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Einfluss unterschiedlicher Beweidungsintensitäten auf Bodenstabilität und Wasserhaushalt eines Steppenbodens in der Inneren Mongolei, VR China

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Influence of various grazing intensities on soil stability and water balance of a steppe soil in Inner Mongolia, P.R. China

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(in order of appearance)

FAO	Food and Agriculture Organisation of the United Nations
P.R.	People's Republic (of China)
MAGIM	Matter Fluxes in grasslands of Inner Mongolia as influenced by stocking rate (Research group founded by the Germa Research Association)
UG79	Grazing intensity: ungrazed since 1979
UG99	Grazing intensity: ungrazed since 1999
WG	Grazing intensity: winter grazing (0.5 SU/ha)
OG=HG	Grazing intensity: overgrazing or heavily grazed (2 SU/ha)
SU	Sheep unit = 1 mothersheep + 1 lamb
c	Cohesion [kPa]
k_{sat}	saturated hydraulic conductivity [cm/d]
k_{unsat}	unsaturated hydraulic conductivity [cm/d]
ANOVA	Analyse of variance
LSD	Leas significant differences
σ'	Effective stress [kPa]

σ	Stress [kPa], surface energy [J*m^{-2}]
u_a	Pore-air pressure [kPa]
u_w	Pore water pressure [kPa]
χ	factor between 0 and 1 reflecting the saturation of the pore system, χ = 0: water free pore system; χ= 1: water saturated pore system.
C	Carbon
F	pulling Force [N]
L	moistened length [cm]
α	Contact angle [°], reciprocal value of air entry
R	Repellency index []
pF	Negative logarithm of matric potential
θ	Volumetric water content [cm^3*cm^{-3}]
θ_s	Volumetric water content at saturation [cm^3*cm^{-3}]
θ_r	Residual volumetric water content [cm^3*cm^{-3}]
n	measure for the smoothness of pore size [], number of samples []
Ψ	matric suction

V Summary – Zusammenfassung

Summary

In Inner Mongolia grassland the production of sheep and goats, including meat, milk and wool, especially the valuable cashmere-wool, is of major economic importance. During recent decades grazing intensities have been increased, which has led to a broad degradation of grassland soils along with growing sensitivity to water- and wind erosion, thus los of nutrients and water. These effects harm productivity and ecological functioning in this region, where water supply is a main limiting factor and dust emissions can affect areas beyond the regional scale.

In this study the effects of four different grazing intensities (heavily grazed, winter grazed, ungrazed since 1999, ungrazed since 1979) on a steppe soil, classified as Calcic Chernozem (FAO), were investigated. For this purpose disturbed and undisturbed soil samples (sampling cylinders, soil aggregates) were analysed concerning their mechanical and hydraulic properties under laboratory conditions. Precompression stress under static and cyclic loading conditions, shear resistance, bulk density, texture, carbon-content, saturated hydraulic conductivity in vertical and horizontal direction, water retention characteristics and the hydrophobic properties of aggregate surfaces and homogenised soil material were measured. The measured data was partly used to model one-dimensional water movement in a grazed and an ungrazed soil profile.

The results prove an influence of grazing on soil stability, soil structure and soil hydraulic functions and properties, which had mostly negative effects concerning soil water balance and sensitivity to wind- and water erosion. The repeated loading-unloading-reloading events as encountered due to grazing animals was compared to static loading in oedometer tests and a dependency of precompression stress on the loading path during the experiment and the mechanical history of the soil could be shown. The study could furthermore demonstrate the complex interrelations between soil mechanical and hydraulic properties and functions exemplarily.

Zusammenfassung

In der Steppe der Inneren Mongolei ist die Produktion von Schafen und Ziegen einschließlich Fleisch, Milch und Wolle, speziell der wertvollen Kaschmirwolle von großer ökonomischer Bedeutung. Während der letzten Jahrzehnte sind die Beweidungsintensitäten erhöht worden, was zu einer weitreichenden Degradation der Steppenböden einhergehend mit erhöhter Empfindlichkeit gegenüber Wasser- und Winderosion, ferner Verlust von Nährstoffen und Wasser geführt hat. Diese Effekte bedrohen die Produktivität und die ökologischen Funktionen in dieser Region, in der Wasser ein Hauptlimitierungsfaktor ist und Staubemissionen weit über die Region hinaus getragen werden.

In der vorliegenden Arbeit wurden die Auswirkungen von vier unterschiedlichen Beweidungsintensitäten (überweidet, Winterweide, unbeweidet seit 1999, unbeweidet seit 1979) auf einen als Calcic Chernozem (FAO) klassifizierten Steppenboden untersucht. Zu diesem Zweck wurden gestörte und ungestörte (Bodenzylinder, Bodenaggregate) Bodenroben bezüglich ihrer mechanischen und hydraulischen Eigenschaften unter Laborbedingungen analysiert. Die Vorbelastung wurde unter statischer und zyklischer Belastung gemessen, des Weiteren wurden Scherwiderstand, Lagerungsdichte, Textur, Kohlenstoffgehalt, gesättigte Wasserleitfähigkeit in vertikaler und horizontaler Richtung, pF-Kurve und Porengrößenverteilung und hydrophobe Eigenschaften von Aggregatoberflächen und homogenisiertem Boden bestimmt. Mit einem Teil der gewonnen Daten wurde die eindimensionale Wasserbewegung in einem beweideten und einem unbeweideten modelliert.

Die Ergebnisse verdeutlichen den Beweidungsweinfluss auf Bodenstabilität, Bodenstruktur und hydraulische Eigenschaften und Funktionen, mit weitgehend negativem Einfluss auf Bodenwasserhaushalt und Empfindlichkeit gegenüber erosiven Prozessen. Die wiederholte Be- und Entlastung wie beispielsweise unter Schaftritt wurde mit statischer Belastung in Ödometerversuchen verglichen und es zeigte sich eine Abhängigkeit der Vorbelastung von der Art des Belastungspfades während des Versuches und der Belastungsgeschichte des Bodens. Ferner konnten exemplarisch die komplexen Zusammenhänge zwischen der Mechanik und Hydraulik des Bodens verdeutlicht werden.

1. General Introduction

1.1 Introduction

Steppe ecosystems can be found in all continents of the world. The temperate Eurasian steppe belt ranges from Eastern Europe to Eastern Asia. According to the FAO (2001), about three quarters of the agriculturally used area in China is grassland. In these areas, drastic changes of land use have happened. During Mao Zedong´s “Great Leap Forward” in the late 50´s and 60´s of the last century, farmers in northern China were forced to give up their nomadic way of life in Inner Mongolia (Gernet, 1997). They had to settle in small villages or individual farms and increased the number of grazing animals. This practice led to an increased grazing intensity close to the settlements and a constant or even decreasing grazing intensity in areas further away from them. In the late 80´s of the last century, the economic policy allowed farmers to benefit directly from increased animal production, because they were allowed to sell the production surplus to the state-directed production plans (Gernet, 1997). This further intensified land use and now overgrazed areas can widely be observed (Zhao et al., 2005; Jian & Meurer, 2001). Recently, the local government aims to reduce grazing pressure by regulating herd size and forbidding goats. The restrictions of the local government lack any scientific basis and additionally the herd size is actually twice as big as allowed and still 10-30 % of the herds are goats.

In Inner Mongolia, P.R. China, increasing grazing intensity has led to a broad degradation of the grassland, followed by increasing soil erosion and desertification (Liu & Wang, 2007; Meyer, 2006; White et al., 2000; Schlesinger et al., 1990). Grazing and treading animals affect the (top) soil due to mechanical damage of the sod and the uppermost soil layers and soil compaction. Grazing also influences the amount and composition of soil organic matter by the export of biomass and its return as excrements. This in turn influences e.g. rooting activity and thus natural regeneration of soil structure by root activity (Greenwood & Mc Kenzie, 2001; Angers & Caron, 1998). Trampling by grazing animals results in the deformation and compaction of the soil, particularly the top soil (Li et al., 2007; Tian et al, 2007; Kurz et al., 2006; Krümmelbein et al., 2006; Martinez & Zinck, 2004; Greenwood & McKenzie, 2001; Villamil et al. 2001; Zhang & Horn, 1996). The intensity and amount of deformation depends on the soil water content and the amount of pressure exerted on the soil; it becomes more distinct and more visible the higher the water content and the stress exerted on the soil is in comparison to the internal soil strength (Sridharan & Gurtug, 2007; Tarawally et al., 2004; Arvidsson et al., 2003; Greenwood & McKenzie, 2001; Horn & Rostek, 2000). The direct relation between mechanical and hydraulic stresses can be derived from the matric suction of a soil which amongst others determines the internal soil strength and which counterbalances the external compounds. However, it has also to be considered that its changes during mechanical loading have strong influence on the mechanical soil strength. Increasing matric suction increases soil strength until the area of the water menisci between soil particles becomes too small to transmit binding forces while less negative matric potential decreases the internal strength (Baumgartl, 2003; Junge, 1999). These mechanisms are described by the effective stress equation (Bishop, 1955, in Baumgartl, 2003):

$$\sigma' = (\sigma - u_a) + \chi(u_a - u_w)$$

with σ' = effective stress; σ = stress; u_a = pore gas pressure; u_w = pore water pressure and χ = factor between 0 and 1 reflecting the saturation of the pore system, $\chi = 0$: water free pore system; $\chi = 1$: water saturated pore system.

The effective stress indicates the soil stabilising stress; the capillary cohesion ($\chi(u_a - u_w)$) which is active in partly saturated soils and strongly influences the height of the effective stress. With increasing soil water content the χ-factor increases and the effective stress decreases. (Pollen, 2007; Baumgartl, 2003; Hartge & Horn, 1999; Junge, 1999; Kezdi, A., 1974). But even in dry soils, as they can frequently be found in the Inner Mongolian steppe, although the footprint of animals may not even be visible compaction of the soil may still occur, along with a loss of macro porosity (Greenwood & Mc Kenzie, 2001). The trampling effect of grazing animals is depending on their weight, hoof size and kinetic energy. The pressure exerted on the soil becomes higher when the grazing animal is moving; while an animal is moving, only three or two and in extreme situations (e.g. while escaping) only one hoof touches the ground, meaning that the whole body mass is transferred by a reduced hoof area. In literature the static contact area pressure of one sheep varies between 60 and

80 kPa (Krümmelbein et al., 2006; Greenwood & Mc Kenzie, 2001, Willat & Pullar, 1983), which also means that under these extreme situations even values of more than 200 kPa can be expected. Scholefield et al. (1985) measured that the pressure of a walking cow is twice as high as the pressure of a standing cow. In all these calculations shearing forces are ignored although they are transmitted on the soil surface by all moving and/or scrabbling animals. We have to consider, that such dynamic shearing movements modify the soil structure and thus decrease soil stability (Peth, 2004) which is more pronounced the wetter the soils are and the more frequent the shearing occurs.

Compaction is characterised by a volume decrease particularly of the coarse pore volume accompanied by an increase of the fraction of smaller pores. Even more sensitive to compaction than the pore volume is the pore continuity (Ball & Robertson, 1994). The decrease of pore volume and pore continuity and the changed pore size distribution affects soil functions, e.g. air- and water conductivity (Zhang et al., 2006; Vogeler et al., 2006; Gebhardt et al., 2006; Krümmelbein et al., 2006; Pietola et al., 2005; Koch et al., 2004; Schäfer-Landefeld et al., 2004; Horn & Rostek, 2000; Whalley et al., 1995; Willat & Pullar, 1983), water retention (Kutilek et al., 2006; Sun et al., 2006; Zhang et al., 2006; Martinez & Zinck, 2004; Villamil, 2001) and soil biological processes (Whalley et al., 1995), although the effects on microorganisms might have been overestimated, as recent studies by Busse et al. (2006) and Bölter et al. (2005) could show no significant effects of compaction on them.

