraulic conductivity related to the new structure formation starting at the soil surface. Furthermore, they found that deeper soil layers became denser and were characterized by higher cohesion and lower saturated hydraulic conductivity. Such findings are in agreement with our results obtained for the LCh WG site where in the first soil horizon, due to soil puddling, no statistically significant differences between k_u in vertical and horizontal direction were found in the range of the matric potentials from pF 0 to pF 2.7 (diameter of pores > 0.006 mm). As a consequence of animal trampling in the previously weakened topsoil followed by enhanced stress propagation to deeper depths a platy soil structure was formed at the transition to the non affected deeper soil horizons what can be proven by the significant horizontal anisotropy of k_u in the macropores of the second horizon at the LCh WG site. However, because these animal-induced changes in pore functions are mostly attributed to the coarser pores and fade off with decreasing pore diameter, the trampling-induced particle rearrangement can also alter the direction of anisotropy besides the effects of layering of soil material caused by accumulation of aeolian sediments. Due to the layering of soil material caused by accumulation of aeolian sediments the k_u in horizontal direction can be higher compared to the vertical direction as it has place at the ungrazed treatments. This is in agreement with Hoffmann et al. (2008b), who found that the dust deposition rates in the Inner Mongolian semiarid grassland equaled 1.3 and 2.4 g m^{-1} d^{-1} at grazed and ungrazed sites, respectively. The differences in hydraulic behavior in medium pores can be also related to the root growth which can form the medium pores. Finally, it has to also be stated that anisotropy of k_u at more negative matric potentials can be also caused by shrinkage of soil which occurs while drying the samples. Dörner and Horn (2006) found that the soil drying can induce a change in direction-dependent behavior of soil which can be explained by differences between shrinkage within the structural and proportional shrinkage ranges.

CONCLUSIONS

The presented results allow us to quantify the hydraulic and air conductivity functions with respect to different land use, vegetation type for different matric potential values.

1) Grazing leads to significant changes in soil structure and through that also in soil functions. Moreover, exclusion from grazing was followed by a recovery process which, depending on the climatic conditions and domination of the main plant species, led to a more or less pronounced recovery of the soil structure, mainly due to creation of the macropores.

2) Changes of the anisotropy of the soil functions depend on the moisture conditions. The pore continuity indices can be applied to evaluate and

classify the changes in air permeability depending on different land use as well as to explain the differences between sites which results from changes in air-filled space and pore connectivity.

3) It can be stated that in order to evaluate and predict the water and gas flux in soil properly, the anisotropy of the soil functions depending on the moisture conditions must be included in future modeling processes.

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CHAPTER IV

(Discussion and Conclusions)

GENERAL DISCUSSION

GENERAL

In the following section the general findings about grazing effects on soil mechanical strength and soil physical functions of Inner Mongolian steppe ecosystems will be discussed. Although the impact of animal trampling and grazing intensity on steppe ecosystem in Inner Mongolia was already well examined, until now there is lack of knowledge regarding the effect of different vegetation type on mechanical and hydrological soil properties and functions. Therefore, particular attention will be paid to differences in soil physical properties between two dominating grassland ecosystems: *Leymus chinensis* and *Stipa grandis*.

SOIL MANAGEMENT AND PERSISTENCE OF SOIL DEFORMATION

Improper land management has become one of the major environmental problems over the last decades. One of the consequences of an increased exploitation of soil resources is soil deformation which mostly has a long-term impact on soil productivity. However, although these problems have already been well examined for arable soils, there is still not enough information on the influence of animals on soil compaction and soil structure deterioration under very sensitive semiarid steppe conditions.

One of the consequences of animal trampling, indicating soil compaction is an increase in soil mechanical strength. This ability of soil to withstand mechanical loading depends on external forces and internal parameters such as: texture, content and composition of organic matter, degree of aggregation or water content and water suction (Horn, 1993). Animal trampling is one of the factors leading to changes in soil mechanical strength due to exerted external forces by animal hooves. The presented results emphasized a significant impact of grazing on soil structure deterioration. Moreover, an increased bulk density and variation of soil mechanical strength indicated soil compaction. It could be seen, that animal trampling leads to alteration of soil mechanical strength on the aggregate and bulk soil scales.