The saturated hydraulic conductivity is not only in general decreased due to a grazing induced formation of a platy structure, it becomes higher in the horizontal compared to the vertical direction and results in anisotropic flow conditions (Dörner 2005; Pagliai & Vignozzi, 2002; Raducu et al., 2002; Weisskopf et al., 2000; Fleige & Horn, 2000; Tigges 2000; Zhang, 1996). The alterations in flow direction and pore continuity by grazing reduces also the water infiltration into the soil because of the loss of macropores open to the surface. Removal of vegetation also decreases the number of root channels that are important for water infiltration into the soil (Kennedy & Schillinger, 2006; Pietola et al., 2005; Alderfer & Robinson, 1947; Johnston 1962, both in Greenwood & McKenzie, 2001; Proffitt et al., 1995). Infiltration is not only decreased due to soil mechanical changes but also changes in water repellency that can even enhance the decrease of water infiltration (Buczko et al., 2006; Lamparter et al., 2006; Pietola et al., 2005). Water repellency also affects capillary rise negatively (Bachmann et al, 2001). The combination of these effects leads to higher runoff rates on grazed compared to ungrazed sites (Johnston, 1962, in Greenwood & McKenzie, 2001). Mechanical and hydrological changes, that are partly interlinked, commonly have negative effects for the productivity of arable (Alakukku, 2000; Hernanz & Sanchez-Giron, 2000; Vorhees, 2000; Hakansson & Medvedev, 1995) and grassland soils (Donkor et al., 2002; Greenwood& McKenzie, 2001) and their ecological functioning. Poor physical quality of soils due to (sub-) soil compaction may, apart from the negative economical impact due to productivity losses, sometimes lead to drastic environmental consequences, such as flood disasters as e.g. encountered lately in central European areas (Akkermann, 2004). In the semi-arid steppe of Inner Mongolia, compaction and structural degradation of the top soil resulting from intense sheep- and goat grazing has led to widespread degradation processes (Krümmelbein et al., 2006; Li et al, 2002; Gong et al., 2000; White et al, 2000; Schlesinger et al., 1990). It is well known that water erosion is a common phenomenon during strong rain events in summer (sometimes more than 100 mm precipitation during 24 h) and is accompanied by severe gully development (Arnaez et al., 2007; Wei et al., 2007). One factor which even facilitates these mass transport phenomena is the deterioration of a continuous interaggregate pore system which is associated with soil structure compaction with an induced increase in the intra-aggregate bulk density and a reduced interaggregate macropore system followed by a more intense soil mechanical shear induced deterioration of the structure and the pore units. Thus, as the final stage also a complete aggregate homogenisation due to shear forces (Peth and Horn, 2006) can occur and results in lower infiltration rates, higher run off and greater probability for water erosion events followed by soil loss. Furthermore wind erosion under dry conditions and/or changes in redoxreactions due to the sealed surface pore openings is mentioned by several authors (Peth & Horn, 2006; Pietola et al, 2005; Martinez & Zinck, 2004; Villamil et al. 2001; Greenwood & McKenzie, 2001; Proffitt et al., 1995). Thus, structure degradation and sparse vegetation not only enhance water-, but also wind erosion (Zhao et al., 2007; Qian et al., 2007; Zhao et al., 2006; Hesse & Simpson, 2006). A higher susceptibility of grazed sites compared to ungrazed sites concerning wind erosion could also be shown for Sahelian sandy rangeland soils by Hiernaux et al. (1999), partly due to the destruction of surface crusts, and by Villamil et al. (2001) for semi-arid southern Argentinean soils due to structural soil degradation. Wind erosion occurs when the shear stress exerted on the surface by wind exceeds the ability of the surface particles to resist detachment and transport (Funk & Reuter, 2006; Cornelis et al., 2004; McKenna Neumann & Nickling, 1994; Skidmore, 1986, Chepil, 1945). It is a function of soil surface roughness, wind erodible particles on the soil surface, percentage of the soil surface covered with non erodible material, e.g. plant residues, and wind speed (Funk & Reuter, 2006; Liu et al., 2003; Fryrear, 1995). Long periods of dryness, interrupted by heavy rain events often encountered in Inner Mongolia during the vegetation period and low temperatures combined with dryness during winter create natural climatic conditions favourable for water- and wind erosion (McKenna Neumann, 2004; Skidmore, 1986). The structural deterioration of the soil itself weakens the stability against wind- and water erosion, the above mentioned modified hydrological properties like e.g. decreased infiltration and increased run off, increase the soil’s susceptibility against erosive processes. Additionally to the structural effects grazing reduces the living and dead aboveground biomass which also protects the soil from wind erosion (Funk & Reuter, 2006; Fryrear, 1995).

Soils have a limited ability to structurally recover from former mechanical deterioration such as compaction (Drewry, 2006; Page-Dumroese et al., 2006; Drewry et al., 2004; Webb, 2002). In general it is known that due to wetting and drying cycles and, consequently, swelling and shrinkage, soil structure is able to recover from a compacted or even homogenised state by forming new aggregates. Because these aggregates are surrounded by the interaggregate pore space, such wetting and drying may also be able to improve the aeration and water infiltration as well as the thermal properties of the soil in dependence of the number and intensity of these swell-shrink processes (Horn et al., 1994). Especially soils with a clay content of more than 12 % show such swelling and shrinkage processes (Scheffer & Schachtschabel, 2002; Horn, 2002). Structure homogenising processes e.g. due to mechanical disturbance of the soil lead to normal shrinkage accompanied by crack formation and separation of the soil into smaller parts (Janssen et al., 2006; Peng et al., 2005). Wetting and drying cycles of homogenised soils create planes of weakness, along which the soil breaks apart into aggregates (Utomo & Dexter, 1982). A formerly disturbed soil can regain part of its strength over a period of time. This effect is known as age-hardening, when the complete strength is regained, it is called thixotropy (Markgraf, et al., 2006; Mitchell, 2002; Utomo & Dexter, 1981). Among the various processes that influence age-hardening, the main processes at constant water content are a) the rearrangement of soil particles into the position of lowest free energy and b) the chemical cementation that can occur at contact points between soil particles. If the water content varies, other factors will have an increasing influence on age hardening. These effects are mainly the effective water stresses during drying which lead to a denser packing of soil particles in the aggregates and swelling and shrinkage processes that can either break or form inter-particle bonds (Caron & Kay, 1992; Horn & Dexter, 1989; Molope et al., 1985). The rearrangement of particles forming structural units depends on the number of swelling and shrinkage cycles, maximum drying intensity and drying history of the soil, mechanical boundary conditions and the amount and composition of organic matter (Horn, 2002). In addition to swelling and shrinkage, which occur not only in soils with high and medium clay contents, but also in sandy or sandy loam soils (Gräsle, 1999; Coquet, 1998), furthermore the strength and stability of aggregates is enhanced by these processes (Roldan et al., 2007; Li et al., 2007; Shaver et al., 2002; Materechera et al., 1994). Werner and Werner (2001) proved that a Chernozem derived from loess that was wheeled twice with 2.5t and had suffered structure homogenisation thereafter approached a more aggregated state within 3 years. Furthermore, Wiermann and Horn (2000) showed that a loess-derived Luvisol exhibited distinct signs of regeneration after a single compaction event, e.g. in terms of increasing macro porosity and gas permeability at 10 cm depth and Horn (2004) proofed that if the wheeling was always restricted to values smaller than the precompression stress, it resulted in a time dependent recovery of soil structure. Northethiopian soils degraded by grazing show distinct signs of regeneration after five years (Mekuria et al., 2007).

Biological activity of soil fauna and flora can further enhance structure formation and -remediation due to various mechanisms (Horn & Dexter, 1989). Soil fauna influences structure due to its grubbing and digging actions in the soil, leaving loosened zones (channels) surrounded by compacted areas (channel walls) (Schrader et al., 2007). Some animals, e.g. earthworms, form very stable excremental aggregates (Joschko et al., 2006; Krück et al., 2006; Scheffer & Schachtschabel, 2002). Bossuyt et al., (2004a, 2004b, 2006) and Pulleman et al. (2005) describe the important contribution of earthworms to micro aggregate formation and incorporation and protection of organic matter in these aggregates. The saprophagous macrofauna can furthermore enhance microbial respiration and -biomass and increase the water retention of the soil due to litter fragmentation and soil mixing, thus organic matter accumulation and -relocation (Frouz et al. 2007). Schrader and Böning (2006) showed that Collembolans play an important role in structure formation of urban German soils.

Plant roots can also influence the recovery of soil structure in various ways. They form continuous vertical pores and therefore disrupt and re-aggregate homogenous soils into smaller units. This is not only due to the mechanical stresses the roots exert on the soil and cause shearing and compressive forces that break the soil, but also to the water uptake of the roots, followed by more intense and more frequent wetting and drying cycles close to the roots, creating more negative pore water pressure (according to the Bishop equation) and inducing crack formation and age hardening of existing soil aggregates as mentioned above. Roots furthermore increase the structural soil stability with fine roots and root hairs growing around soil aggregates (Goss, M.J., 1987, in Greenwood & Mc Kenzie, 2001); fungal hyphae can be associated to plant roots and further enhance the binding of soil aggregates (Tisdall & Oades, 1979, in Greenwood & Mc Kenzie, 2001), as well as plant residues (Tisdall, 1994). Former studies revealed a positive correlation between root mass and porosity in pastures (Gradwell, 1960, in Greenwood & Mc Kenzie, 2001) and an increased infiltration due to macropores created by living roots. Even when these roots are dead, the continuity of the old root channels and the cracks created by shrinkage due to root water uptake persisted and kept the infiltration rate at a high level (Prieksat et al., 1994). Czarnes et al. (2005) showed that the exudates of plant roots and microbes in the rhizosphere together with intense wetting- and drying-cycles change the soil structure. They suggested that artificial root mucilage analogues have stabilising effects on soil structure, because they increase the strength of bonds between particles and decrease the wetting rate. Recently advanced X-ray microtomographies of soil aggregates allow to show the complexness of intra-aggregate pore systems (Peth et al, 2007, Schrader et al., 2007; Young & Crawford, 2004; Werner & Werner, 2001) and allow to prove that soil micro organisms significantly contribute to the processes of aggregate formation by improving their habitat (Feeney et al., 2006), inducing crack formation in the soil (Preston et al., 2001) and by rearranging clay particles adjacent to them (Chenu, 1993, 2001). The advanced possibilities of 3D images are suitable to characterize the spatial distribution of microbial activity that plays an important role in the carbon balance of the soil (Chenu et a., 2001; Jasinska et al., 2006), hence, micro organisms can also influence the amount and distribution of water repellency; carbon in turn influences soil wettability (Hallett & Young, 1999; Hallett et al., 2004) and mechanical stability (Mataix-Solera & Doerr, 2003; Chenu et al., 2000; Horn, 1994). Herrick and Lal (1995) pointed out the importance of excretal return to tropical pastures to keep soil organisms active and maintain good physical pasture properties. Recapitulating it can be stated that soil flora and fauna, including micro organisms and, accordingly, carbon content and -composition and mechanical as well as hydraulic processes are closely interlinked with each other and with external factors such as climate and management.

The study area is situated in the Xilin river catchment, Inner Mongolia, northern part of P.R. China (E116°42' N43°38'). The sampling site belongs to the Inner Mongolia Grassland Ecosystem Research Station (IMGERS) of the Chinese Academy of Sciences, with a typical *Stipa grandis*- and *Leymus chinensis*-steppe vegetation, respectively. The mean annual precipitation is about 300 mm with mainly sporadic intense rainfalls and 60-80% of the precipitation in June and August. The vegetation period lasts from May to September. The annual mean temperature of the last twenty years of the area is 0.7°C with a maximum monthly mean temperature of 19°C in June and a minimum monthly mean temperature of about -21°C in January. A detailed site description was given by Bai (2004). The general objective of this study in the framework of the research group “MAGIM” (Matter Fluxes in Inner Mongolia as influenced by stocking rate, http://www.maim.net) is to characterise how various grazing intensities and protection from grazing, respectively, influence soil mechanical strength and soil water balance on the plot scale. The study presented here considers the following objectives in detail in three parts:

1.2 Objectives:

I) As introduced above, grazing has an influence on soil structure, thus also affects properties like bulk density and mechanical strength. This is indicated amongst others by the values of precompression stress and shear resistance. Furthermore functions like saturated hydraulic conductivity and its anisotropy are changed due to the structural change. The first part of the study shows these effects:

“Influence of various grazing intensities on soil stability, soil structure and water balance of grassland soils in Inner Mongolia, P.R. China.”

II) Grazing induced compaction is characterized by a change of soil mechanical properties, e.g. precompression stress. Soils have an internal strength caused by the in situ soil development, by wetting and drying cycles, drying intensity and biological activity. If the internal soil strength is exceeded by external stresses, soils react with plastic (irreversible) deformation, while at stresses smaller than the threshold value each deformation is reversible, i.e. elastic (Kezdi, 1974; Hartge & Horn, 1984). This transition from elastic to plastic deformation is defined as precompression stress, which is also called preconsolidation pressure (Casagrande, 1936; Kezdi, 1974, Hartge & Horn, 1984). Plastic deformation also leads to a further deformation of deeper depths. This deformation depends on the contact area pressure and the total contact area, e.g. of wheels (Fazekas, 2005; Horn & Rostek, 2000; Horn et al., 2000) and hoofs of grazing animals (Greenwood & McKenzie, 2001). Deformation caused by grazing animals normally affects mostly the top soil (Krümmelbein et al., 2006; Martinez & Zinck, 2004; Greenwood& McKenzie, 2001; Zhang & Horn, 1996). It is often stated, that the determination of precompression stresses under static loading conditions may not quite resemble field conditions, because soils are loaded repeatedly with a sequence of short intermittent loading-unloading-reloading events or with a high number of loads over time. Such dynamic loading conditions are encountered e.g. at multiple wheel passes or in grassland soils due to animal trampling. That is why we determined the precompression stress of undisturbed soil samples as cyclic and static loading paths:

“Determination of precompression stress under static and cyclic loading.”

III) Grazing has an influence particularly on soil hydraulic properties and functions, because also most soil mechanical and -structural changes affect soil hydrological properties and functions (Horn & Smucker, 2005; Horn, 2004; Bejat et al., 2000; Horn et al., 1993; Bakken et al., 1987; Basak, 1972). Parameters like texture, water retention properties, pore size distribution and hydrophobic features change under the influence of grazing and protection from grazing, respectively. These changes have consequences for the modelling of the water movement in the soil profile, because the hydrological parameters directly or indirectly influence the modelling results as shown in the third part of the study:

“Grazing induced alterations in soil hydraulic properties and functions in Inner Mongolia, P.R. China.”

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2 Influence of various grazing intensities on soil stability, soil structure and water balance of grassland soils in Inner Mongolia, P.R. China

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2.1 Abstract

The experimental area is situated about 500 km north of Beijing in the Xilin river catchment. The investigated soils are Chernozems under *Leymus chinensis*- and *Stipa grandis* steppe and the annual precipitation is about 300 mm.

Increasing grazing intensities (sheep, goats) in Inner Mongolia, P.R. China, are reported to lead to an increasing degradation of the grassland followed by increasing soil erosion and desertification (Ojima et al., 1993; White et al., 2000; Schlesinger et al., 1990). It was explained by a soil structure change by sheep trampling and may result in a reduced infiltration of water and strength of the soil. Therefore the danger of surface run-off, accompanied by an enhanced erosion of the soil, is increased.

To estimate the influence of grazing on soil physical properties we investigated four plots that had different grazing intensities (overgrazed, winter grazed, ungrazed since 1979, ungrazed since 1999). To quantify soil stability the precompression stress value and the shear resistance of the bulk soil and the tensile strength of soil aggregates were determined. Furthermore, the saturated hydraulic conductivity was measured in vertical and horizontal direction to estimate the influence of trampling on soil functions.

Soil mechanical properties and soil hydraulic functions have found to be influenced by grazing which is reflected by decreasing shear resistance and hydraulic conductivity with increasing grazing/trampling intensity. Furthermore, the anisotropy of the saturated hydraulic conductivity is affected by trampling.

Dynamic compressive and shearing loads generated by sheep trampling result in soil structure degradation with negative consequences for plant available water and soil erosion.

Keywords: trampling, soil structure, grassland, hydraulic conductivity, precompression stress

2.2 Introduction

Increasing grazing intensities, mainly by sheep and goats, in Inner Mongolia, P.R. China, have lead to a regional degradation of the grassland. Reduced soil cover and infiltration rates result in increasing soil erosion and intensify the process of desertification. Within a joint research project "MAGIM" (Matter Fluxes in Grasslands of Inner Mongolia as influenced by stocking rate) nine subprojects incorporating agricultural and environmental sciences investigate the effects of various land use systems on water- and matter fluxes and on soil erosion. Here the effects of different grazing intensities on soil stability and soil hydraulic properties on the plot scale are represented and consequences for physical and environmental properties are discussed.

2.3 Material and methods

The experimental area is situated in Inner Mongolia, P.R. China, ca. 500 km north of Beijing close to the city of Xilinhot. The investigated soils are Chernozems under *Leymus chinensis*- and *Stipa grandis*- steppe, respectively. The mean annual precipitation is about 300mm with mainly sporadic intense rainfalls.

We investigated four plots with different grazing intensities (Ungrazed since 1979 = UG79, Ungrazed since 1999 = UG99, Winter Grazing with 1.3 sheep units = WG and Overgrazed = OG), where undisturbed soil samples in four different depths (4-8 cm; 18-22 cm; 30-34 cm; 40-44 cm) were taken.

Precompression stresses were determined under confined compression behaviour (Multistep-oedometer, drained) and the shear parameters have been measured in a frame shear test under consolidated and drained conditions for the first two depths. Before testing the samples have been equilibrated to a standard matric suction of -30 kPa using a suction plate assembly. Saturated hydraulic conductivities were determined with the falling head method for all 4 depths for vertically orientated samples. Additionally the saturated hydraulic conductivity was measured also in the horizontal direction in the first two depths to be able to characterize the anisotropy of the saturated hydraulic conductivity.

2.4 Results and discussion

2.4.1 Precompression stress

The values of precompression stress are lowest in the first depth of the ungrazed sites (UG 79, UG 99). Precompression stresses at the grazed sites (WG and OG) are higher and reflect the static ground contact pressure of an average sheep (80 kPa) (figure 1). On the ungrazed sites higher values of precompression stress were found in the second depth, mainly because no external mechanical load (trampling) was applied apart from the soil overburden pressure. On the WG site, in contrast, higher values of precompression stress are detected in the first depth compared to the second depth. This higher precompression stress in the first depth compared to the second depth is likely to be due to sheep trampling which affects mostly the topsoil layer up to a depth of 10-15 cm (Zhang & Horn, 1996). At the OG site there was no significant difference in precompression stresses between the first and the second depth observed which indicates a deeper penetration of soil stresses and deformation with increasing (repeated) trampling activity.

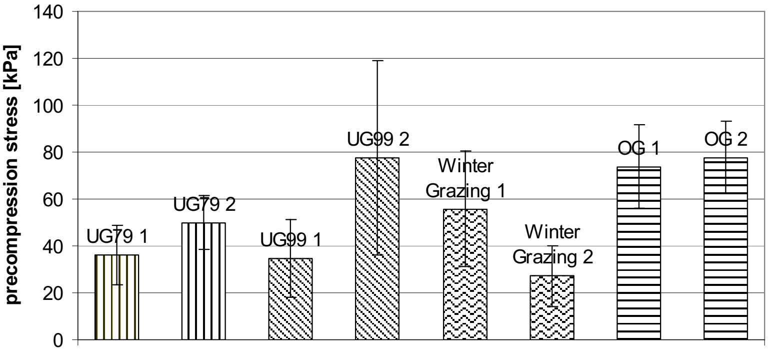

Figure 2.1: Precompression value [kPa] for Ungrazed since 1979 (UG79), Ungrazed since 1999 (UG99), Winter Grazing (WG) and Overgrazed (OG) sites. (1) denotes the first and (2) the second depth. The error bars show the standard deviation

On the one hand higher values of precompression stress point at a higher mechanical soil stability meaning that the higher values of precompression stress in the first depth of the grazed sites show that grazing and sheep trampling respectively both enhance the soil stability (Greenwood et al., 1997) and mirror previously applied mechanical loads. This can be seen from the good match of measured precompression stresses (~80 kPa) on the grazed sites with the calculated static ground contact pressure of a sheep (also ~80 kPa). The increase of precompression stresses is achieved by soil deformation/compression leading to an increase in number of particle contacts, thus increasing the mechanical resistance of the deformed soil structure. Soil compression, on the other hand, also results in a reduction of pore volume and a change in pore geometry which might adversely affect soil functions.

2.4.2 Bulk density

The bulk density is always lower in the first depth than in the second depth of each treatment. The lowest bulk density values of the first depth were found in the ungrazed sites (UG79, UG99), which are not significantly different from each other. The highest bulk density of the first depth can be found on the OG site while intermediate values of bulk density were analysed on the intermediately grazed (WG) (figure 2).

The values of bulk density of the first depth indicate the compressive effect of grazing on the soil, which is especially true for the topsoil layer (Willat & Pullar, 1983; Donkor et al., 2001, Greenwood & Mc Kenzie, 2001; Hiernaux et al., 1999).

However, the results of bulk density also show that there is not necessarily a relation between bulk density and soil stability which is represented by the precompression stress (figure 1), Although the precompression stress at the WG site is higher in the first than in the second depth, the bulk density is higher in the second compared to the first depth. Furthermore, on the OG site differences in bulk density can be detected though there are no significant differences in precompression stresses.

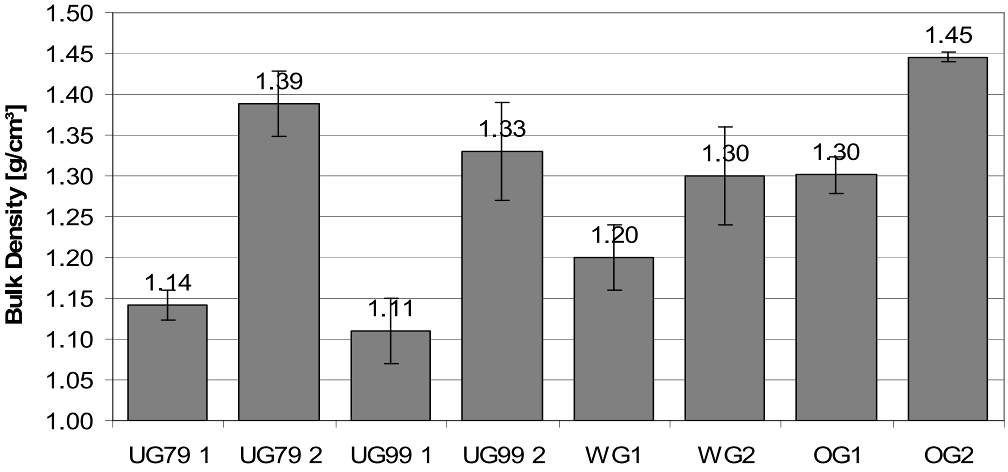

Figure 2.2: Bulk density [g/cm³] for Ungrazed since 1979 (UG79), Ungrazed since 1999 (UG99), Winter Grazing (WG) and Overgrazed (OG) sites. (1) denotes the first and (2) the second depth. The error bars show the standard deviation

2.4.3 Shear resistance

The comparison of the Mohr-Coulomb failure lines of WG (figure 3a) and UG79 (figure 3b) proofs that grazing leads to an increased cohesion (c). This is due to the increased number of contact points between the soil particles as the soil deforms during trampling. However, at the same time the angle of internal friction is decreased due to structure destruction caused by particle rearrangements during soil deformation.

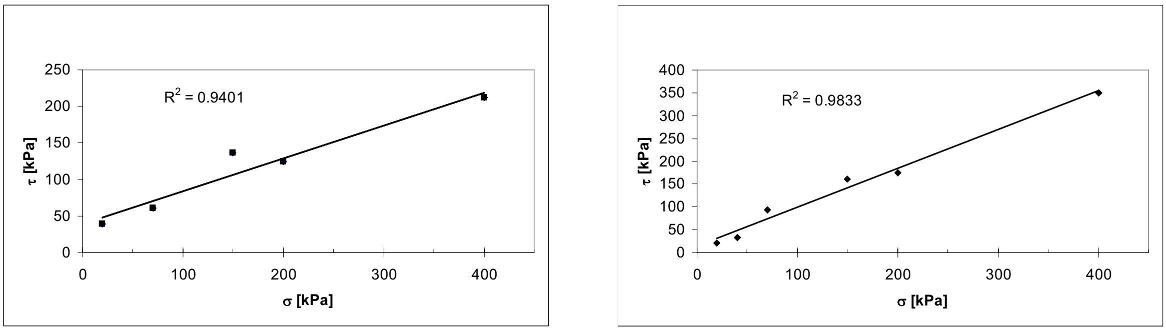

Figure 2.3a

Figure 2.3b

Figure. 2.3: Mohr-Coulomb failure line for the topsoil of the winter grazed site (WG) (a) and the ungrazed site (UG79) (b). Cohesion=38,8 kPa, angle of internal friction=24,9° for WG (a) and 14,2 kPa and 40,4° for UG79 (b), respectively.