One of the more important properties is the mechanical strength of aggregates, which often indicates the response of the whole soil system to management variations. Thus, knowledge about these properties is important to understand the macro-scale soil functions (Blanco-Canqui et al., 2005). The alteration of aggregate mechanical strength due to animal trampling can be caused by changes in the amount of contact points between aggregates, organic matter content or water content. Tensile strength is, among others, one of the most useful measure of strength of aggregates and a sensitive indicator of the soil condition (Dexter and Kroesbergen, 1985). The results revealed higher values of tensile strength at the grazed treatments compared to the ungrazed ones, which can indicate a disruption of aggregates followed by compaction due to animal trampling. The mechanical stresses exerted by animal hooves press soil mineral particles together which, in addition, are packed in a denser way and lead to an increased mechanical stability of aggregates (Fabiola et al., 2003; Khaidapova and Pestonova, 2007).

A decrease in tensile strength at ungrazed sites can reflect soil structure recovery and reformation followed by exclusion from grazing. One could expect that the sites richer in organic matter will be characterized by higher stability of aggregates due to higher content of particulate organic matter and neutral sugars (Steffens et al., 2009). However, also the differences in degree of protection and mineralization of organic matter should be considered. In general, well developed soil structure has a hierarchical nature where the higher order is represented by macro-aggregates which are composed of micro-aggregates and the latter ones are built of single particles (Dexter, 2002). Such hierarchy in aggregation cannot be found at the grazed sites because of a continuous impact of animal trampling. Dexter (1988) described that the aggregate compounds of the lower hierarchical order are more dense, have higher internal strength and, therefore, are more rigid compared to compounds of the next order. In addition, the micro-aggregates are linked and glued by roots and hyphae, which can be easily decomposed, leading to further decline in the stability which can explain lower tensile strength of aggregates at the ungrazed sites (Wiesmeier et al., 2010).

In addition, the presented results revealed differences in mechanical strength of aggregates between two investigated vegetation types which can be related to the differences in organic matter content and its composition at the *Leymus chinensis* and *Stipa grandis* sites. Long-term studies on biomass productivity of *Stipa grandis* and *Leymus chinensis* steppe ecosystems, conducted in Inner Mongolian grassland showed higher aboveground biomass production of the *Leymus chinensis* site compared to the *Stipa grandis* (Bai et al., 2004). The higher aboveground biomass production at the *Leymus chinensis* site contributes to higher input of organic matter to soil (Wiesmeier et al., 2009) which can explain higher values of tensile strength at the *Leymus chinensis* site.

However, the differences in mechanical strength were observed not only on aggregate scale, but were also found in bulk soil. Animal trampling had an influence on soil compressibility and strength of bulk soil. An increase in precompression stress values in the topsoil of grazed treatments (which reflected ground contact pressure of one sheep hoof) compared to ungrazed sites indicated an impact of animals on soil mechanical strength. In addition, the lower strain of grazed treatment and lower coefficient of cyclic compressibility compared to the ungrazed one emphasized differences in sensitivity of soil to deformation under applied mechanical stresses and indicated soil compaction and higher resistance to deformation of the grazed site (da Veiga et al., 2007) which indicates also changes in soil structure. Furthermore, differences in precompression stress between two grassland ecosystems revealed alteration of soil mechanical strength depending on vegetation type and pointed out that the *Stipa grandis* site experienced higher mechanical stresses in the past compared to the *Leymus chinensis* site.

Apart from the mechanical management interactions concerning aggregate and bulk soil strength, the whole discussion would be incomplete, if the effects of hydraulic stresses on soil strength and the coupled mechanical and hydraulic stresses would not be discussed.

It is well known that soil mechanical strength strongly depends on soil hydraulic stresses as can be derived from the matric potential. The relation between soil mechanical strength and matric potential is described by the effective stress equation (Bishop, 1959) which explains that the effective stress (which indicates the soil stabilizing stress) depends on the total stress and the pore water pressure. According to the effective stress equation the more negative the pore water pressure the closer the soil particles are pulled by water menisci and the more pronounced the stress increase (Semmel et al., 1990). An increased tensile strength of aggregates under drier conditions (i.e. at the temperature of 40 °C) compared to tensile strength under wetter conditions (matric potential of -300 hPa) point out this significant influence of water menisci forces on soil mechanical strength, which is in agreement with the findings of Mosaddeghi et al. (2006).

An alteration of soil mechanical strength due to animal trampling, however, strongly proves the interactions between mechanical and hydraulic stresses. Reduction of pore space due to grazing can be followed by alteration of pore water pressures which can become either negative or positive, depending on a degree of soil water saturation. An application of stress to soil can cause a decline in the amount of macropores and increase in amount of smaller pores which can lead to development of more negative pore water pressure and increase in strength. However, if the drainage of water is too slow as the pressure gets to the soil, the pore water pressure becomes less negative and soil becomes weaker due to destabilizing effect of pore water pressure which leads to a pronounced rearrangement of soil particles (Fazekas and Horn, 2004; To and Kay, 2005). Therefore, it can be expected, that animal trampling practiced under wetter conditions leads to more pronounced soil degradation, disruption of aggregates or even a total soil homogenization (Warren et al., 1986; Dexter, 1990).