2.4.4 Saturated hydraulic conductivity

The values of saturated hydraulic conductivity are highest on the UG79 site with decreasing values for increasing depth (figure 4). The UG99 site shows a similar trend as the UG79 site, but with generally lower values. On the WG site there is also a similar trend detectable apart from the first depth where the saturated hydraulic conductivity is lower compared to the ungrazed sites.

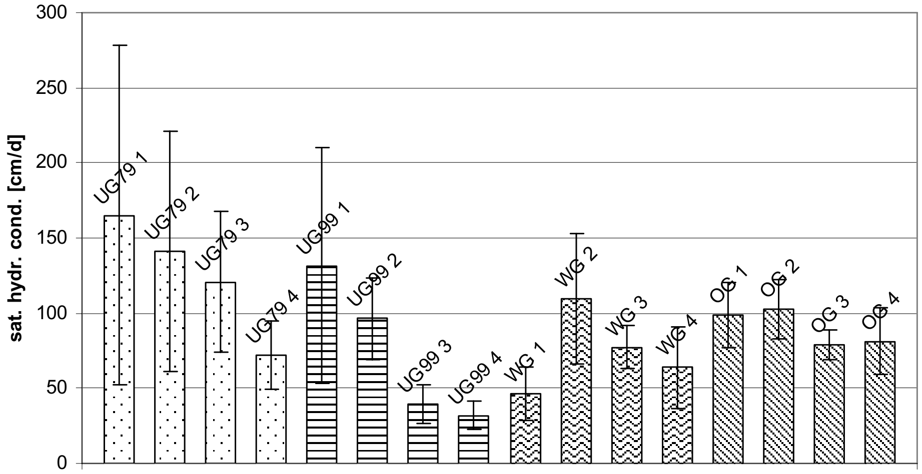

Figure 2.4: Influence of grazing on saturated hydraulic conductivity [cm/d]. 1; 2; 3; 4 denote the four different depths. The error bars show the standard deviation.

This lower value is again assumed to be due to grazing/trampling, which affects mostly the upper 10 to 15 cm (Zhang & Horn, 1996), whereas mainly wider coarse pores (> 50 µm), which are the dominant fraction of pores conducting water near saturation, are reduced due to sheep trampling (Greenwood et al., 1997; Willat & Pullar, 1983). The higher standard deviation on the ungrazed sites can be explained by structure reformation which causes a greater heterogeneity of the values of saturated hydraulic conductivity. The relatively low standard deviation on the OG site and the first depth of the WG site, in contrast, can be explained by soil homogenization caused by repeated sheep trampling. The relatively high level of saturated hydraulic conductivity on the OG site in all depths compared to the other sites is suggested to be related to a more sandy soil texture.

Like it has been shown for the precompression stresses, the saturated hydraulic conductivity compared with the bulk density of the soil proofs no necessarily interrelation between the two. For example, the saturated hydraulic conductivity on the WG site is lower in the first than in the second depth, while the bulk density is higher in the second and lower in the first depth. This underlines the importance of soil structure for hydraulic functions and at the same time it shows that the use of the bulk density as an indicator for the change of soil functions caused by grazing/trampling is quite restricted.

2.4.5 Anisotropy of saturated hydraulic conductivity

On the WG site there are higher values of the saturated hydraulic conductivity in the horizontal than in the vertical direction (figure 5). This points at a platy soil structure on the grazed site developed under repeated mechanical loading of the soil due to sheep trampling (Zhang, 1996), mainly in the upper 10-20 cm (Martinez & Zinck, 2004). In contrast to the grazed site (WG) the ungrazed site (UG79) reveals a significantly higher saturated hydraulic conductivity in the vertical than in the horizontal direction. The vertical anisotropy can be explained by the (re)generation of vertical cracks resulting from soil shrinkage as well as biological activity at the ungrazed site (UG79) since the pasture has been excluded from grazing. At the grazed site (WG), however, this process of structure formation is continuously interrupted by animal trampling leading to the inversion of the anisotropy ratio.

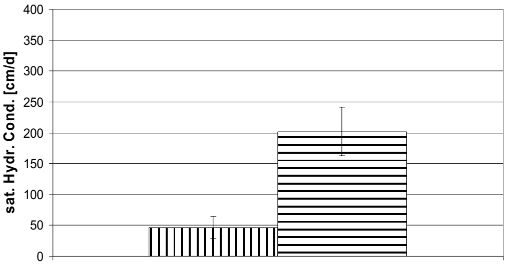

Figure 2.5a

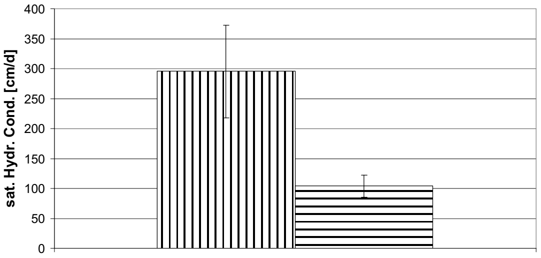

Figure 2.5b

Figure. 2.5: Saturated hydraulic conductivity [cm/d] for the winter grazed site (WG) (left) and the ungrazed site (UG79) (right) as afunction of sampling direction. Vertical stripes = vertical saturated hydraulic conductivity, horizontal stripes = horizontal saturated hydraulic conductivity. The error bars show the standard deviation.

Surprisingly, at the heavily grazed site (OG), no anisotropy in the saturated hydraulic conductivity could be found (figure 6). This can be explained by the homogenisation of the soil caused by repeated sheep trampling, which leads to a more or less random (re)arrangement of soil particles overturning any structure related preference in flow direction. There is a trend, however, of higher values of saturated hydraulic conductivity in the vertical direction, which again point at a beginning structure reformation due to normal shrinkage (i.e. virgin shrinkage) resulting in vertically oriented cracks (Babel et al., 1995). Nevertheless, this newly formed structure is not yet stable enough to sustain the mechanical loads imposed by subsequent sheep trampling and is therefore considered to be of short effect when grazing is continued. Furthermore, it can be stated that although the texture of the OG site is more sandy than on the other plots, the saturated hydraulic conductivity is decreased by almost 65% compared to the site UG79 and by almost 35% compared to the site WG.

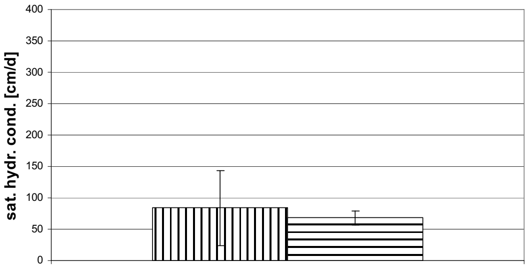

Figure 2.6: Saturated hydraulic conductivity [cm/d] for the heavily grazed site (OG) as a function of sampling direction. Vertical stripes = vertical saturated hydraulic conductivity, horizontal stripes = horizontal saturated hydraulic conductivity. The error bars show the standard deviation.

2.5 Conclusion

The values of precompression stress have been increased by sheep trampling during grazing in the topsoil layer, which points at a structural change of the soil accompanied by an increase in soil stability. This, on the one hand, results in a higher resistance of the soil to deformation caused by further trampling. On the other hand it proves that animal trampling leads to a change in soil structure which has consequences for soil functioning such as the hydraulic conductivity. Furthermore, precompression stresses at the overgrazed site emphasize the effect of repeated loading on soil deformation indicated by the deeper penetration of the zone of compaction. Degradation of the soil structure in deeper soil horizons particularly has negative long term effects for the water storage capacity and water balance, since structure re(forming) processes (shrinking-swelling, biological activity) are less efficient in the subsoil compared to the topsoil. To investigate effects of soil deformation due to repeated loading cyclic loading oedometer tests will be conducted in further studies. The values of cohesion and the angle of internal friction also reflect the structural change of the soil during grazing and protection from grazing, respectively. The cohesion is increased by grazing through the increasing number of contact points between soil particles while the angle of internal friction is reduced by weakening the soil structure.

Although bulk density is affected by sheep trampling, especially in the first depth, it is not a good indicator to characterize soil functions such as soil stability and saturated hydraulic conductivity. Therefore, detailed analyses on the mechanical stability (e. g. precompression stress) and on hydraulic functions (k_{sat}, k_{unsat}) are necessary to estimate the effect of grazing intensity on soil quality in terms of its physical properties.

In this study it could be shown that grazing decreases the saturated hydraulic conductivity which is most obvious for the topsoil layer. However, this will reduce the infiltration capacity of the soil and may, especially during heavy rainstorms which are not seldom encountered in Inner Mongolia, lead to increased surface runoff and hence initiate soil erosion. The risk for horizontal water flow and hence solute and particle bound nutrient transport is also indicated by the anisotropy of the saturated hydraulic conductivity at the winter grazing site which is the result of the development of a platy soil structure.

Despite the fact that this anisotropy was not found at the heavily grazed site, which in this case is assumed to be the result of soil homogenisation, it is likely to occur in cases where soil texture contains a higher fraction of clay particles. Under such circumstances both the low saturated hydraulic conductivity in the subsoil as well as the possible development of a platy soil structure under heavy trampling may increase the risk for soil degradation. Under the prevailing climatic conditions in Inner Mongolia soil water is one of the most limiting factors for plant growth, and therefore especially the change in hydraulic conductivity resulting from soil deformation is of major importance for future pasture productivity. Our results show that heavy grazing adversely affects soil hydraulic functions and therefore is assumed to be one of the reasons for less productive pastures.

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3 Determination of precompression stress of a variously grazed steppe soil under static and cyclic loading

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3.1 Abstract

In many land use systems all over the world soil deformation is a major problem due to increasing land use intensity. On arable soils machine traffic is continuously intensified with respect to load and wheeling frequency leading to (sub-) soil compaction. Depleted soil functions, in particular reduced hydraulic conductivities and impeded aeration, may as a consequence also decrease crop growth and productivity as well as the filtering and buffering capacity of the soils. Therefore, it is necessary to quantify the mechanical soil stability in order to evaluate the potential risks for irreversible soil deformation. A commonly applied method is the determination of the precompression stress for which the soil is compressed under static loading conditions in oedometer tests. The determination of precompression stresses under static loading may not quite resemble the conditions encountered in the field, where soils are loaded repeatedly with a sequence of short intermittent loading-unloading-reloading events or with a high number of loads over time. Such dynamic loading conditions are encountered e.g. at multiple wheel passes or in grassland soils due to trampling animals. In this study we present a comparison of a standard (static loading) and a modified (cyclic/dynamic loading) oedometer test using data of a Calcic Chernozem from the Inner Mongolian steppe under various grazing intensities. Static loading lasted for 10 mins per loading step, while the dynamic/cyclic loading was carried out by 30 secs loading and following 30 secs unloading (= 1 cycle) for in total 20 cycles. Differences between statically and cyclically determined precompression stresses at identical time of loading show lower values for the statically determined precompression stress values compared to those determined dynamically. Among the dynamically determined

precompression stresses, the values decrease with increasing number of loading cycles and loading time, respectively. This is particularly true for the ungrazed sites, while the soils with a higher initial soil strength showed an opposite behaviour because of a more pronounced aggregate rearrangement during 20 cycles compared to one cycle.

Thus, it could also be proofed that increased grazing intensities lead to structure deformation and increased sensitivity to wind- and water erosion followed by severe land degradation of grassland soils, particularly in semi-arid areas. Arable soils can exhibit compaction effects down to deeper depths if the precompression stress is exceeded by wheeling machines and wheeling frequency increases; soil structure is endangered to become disturbed and homogenised, the number of contacts between soil particles is increased. Furthermore, hydraulic effects, e.g. positive pore water pressure due to intense shearing and kneading processes induced by machinery or grazing animals can enhance this structural deterioration.

Thus, dynamic or cyclic loading results in an intense soil deformation which also causes a serious change in ecological and soil physical properties like hydraulic conductivity or gas flux.

Keywords: Grazing, Precompression stress, Cyclic loading, Effective stress, Steppe soil

3.2 Introduction

Arable soils are mechanically loaded in various ways. They are wheeled by various machinery which in addition increases in mass as well as in number of wheeling frequency (Peth&Horn, 2006; Zapf, 1997). Soils have, however, also an internal soil strength caused by the in situ soil development, by wetting and drying cycles, drying intensity, and biological activity. If the internal soil strength is exceeded by external stresses, soils react with plastic (irreversible) deformation, while at stresses smaller than that threshold value each deformation is reversible i.e. elastic (Hartge & Horn, 1984; Kezdi, 1974). This transition from elastic to plastic deformation is defined as precompression stress (also preconsolidation pressure). Plastic deformation can be caused by agricultural machinery and by animals, e.g. cattle or sheep, if the precompression stress is smaller than the applied stresses in the different soil horizons. Plastic deformation due to applied loads can affect deeper depths when the contact area pressure, e.g. of wheels, is high (Fazekas, 2005; Horn & Rostek, 2000; Horn et al., 2000), while deformation caused by grazing animals normally affects mostly the top soil (Krümmelbein et al., 2006; Brye & West, 2005; Drewry, & Paton, 2005; Martinez&Zinck, 2004; Greenwood& McKenzie, 2001; Zhang & Horn, 1996). Soil compaction is associated with a volume decrease predominantly caused by the destruction of coarser pores while the fraction of smaller pores is increased. The volume reduction and change in pore size distribution affects soil functions such as air- and water conductivity (Heuer et al., 2006; Gebhardt et al., 2006; Krümmelbein et al., 2006; Pietola et al., 2005; Czyz, 2004; Horn & Rostek, 2000; Whalley et al., 1995; Willat and Pullar, 1983), water retention (Kutilek et al., 2006; Zhang et al, 2006; Sun et al., 2006; Martinez & Zinck, 2004) and soil biological processes (Pankhurst et al., 2003; Jensen et al., 1996; Whalley et al., 1995). These changes commonly have negative effects for the productivity of arable (Arvidsson, 2001; Ishaq et al., 2001; Ehlers et al., 2000 Alakukku, 2000; Vorhees, 2000; Hernanz & Sanchez-Giron, 2000; Hakansson & Medvedev, 1995) and grassland soils (Martinez & Zinck, 2004; Donkor et al., 2002; Greenwood & McKenzie, 2001) and their ecological functioning. Poor physical quality of soils due to (sub-) soil compaction may, apart from the negative economical impact due to productivity losses, sometimes lead to drastic environmental consequences, such as flood disasters as e.g. encountered lately in central European areas (Akkermann, 2004). In the semi-arid steppe of Inner Mongolia compaction and structure degradation of the top soil resulting from intense sheep- and goat grazing has led to widespread soil erosion and degradation processes (Li et al., 2007, Meyer, 2006; Krümmelbein et al., 2006; Gong et al., 2000; White et al, 2000; Schlesinger et al., 1990).

A commonly used method to determine the precompression-stress, hence stability of soils against mechanical loading, is the determination under static loading conditions in oedometer tests (Arvidsson & Keller, 2004; Keller et al., 2004; Hartge & Horn, 1992). For this purpose undisturbed soil samples are stressed in an oedometer under drained conditions, while subsequent loads are applied statically for a given time until no further settlement can be detected. However, it is often stated that the determination of precompression stresses under static loading conditions may not quite resemble field conditions, because soils are loaded repeatedly with a sequence of short intermittent loading-unloading-reloading events or with a high number of loads over time. Such dynamic loading conditions are encountered e.g. at multiple wheel passes or in grassland soils due to animal trampling. Peth and Horn (2006) introduced the term “cyclic loading” as a loading path that exhibits regularity both in terms of time and magnitude of load application. They defined cyclic loading as the application of a constant load at a constant frequency of loading and unloading for a predefined time. However, it is still unknown how far these two approaches result in different precompression stress values and to what extent also the alterations in the initial structural strength and soil hydraulic properties affect the pattern of the stress strain curves. That is why we determined the precompression stress of undisturbed soil samples as cyclic and static loading paths.

3.3 Material and methods

3.3.1 Soil and experimental area

Soil samples were taken from Inner Mongolia, northern part of P.R. China (E116°42' N43°38'). The sampling site belongs to the Inner Mongolia Grassland Ecosystem Research Station of the Chinese Academy of Sciences. The soil from Inner Mongolia is classified as a Calcic Chernozem (FAO, 2006) under four different grazing intensities: One site is ungrazed, which means fenced, since 1979 (UG79), one fenced and ungrazed since 1999 (UG99), one winter grazing site (WG) and one heavily grazed site (HG). Before fencing the area all sites were grazed in the same way. Here the results of the first soil depth (4-7cm) are shown.

3.3.2 Determination of precompression stress

All samples have been equilibrated to a standard matric suction of -30 kPa prior to the measurement. The determination of precompression stress was conducted with a standard oedometer device. Stresses were applied with a pneumatic piston under confined compression. Free drainage was ensured by sinter metal plates beneath and above the soil sample. During the whole measuring process the vertical displacement (settlement) of the soil sample was recorded by a potentiometric displacement transducer. The precompression stress was determined i) under static and ii) under cyclic loading. For the determination under static loading stepwise increasing loads were applied for a constant time span of 10mins per loading step (figure 1).

For the determination under cyclic loading stepwise increasing loads were applied in loading cycles. One loading cycle consists of 30 s loading and 30 s unloading, 20 cycles were applied per loading cycle (figure 1).

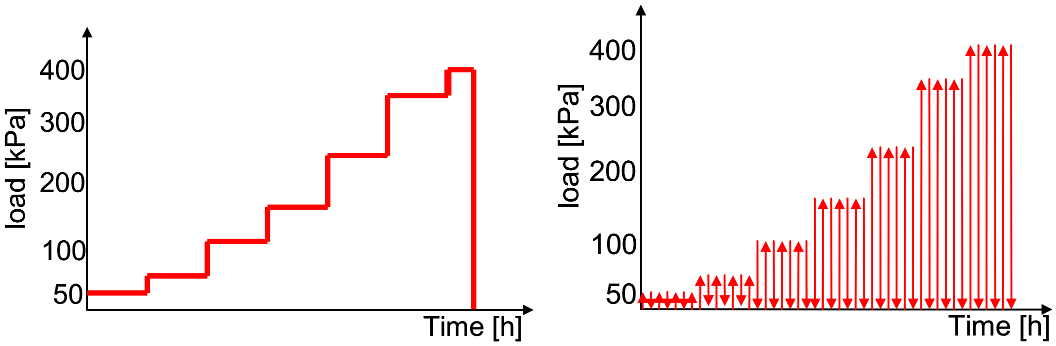

Figure 3.1: Schematic diagram showing the loading paths for the standard and modified oedometer test. (Left) Static loading path; (right) dynamic loading path.

To obtain an equivalent loading time per load step in both tests 20 load cycles were applied in the cyclic loading test corresponding to 10min total loading time.

Precompression stress values have been determined graphically according to Casagrande (1936).

3.3.3 Statistical analyses

The statistical analyses were done using the STATISTICA 7.0 software, StatSoft Inc. (1984-2004). From the data an analysis of variance (ANOVA) was conducted and post-hoc the Fisher LSD-test has been accomplished. Results have been classified to be statistically significant at a level of significance of $p<0,05$.

3.4 Results

Precompression stresses of the topsoil layer determined from the standard test (i.e. static loading) are higher at the grazed sites WG and HG compared to the ungrazed sites UG79 and UG99 (figure 2). The heavily grazed site shows the highest values reaching the average static ground contact pressure of a sheep hoof of about 80 kPa. The values of precompression stress on the ungrazed sites are about 40 kPa, which is similar to those of ploughed and therefore weakened A-horizons (Fazekas, 2005). The ANOVA test revealed that grazing intensity is a significant factor influencing the statically determined precompression stress. According to the Fisher LSD-test within the two groups of grazed and ungrazed sites no statistical differences between grazing intensities can be detected, but between grazed and ungrazed sites the differences are significant.

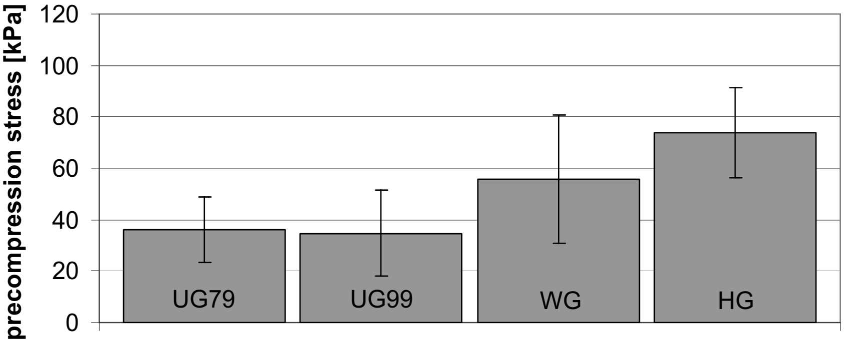

Figure 3.2: Values of precompression stress determined from static oedometer tests as a function of grazing intensity. UG79: ungrazed since 1979; UG99: ungrazed since 1999; winter grazing: WG and heavily grazed: HG. Sampling depth 4-7cm. Error bars show standard deviation.

Figure 3 shows a comparison of precompression stresses determined from the static loading test and the first and the 20th loading cycle from the cyclic test. The determination after the first loading cycle (modified test) generally results in the highest values of precompression stress with exception of site HG where no statistically significant differences between the differently determined precompression stress values are observed. Furthermore, after the first loading cycle the differences between the various grazing intensities are relatively small and therefore not statistically significant. The precompression stress after 20 loading cycles shows on the ungrazed sites (UG79, UG99) decreasing values compared to the values determined after the first loading cycle, although the decrease is statistically not significant. On the grazed sites (WG, HG) no statistically significant difference of precompression stress between statically determined and cyclically determined values can be detected. The statically determined values in comparison to the dynamically determined ones show in all cases the lowest values of precompression stress, yet, the differences are only of statistical significance on the ungrazed sites. The scattering of the values is highest for the statically determined ones (n=3).

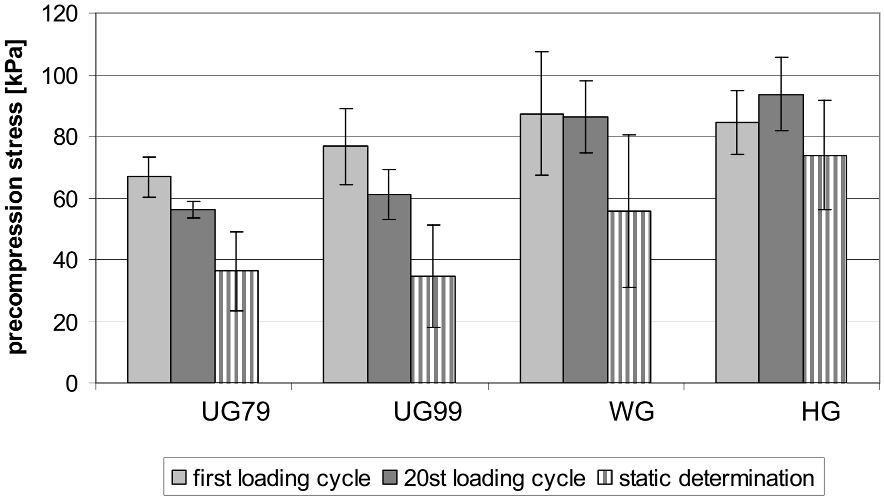

Figure 3.3: Values of precompression stress [kPa]; dynamic determination, a) after the first loading cycle (light grey), b) after the 20th loading cycle (dark grey) and static determination (striped). Sampling depth 4-7cm. Error bars show standard deviation

With increasing applied stresses and settlement, the matric suction increase becomes more distinct (figures 4 and 5). Furthermore the difference of matric suction between loading and unloading increases. At the beginning of cyclic loading test, while smaller loads are applied, the differences between matric suction during loading and unloading are about 2hPa and at the end of the measurement, it reaches about 20hPa (figure 4).