Furthermore, changes in soil mechanical strength can be also attributed to repeated loading and unloading which leads to further rearrangement of soil particles due to changes in degree of saturation, which is higher during loading and lower during unloading. Repeated changes in degree of saturation during loading and unloading are accompanied by decrease in shear resistance between soil particles and aggregates (Krümmelbein et al., 2008). Variation of soil strength related to alteration of matric potential is the more pronounced the more often the soil is loaded. The results presented in these studies revealed that frequent loading has led to stronger soil deformation related to more intensive particle rearrangement compared to static loads. Moreover, the results of precompression stress of repeatedly loaded samples revealed decrease in soil strength with increasing amount of loading-unloading events. Furthermore, the results revealed the importance of the impact of the load on differences in soil matric potential between loading and unloading which were higher the higher the load. This is in agreement with Seguel and Horn (2005) who found that the pore water pressure became even positive when soil was loaded with mechanical stresses of > 300 kPa.

It must be stated that knowledge about an influence of soil moisture status on soil mechanical strength is important for prediction of soil deterioration and compaction (Arvidsson et al., 2003; Tarawally et al., 2004). Because *the Leymus chinensis* site is characterized by relatively higher precipitation and therefore higher soil moisture content compared to the *Stipa grandis* site, therefore it can be expected that soil structure deterioration due to grazing will be more pronounced at this site, which was proven in these studies.

Based on the obtained results, it can be stated, that animal trampling has a broad effect on soil mechanical strength. The impact of animals is attributed to exerted mechanical stresses leading to mechanical deterioration of soil structure which is even more pronounced due to a cyclic nature of loadings. Furthermore, variation of soil strength is caused by reduction of soil organic matter content as well as a decline in the aggregation degree caused by animal trampling.

CONSEQUENCES OF GRAZING MANAGEMENT ON THE SUSTAINABILITY OF SOIL PHYSICAL FUNCTIONS UNDER VARIOUS CLIMATIC CONDITIONS

Deterioration of soil structure caused by grazing is accompanied by changes in soil functions related to degradation of pore continuity. Furthermore, it was also shown in these studies that a degree of degradation of soil functions due to applied stresses by animals depended on the trampling intensity or the moisture conditions during the stress application.

Relations between the macro-porosity and hydraulic conductivity were investigated widely (e.g. Gebhardt et al., 2006). However, the amount of macro-pores is not the main factor affecting soil conductivity. Osunbitan et al. (2005) found only a weak relationship between conductivity and porosity and Wahl et al. (2003) explained low values of water infiltration ratios by poor connectivity of pores. This dependency is not only true for the saturated hydraulic conductivity but also for the unsaturated matric potential range as it was also shown by Dörner (2005) who also proved the increasing anisotropy of water flux behavior under unsaturated conditions. Decrease in soil hydraulic functions due to animal trampling can be explained by soil aggregate rearrangement and homogenization which lead to decline in continuity of pathways for water flow (Hartge, 1994). Furthermore, these processes are accompanied by stronger swelling and shrinkage processes which can lead to formation of new cracks and increase soil macro-porosity (Horn and Smucker, 2005).

Furthermore, alteration of soil structure due to grazing is followed by changes in direction-dependent soil behavior. An impact of grazing on soil structure could be already seen from the results of anisotropy of precompression stress which indicated significant rearrangement of soil particles and creation of a platy soil structure, which is supported by the results of anisotropy of saturated hydraulic conductivity. Higher horizontal water flow is attributed to occurrence of horizontal cracks which is in agreement with other authors who found an anisotropic water flux related to formation of platy soil structure (Dörner and Horn, 2006; Sander et al., 2008).

Moreover, the results also indicated that a direction-dependent soil behavior can vary depending on moisture conditions. Usually, under saturated or near to saturated moisture conditions the flow of water is mostly attributed to the large inter-aggregate pores which form the pathways for a rapid water movement. However, under drained conditions water redistributes through smaller intra-aggregate domain which can also manifest an anisotropic behavior (Carminati et al., 2008). The higher horizontal water flow at the *Stipa grandis* site was found only in macro-pores which are concerned to be the most susceptible to compaction (Peth and Horn, 2006).