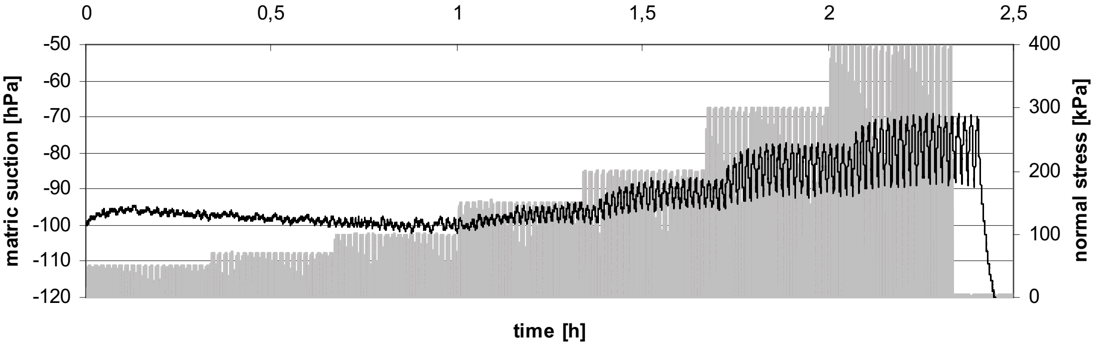

Figure 3.4: Black line: matric suction [hPa] during cyclic determination of precompression stress. Grey line: normal stress [kPa] during cyclic determination of precompression stress.

During the cyclic loading test an elastic behaviour of the soil during unloading can be detected (figure 5 and 6). The settlement during loading is partly reversed (rebound) and it increases from the first to the 20th loading cycle of one loading step and from one loading step to another. The rebound increases with increasing settlement (figure 5).

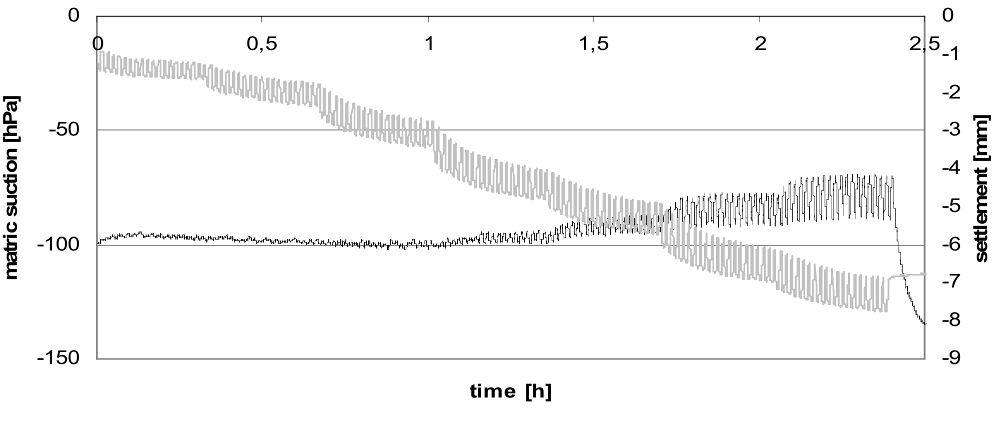

Figure 3.5: Matric suction (black line) and settlement (grey line) during the cyclic loading test. Sample origins from the UG79 site

In figure 6 the matric suction [hPa] and settlement [mm] are displayed as an example not for the whole cyclic loading test, but only for about 3,5 mins. The load that was applied at that time of the experiment was 150 kPa. During loading, the matric suction increases from about -99 hPa to about -95h Pa, while the settlement amounts to about -4,5mm with a rebound of about 1mm.

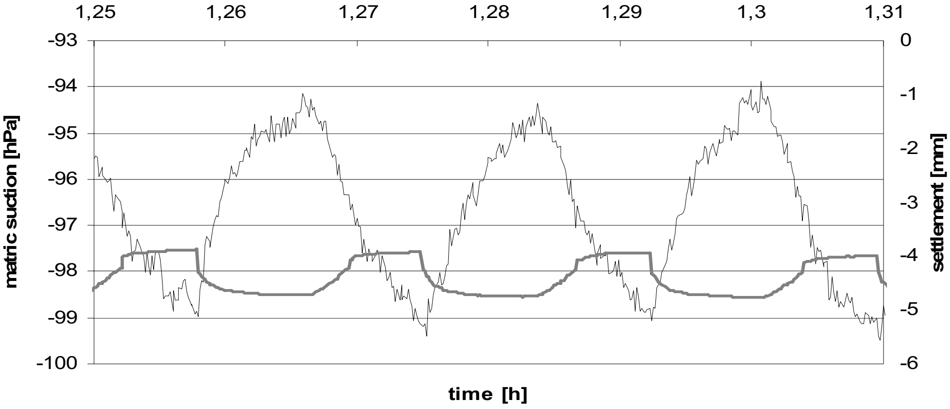

Figure 3.6: Matric suction (grey line) and settlement (mm) (black line) during 0,06h of cyclic loading test with 150kPa.

The recompression parts of the stress-strain relation of the cyclic loading test are similar after the first and after 20 loading cycles (figure 7), also the virgin compression parts are similar, but a greater settlement after the 20th compared to after one loading cycle results in a lower precompression stress. The stress-strain relation of the static loading test (figure 7) reveals a recompression- and a virgin compression part which are less steep compared to the stress-strain relations of the cyclic loading test. The settlement is more pronounced per loading step, which results in the lowest precompression stress of the oedometer tests shown.

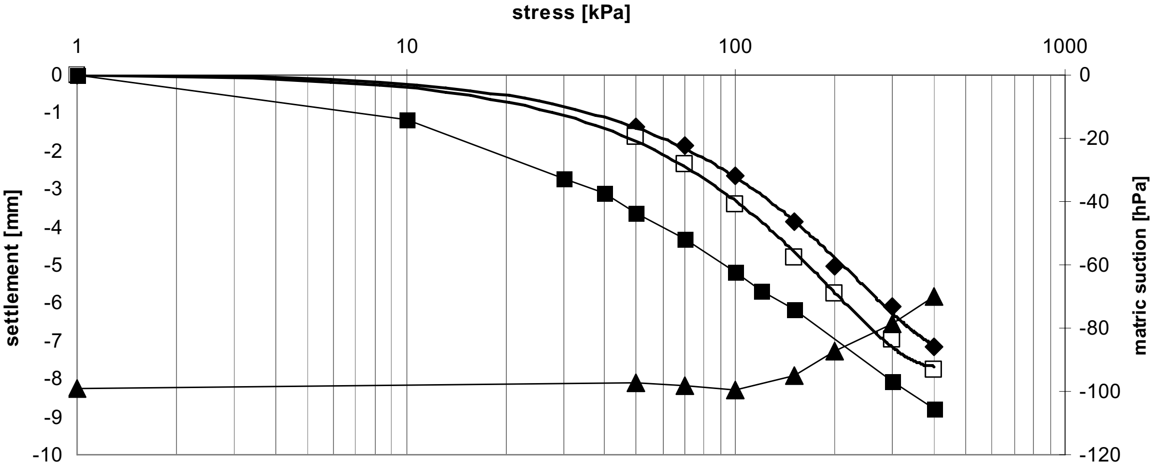

Figure 3.7: stress-strain relation. Rhombi: Cyclic determination, settlement after the first loading cycle. White squares: Cyclic determination, settlement after the 20th loading cycle. Black squares: static loading (10mins/loading step). Triangles: matric suction during the cyclic loading measurement.

3.5 Discussion

The statically determined values of precompression stress for the depth 4-7cm, which is most affected by sheep grazing and sheep trampling, respectively (Krümmelbein et al., 2006; Drewry & Paton, 2000; Zhang&Horn, 1996), are lowest for the ungrazed sites (UG79, UG99) as they could recover from sheep trampling for up to 27 years. Such recovery, especially under the specific site conditions with intense freezing and thawing as well as pronounced drying and improved soil biological activity of flora and fauna under these climatic steppe conditions, created smaller crumbles and weak aggregates which can be also derived from the small bulk density values both for the bulk soil and single aggregates (Krümmelbein et al. 2006). Such recovery of the soil was also proven by Werner and Werner (2001) for a Chernozem derived from loess which was wheeled twice with 2.5t and had created structure homogenisation thereafter approached a more aggregated state again within 3 years. Furthermore, Wiermann and Horn (2000) showed that a loess-derived Luvisol exhibited distinct signs of regeneration after a single compaction event, e.g. in terms of increasing macro porosity and gas permeability at 10 cm depth and Horn (2004) proofed that if the wheeling was always restricted to values smaller than the precompression stress it resulted in a time dependent recovery of soil structure.

However, this loosening of the soil along with increasing coarse pore space leads to an enhanced sensitivity to mechanical loading (Rücknagel et a., 2007; Fazekas, 2005). This sensitivity increases with loading time (Fazekas, 2005), irrespective if the load application is statically or if several short loading times add up. Lebert et al. (1989) found a time dependency of the settlement, meaning that precompression stress increases with decreasing loading time. From the results of the cyclic loading it can be stated, that short time loading events sum up – however, the interaction between the mechanical and the hydraulic stress passes affect the final soil strength, too. Datta et al. (1980) stated that in sand the development of pore water pressure under cyclic loading is depending on the hydraulic conductivity during loading. Larson and Gupta (1980) found out that during stress application either a decrease in the matric potential or an increase can be detected depending on the amount of air filled pores and the pore continuity. The presence of positive pore water pressure decreases the stability against compressive and shearing forces and reduced mechanical stability in turn decreases the susceptibility of the soil against the increase of pore water pressure. Changes in matric suction affect the mechanical stability of the soil; the effective stress is decreased with increasing pore water pressure (decreasing matric suction).The effective stress equation by Bishop (1959) describes this mechanism:

$$\sigma' = (\sigma - u_a) + \chi(u_a - u_w)$$

with σ' = effective stress; σ = stress; u_a = pore gas pressure; u_w = pore water pressure and χ = factor between 0 and 1 reflecting the saturation of the pore system, $\chi = 0$: water free pore system; $\chi = 1$: water saturated pore system.

With increasing water saturation of the pore system the soil structure is weakened due to the loss of capillary cohesion (Junge, 1999; Baumgartl, 2003). The mechanical loading of a soil is connected to the mobilisation of internal shear resistance to overcome the external load; if the soil strength is exceeded, it reacts with an increase in the number of contacts between soil particles (Hartge & Horn, 1984). It is also well known that apart from gravity and additional applied external stresses also internal forces like water menisci or interparticle (i.e. cohesive and adhesive) forces result in an alteration of the particle rearrangement. This increase in particle contacts is also reflected by the increasing bulk density due to grazing and trampling animals (Krümmelbein et al., 2006), an increased bulk density due to grazing can also be found in literature; Huang et. al (2007) proved it for other Northern Chinese soils and Brye and West, (2005) for silt-loam soils in the northern Great Plains, USA. When, due to particle mobilisation, the spatial order of particles is changed in a way that the resulting reactive forces exceed the resulting force affecting the particle, the structure becomes stable again and the forces that affect the particles must become greater to further deteriorate the soil structure. This is true for aggregates as well as for primary particles in aggregates and in the soil as a whole (Hartge & Horn, 1999).

The concept of precompression stress assumes that mechanical loading of a soil, which causes stresses below the precompression stress will completely be converted into elastic deformation (Horn, 1989). However, due to the repeated application of the same load, soils tend to show slight compaction (plastic deformation) even though the precompression stress is not exceeded (Peth & Horn 2006; Fazekas & Horn, 2005; Peth & Horn, 2004; O´Sullivan et al., 1999; Lebert et al., 1989). These findings are also in agreement with our data, which show, that during the 20 loading cycles of each loading step and even if the applied load is kept below the precompression stress we could detect a slight additive settlement which defines the deformation as partly plastic. Therefore cyclic loading can, due to pore water pressure changes that induce a decreasing shear resistance between soil particles and aggregates, lead to compaction even though the load is kept below the precompression stress of the soil (Peth & Horn, 2006; Fazekas & Horn, 2005, Fazekas, 2005; Larson & Gupta, 1980). Such deformation is called creep (Peth & Horn, 2006; Wang, 2000) and can be explained with enhanced particle mobility due to stress release and with the even only minor pumping effect of water due to the height change of the sample during unloading. This however is supported by own results showing the decrease of matric suction during loading and its increase during unloading, while the difference of matric suction between loading and unloading increases with increasing load. The fading off of the additional height loss during repeated loading and unloading depends on the accomplishment of an equilibrium state where the stress dependent rearrangement of particles and matric potential dependent weakening are of identical importance and both smaller than the internal soil strength. Peth and Horn (2006) described that even 100 loading cycles did not allow reaching this equilibrium in homogenized sandy soils, while under structured site conditions we could not detect such an equilibration after 20 cycles.

The values of precompression stress under cyclic loading are in general dependent on the number of loading cycles or time of loading. If we consider the 1st loading cycle of 30 s we can not detect a balanced situation comparable to the final settlement of a sample, where the mobilised soil strength due to the spatial rearrangement of soil aggregates, fragments and particles, which requires time, has reached a maximum and only mechanical stress application that exceeds former applied stresses can induce further structural changes (Hartge & Horn, 1999). If the number of cycles is increased, it results not only in a more complete drainage off of access soil water which in between had resulted in a more pronounced settlement and smaller values of precompression stress due to the weakening, but which also changed the applied soil stresses also from the total to the effective stress components. That is a reason for the relatively high values and small differences of precompression stress among the various grazing intensities after the 1st loading cycle.

If we now compare the obtained data of the static and the dynamic compression test, we can proof that the static loading test results in the most extensive compression of the soil sample and therefore in the lowest precompression stress which is nearly identical to those values obtained under more frequent dynamic cyclic loading. In addition it can also be confirmed that the static loading resembles to minimal internal soil strength as already discussed in detail by Lebert et al. (1989).

On the grazed sites no significant differences concerning the precompression stress between the first and the 20th loading cycle can be detected, but the values of the ungrazed sites after 20 loading cycles approach those of the static determination, because the settlement per loading step is more pronounced after 20 loading cycles. The fact, that on the ungrazed sites the precompression stress depends on the kind of determination and that this dependency decreases with increasing grazing intensity, points at the decreasing sensitivity to a) mechanical loads in general and b) cyclic mechanical loading particularly with increasing grazing intensities. It is known that the mechanical history of a soil influences its behaviour while being mechanically loaded and that the behaviour of soils under cyclic loading is depending on the stress path followed before the cyclic loading test (Koba & Stypulkowski 1980), here the grazed sites have been loaded cyclically before due to grazing sheep in contrast to the ungrazed sites.

The scattering of the values that tends to decrease from the first to the last loading cycle points at a more complete rearrangement of particles with increasing number of loading cycles. The relatively high scattering of the statically determined values of precompression stress gives a hint on the rearrangement of soil particles or aggregates that is further advanced using cyclic loading compared to static loading, although the total settlement during static loading is higher.

3.6 Conclusions

Static load application should allow reaching the final settlement at each loading step and thus the determination of minimal soil stability. Cyclic load application under laboratory conditions can be utilized to determine the precompression stress caused by mechanical short time soil loading (e.g. grazing animals, wheeling processes by agricultural machinery). The fact that with increasing number of loading cycles the values of precompression stress approach more and more the statically determined ones (as it is the fact for the Inner Mongolian soil), furthermore shows, that the static determination of precompression stress is useful to characterise soil stability, because many short time mechanical loadings of a soil in the end seem to have similar consequences for the soil as one long time loading. However, the changes in pore water pressure are more pronounced during cyclic compared to static loading which under wetter initial soil conditions can even cause a more intense and complete soil structure deterioration and a reduction in the hydraulic conductivity or gas fluxes. This concern becomes more pronounced as modern agriculture forces farmers to imply a higher frequency of wheeling partly linked with higher stresses applied during the production process.

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4 Grazing induced alterations in soil hydraulic properties and functions in Inner Mongolia, P.R. China

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Submitted to: Ecological Modelling

4.1 Abstract

Increasing grazing intensities of sheep and goats in Inner Mongolia, P.R. China, are reported to lead to an increasing degradation of the steppe grassland followed by increasing soil erosion and desertification. The experimental area is situated about 500 km north of Beijing in the Xilin river catchment. The investigated soils are Calcic Chernozems (FAO) under *Leymus chinensis*- and *Stipa grandis* steppe with an annual precipitation of about 350 mm (averaged recent 20 years).

We investigated four plots of different grazing intensities (heavily grazed, winter grazed, ungrazed since 1999, ungrazed since 1979). Soil properties and functions are influenced by grazing, which is reflected by decreased values of saturated hydraulic conductivity and its anisotropic development in vertical and horizontal direction, by decreased total pore volume and modified water retention characteristics, a coarser texture, decreasing C-content and a decreased hydrophobicity of the soil. The above mentioned parameters were partly used to model the effective evapotranspiration, transpiration and evaporation of a grazed and an ungrazed site. The modelling results reveal higher evapotranspiration on the ungrazed site in comparison with the grazed site due to dense vegetation, high amounts of biomass and decreasing runoff and drainage. Given the same evapotranspiration, grazing decreases transpiration and increases evaporation due to sparser vegetation on the grazed site.

4.2 Introduction

In Inner Mongolia, P.R. China, increasing grazing intensity has lead to a broad degradation of the grassland, followed by increasing soil erosion and desertification. Trampling by grazing animals results in the deformation and compaction of particularly the top soil (Krümmelbein et al., 2006; Brye & West, 2005; Drewry & Paton, 2005; Martinez & Zinck, 2004; Greenwood & McKenzie, 2001; Zhang & Horn, 1996). Compaction is characterised by a volume decrease particularly of the coarse pore volume accompanied by an increase of the fraction of smaller pores. The decrease of pore volume and the changed pore size distribution both affect e.g. air- and water conductivity (Heuer et al., 2006; Gebhardt et al., 2006; Krümmelbein et al., 2006; Pietola et al., 2005; Czyz, 2004; Horn & Rostek, 2000; Whalley et al., 1995; Willat & Pullar, 1983), water retention (Kutilek et al., 2006; Zhang et al, 2006; Sun et al., 2006; Martinez & Zinck, 2004) and soil biological processes (Pankhurst et al., 2003; Jensen et al., 1996; Whalley et al., 1995). The saturated hydraulic conductivity is not only in general decreased due to grazing, but it becomes higher in the horizontal compared to the vertical direction (Krümmelbein et al., 2006; Pagliai & Vignozzi, 2002; Raducu et al., 2002; Weisskopf et al., 2000; Zhang, 1996) due to the formation of a platy structure (Pagliai et al, 2003; Horn et al., 2003, Vandenbygaart et al., 1999). The water infiltration into the soil is decreased by grazing due to the loss of macropores (Kutilek et al., 2006; Shestak & Busse, 2005) that are open to the surface (Pietola et al., 2005) and removal of vegetation (Alderfer & Robinson, 1947; Johnston, 1962, both in Greenwood & McKenzie, 2001; Proffitt et al., 1995) and due to increased water repellency (Buczko et al., 2006; Lamparter et al., 2006; Pietola et al., 2005). The combination of these effects leads to higher runoff rates on grazed compared to ungrazed sites (Johnston, 1962, in Greenwood & McKenzie, 2001). Zhao et al. (2006) proved that fencing of the ungrazed sites resulted in increased water repellency of the soil due to higher contents of organic matter which was supposed to also prevent soil water from evaporation and keep the soil water content at a higher level during dry weather periods (Bachmann et al, 2001). Grazing induced changes commonly have negative effects for the productivity of grassland soils (Martinez & Zinck, 2004; Donkor et al., 2002; Greenwood & McKenzie, 2001) and their ecological functioning. Poor physical quality of soils due to soil compaction not only leads to negative ecological consequences, but it implies also economical concerns. In the semi-arid steppe of Inner Mongolia compaction and structure degradation of the top soil caused by sheep- and goat grazing of increasing intensities have led to broad soil erosion and degradation (Gong et al., 2000; White et al, 2000; Schlesinger et al., 1990). Here soil hydraulic properties and functions and the effects of various grazing intensities on them are shown. The measured parameters were partly used to model the water movement with HYDRUS-1D. Exemplary modelling results of the effective evapotranspiration, transpiration and evaporation for three vegetation periods (2004, 2005, and 2006) are shown.

4.3 Material and methods

4.3.1 Site description, soils, soil sampling

The experimental area is situated in Inner Mongolia, northern part of P.R. China (E116°42' N43°38'). The sampling site belongs to the Inner Mongolia Grassland Ecosystem Research Station (IMGERS) of the Chinese Academy of Sciences, with a typical *Stipa grandis*- and *Leymus chinensis*- steppe vegetation, respectively. The mean annual precipitation is about 350 mm with mainly sporadic intense rainfalls and 60-80 % of the precipitation from June to August. The vegetation period lasts from May to September. The annual mean temperature of the last twenty years of the area is 0.7°C with a maximum monthly mean temperature of 19°C in June and a minimum monthly mean temperature of about -21°C in January. A detailed site description was given by Bai (2004).

We investigated four plots with different grazing intensities. Two plots were protected from grazing since 1979 (UG79) and 1999 (UG99), respectively. Two plots were grazed, one only during winter time with 0.5 sheep units/ha (WG) and one was heavily grazed with 2 sheep units/ha during the whole year (HG). One sheep unit represents a sheep with a lamb. Before fencing the area, all sites were grazed with more or less the same grazing intensity. The soil is classified as a Calcic Chernozem with a sandy loam texture on the UG79 and HG site, a sandy clay loam texture on the UG99 site and a loam texture on the WG site (FAO, 2006) (table 1).

On each plot undisturbed soil samples (cylinders, 100 cm^3) were taken at a depth of 4-8 cm in three profiles which were arranged downhill along a catena in a distance of about 15m. Undisturbed soil aggregate samples (diameter ~2 cm) were taken in the depth of 2-20 cm.

4.3.2 Laboratory measurements

The soil texture was determined according to the method introduced by Atterberg (1912), described by Schlichting et al. (1995).

Total C content was determined coulometrically, while for the determination of the water retention characteristics undisturbed soil samples (100 cm^3, n=5) were equilibrated to matric suctions <6 kPa on sand boxes, to matric suctions from 6 to 50 kPa on ceramic suction plates and to matric suctions from 50 to 1500 kPa with the pressure method (For more details see Schlichting et al., 1995; Hartge & Horn, 1992).

The sorptivity of water and ethanol was measured on the surface of undisturbed soil aggregates (diameter ~2cm, n=20), which were equilibrated to a standard matric suction of -30 kPa and oven dried at 40°C; afterwards the repellency index R was calculated according to Hallett and Young (1999).

The contact angle of sieved (<2mm) and oven dried (40°C) samples was measured using the Wilhelmy plate method (n=3), where a Pt-plate is covered with the homogenised soil material, dipped into a moistening liquid (water) and pulled out again. From the force that is needed to pull out the sample, the contact angle can be calculated as follows:

$\sigma = F/L \cos\alpha$, after conversion: $\cos\alpha = F/L\ \sigma$

with σ = surface energy, F = pulling force, L =moistened length, α = contact angle (Manual Krüss Tensiometer K100, 2001).

The contact angles were also calculated from the repellency index R, as long as the contact angle was below 90°, because at a contact angle of 90° no water would infiltrate into the soil.

Calculation contact angle (CA): CA=(arcos(1/R) [radian measure] (Hallett, 2007, per comms.).

4.3.3 Statistical analyses

The statistical analyses were accomplished using the STATISTICA 7.0 software, StatSoft Inc. (1984-2004). From the data an analysis of variance (ANOVA) was conducted and post-hoc the Fisher-LSD test has been carried out. Results have been classified to be statistically significant at a level of significance of $p<0,05$.

4.3.4 Modelling

The modelling of soil water movement inside the soil profile was performed with the HYDRUS-1D model (Simunek et al., 1998). HYDRUS 1-D is a finite element model for simulating the one-dimensional movement of water, heat, and multiple solutes in variably saturated media. The program numerically solves the Richards' equation for saturated and unsaturated water flow and Fickian-based advection dispersion equations for heat and solute transport.