Because at the *Leymus chinensis* site grazing takes place only during the winter time, under wetter conditions, therefore an impact of animal trampling on soil at this site can be more pronounced leading to soil puddling, more intensive homogenization, followed by intensified swelling and shrinkage processes which lead to an increase in water infiltration into soil (Janssen and Lennartz, 2006; Janßen et al., 2006; Lennartz et al., 2009) and anisotropy of hydraulic conductivity in vertical direction. However, this situation takes place only under saturated or near-to-saturated conditions, while under unsaturated conditions a close-to-isotropic water flow in macro-pores can be found which confirms significant destruction of pore continuity at the grazed treatment of *Leymus chinensis* site. It is in agreement with results of air conductivity which was significantly lower at the grazed treatment compared to an ungrazed one at this site.

The presented results also indicated an improvement of soil functions due to processes related to soil reformation following exclusion from grazing. Soil structure regeneration requires, apart from time, additional physical, biological and chemical processes such as intensive and repeated wetting and drying, freezing and thawing, root growth or expansion of soils by animals, inorganic and organic bindings, which lead to soil aggregation, increase in the amount of pores as well as their continuity and tortuosity (Horn, 1990). Formation of soil structure is usually a long-term process and the time needed for soil recovery from deterioration depends on e.g. degree of soil degradation or climatic conditions (Seybold et al., 1999). Lavado and Alconada (1994) found no improvement of soil physical properties after twelve years from exclusion from grazing while Greenwood et al. (1998) found significant recovery of soil physical properties already after 2.5 years since exclusion from grazing.

The first aggregation process, after previous soil structure deterioration caused by grazing, starts always by creation of vertical cracks, caused by shrinkage, which define a prismatic structure. Further wetting and drying cycles lead to creation of smaller aggregates and due to shearing forces formation of blocky and subangular-blocky structure takes place (Seguel and Horn, 2006). This suggests that with alteration of soil structure the anisotropy of soil functions also changes while in well developed soil structure, like crumby, an isotropic soil behavior should be expected. The results of saturated and unsaturated hydraulic conductivities found in the first soil horizon of ungrazed treatments revealed isotropic or near-to-isotropic soil functions which indicated a good soil structure recovery after 30 years of exclusion from grazing. Furthermore, the results of saturated hydraulic conductivity and air conductivity suggested a better recovery of soil functions at the *Leymus chinensis* site compared to the *Stipa grandis* site.

Together with an increase of pores and their continuity followed by exclusion from grazing a more rigid soil pore network could withstand applied stresses. Thus, the ungrazed treatments could maintain their conductive functions even after application of mechanical stresses.

Finally, an alteration of soil functions due to changes in water repellency could be proven in these studies. The consequences of water repellency on environment are related to retardation of infiltration rates, increase in surface runoff or enhanced soil erosion (Arye et al., 2007). The results revealed that the *Leymus chinensis* site was characterized by higher aggregate water repellency and contact angles compared to the *Stipa grandis* site which can be explained by higher organic matter content at the *Leymus chinensis* site. This is in agreement with other authors who pointed out an impact of organic matter on soil water repellency (Dekker and Ritsema, 2000; Urbanek et al., 2007; Zavala et al., 2009).

CONCLUSIONS

The results presented in this work revealed the effect of grazing on soil mechanical strength and soil physical functions in Inner Mongolia, China. It was shown that soil mechanical and hydraulic properties are closely related to each other. Moreover, it was proven that an intensity of degradation of soil physical properties caused by grazing and soil structure recovery depend on soil moisture conditions.

Based on the presented results it can be stated that:

- Grazing has led to changes in soil mechanical strength and soil physical functions on aggregate and bulk soil scale.
- Soil compaction caused by animal trampling resulted in an increase in soil mechanical strength, decline in soil compressibility, formation of platy soil structure and increase in risk of soil erosion.
- Through homogenization and rearrangement of soil particles grazing influenced soil functions leading to a decline in pore continuity.
- Soil structure deterioration was more pronounced at the *Leymus chinensis* site compared to the *Stipa grandis* site which was related to different moisture conditions and therefore more intense soil puddling occurred at the *Leymus chinensis* site.
- Long-term exclosure from grazing indicated significant improvement of soil physical properties due to processes of soil recovery such as intensive and repeated wetting and drying, freezing and thawing, root growth or inorganic and organic bindings.
- The recovery of soil mechanical strength and soil physical functions was more intensive at the *Leymus chinensis* site compared to the *Stipa grandis* site.

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