4.4 Results

4.4.1 Texture and carbon content

The highest sand content was found on the HG site, where the silt and clay content is depleted compared to the other sites (table 1), while the WG site showed the highest contents of silt and clay accompanied by the lowest sand content among the various grazing intensities. At the UG79 site lower clay and silt contents were accompanied by a higher sand content compared to UG99.

The carbon-content is similar among the ungrazed sites and the WG site and ranges at about 2% while the carbon-content of the HG site is decreased to about 1,4%.

Table 4.1: Texture and total C-content of the four sites, depth: 4-7cm.

Site	Sand [%] mean/stand.dev.	Silt [%] mean/stand.dev.	Clay[%] mean/stand.dev.	total C-content mean [%]
UG79	60,9/2,70	24,9/3,67	14,2/0,96	2,2
UG99	53,1/1,33	26,7/0,93	16,2/0,4	2,0
WG	51,6/2,46	30,2/2,79	18,2/0,33	2,2
HG	67,9/3,54	20,6/2,92	11,5/0,98	1,4

4.4.2 Water retention, pore size distribution

The comparison of the water retention curve of UG79 and HG reveals a decrease of total pore volume from almost 57 % (UG79) to about 50 % (HG) due to grazing and/or prevention from grazing, respectively (figure 1).

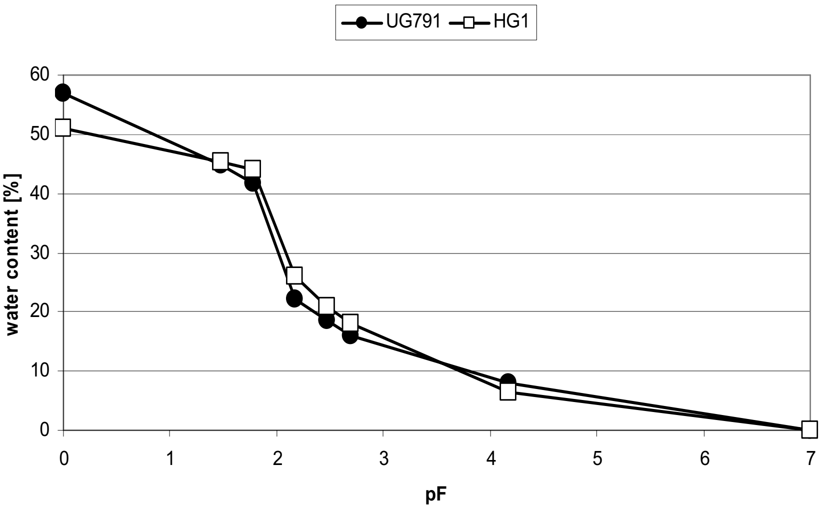

Figure 4.1: Water retention curves of ungrazed since 1979 (UG79 (circles)) and heavily grazed site (HG (squares)), 4-8cm depth.

The pore size distribution is changed due to grazing. The HG site displays ~50 % reduction of air capacity compared to the other sites, which is a significant decrease. It is identical in the latter ones (figure 2). The field capacity of the HG site is increased, while on the other sites the values are similar with a tendency of higher values on the UG site. The site specific differences among the values of field capacity are of no statistical significance. The permanent wilting point, which depends mostly on soil texture, shows similar values on UG79 and HG and on UG99 and WG with higher values on UG99 and WG. The differences between UG79, UG99 and WG are not significant, also not the differences between UG79 and HG. The differences between UG99 and WG compared to the HG site are of statistical significance.

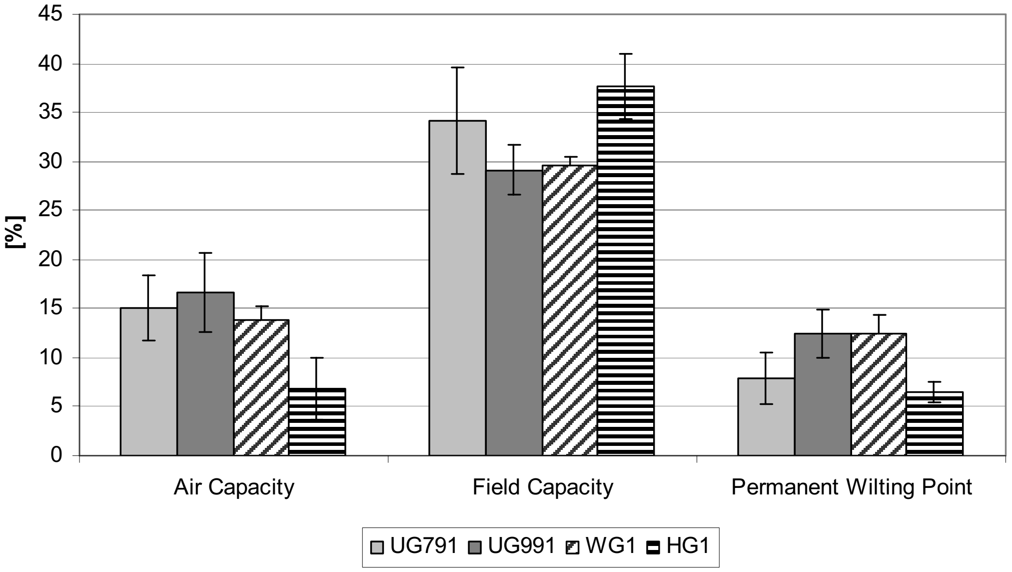

Figure 4.2: Pore size distribution of the various grazing intensities (ungrazed since 1979=UG79, ungrazed since 1999=UG99, winter grazing=WG and heavily grazed=HG). Air Capacity: <pF1,8; Field Capacity: pF1,8-4,2; Permanent Wilting Point: pF>4,2. Error bars show standard deviation.

4.4.3 van Genuchten Parameters θr, θs, α, n and m

The van Genuchten (1980) analytical model (equation 4.1) was fitted to the retention data using the RETC code (van Genuchten et al., 1991), leading to the input parameter values of θr, θs, α, m and n (table 2):

$$\theta(\psi) = \theta_r + \frac{(\theta_s - \theta_r)}{[1 + |\alpha\psi|^n]^m} \qquad \psi \leq 0$$

Equation 1

in which θs and θr are the saturated and residual water contents [m^3 m^{-3}], respectively, and α [m^{-1}], n [without unit], and m [1-1/n] are empirical shape parameters. α is an empirical parameter whose inverse is often referred to as the air entry value or bubbling pressure. It should be considered that α, n and m are regressive values from the analytical model with no actual physical meaning. Very high grazing intensity (HG) causes θs and especially θr to decrease. The ungrazed sites and WG site show similar values of most of the parameters, while at the HG site grazing had a pronounced influence. The saturated hydraulic conductivity is decreased with increasing grazing intensity, with exception of the HG site.

Table 4.2: The van Genuchten Parameters α (α=reciprocal value of air entry), n (n=measure for the smoothness of pore size distribution) and α(m-1) (m= 1-1/n) and saturated hydraulic conductivity for the various grazing intensities (ungrazed since 1979=UG79, ungrazed since 1999=UG99, winter grazing=WG and heavily grazed=HG), 4-8 cm depth.

Treatment	**θr $[cm^3/cm^3]$**	**θs $[cm^3/cm^3]$**	**α [m-1]**	**n []**	**sat. hydr. cond. [cm/d]**
UG79	0,110	0,570	0,027	1,855	164,96
UG99	0,110	0,525	0,012	1,911	82,30
WG	0,112	0,551	0,020	1,681	54,67
HG	0,047	0,524	0,016	1,668	93,03

4.4.4 Repellency index R

Irrespective of the various grazing intensities, in the depth of 2-20 cm the repellency indices of soil aggregate surfaces range on the sub critical water repellency level, i.e. the infiltration and evaporation of water into or out of the soil is alleviated but not impeded (figure 3). Although there are only small differences of no statistical significance, there is a tendency of decreasing water repellency with increasing grazing intensity.

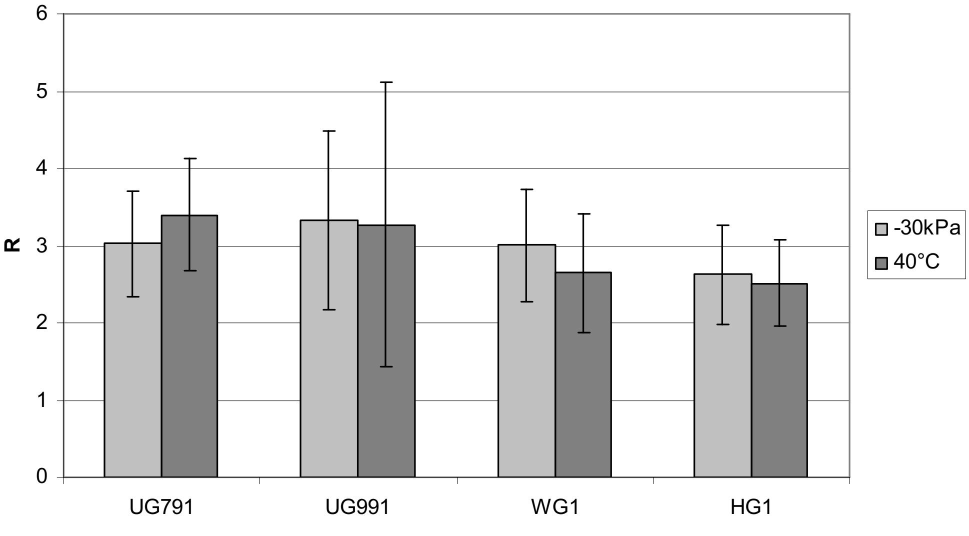

Figure 4.3: Water repellency index R of soil aggregate surfaces from a depth of 2-20 m for the four different grazing intensities (ungrazed since 1979=UG79, ungrazed since 1999=UG99, winter grazing=WG and heavily grazed=HG). Classification of R: R≤1: totally non repellent; 1<R<1,95: non repellent; R>1,95: sub critically water repellent. Error bars show standard deviation.

4.4.5 Contact angle

4.4.5.1 Calculated values

From the repellency index R the contact angle between soil and wetting liquid (water) can be calculated. These calculated contact angle values vary between 60 and 70 degrees and are not significantly different (figure 4). The height of the contact angle indicates, similar to the values of the repellency index R, that neither infiltration nor capillary rise is completely prevented, as it would be the case for contact angles from 90° onwards, but hindered.

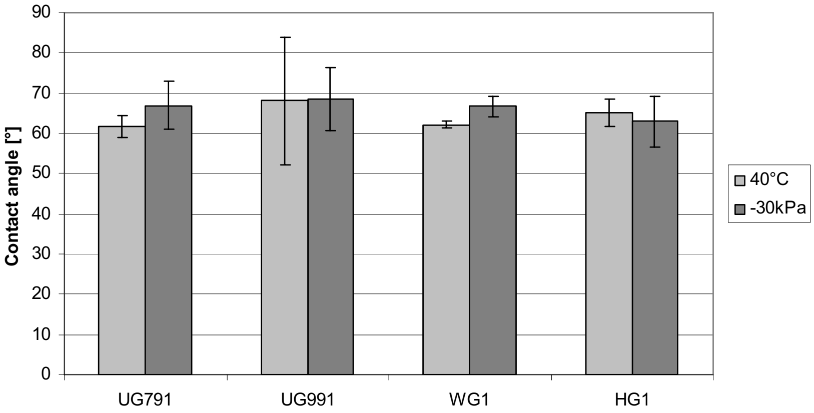

Figure 4.4: Contact angles [°], calculated from the water repellency index R measured on the surface of soil aggregates from a depth of 2-20 cm for the four different grazing intensities (ungrazed since 1979=UG79, ungrazed since 1999=UG99, winter grazing=WG and heavily grazed=HG)at a suction of -30kPa (dark grey) and oven dried at 40°C (light grey). Error bars show standard deviation.

4.4.5.2 Measured values

The contact angles measured using the Wilhelmy plate method are more heterogeneous compared to values calculated from the water repellency index R (comp. figure 4 and 5). The tendency of decreasing height of contact angle with increasing grazing intensity is statistically significant; UG79 as an exception from decreasing repellency with increasing grazing intensity shows contact angle values as small as the mean contact angle of HG, the differences between UG79 and HG are statistically not significant.

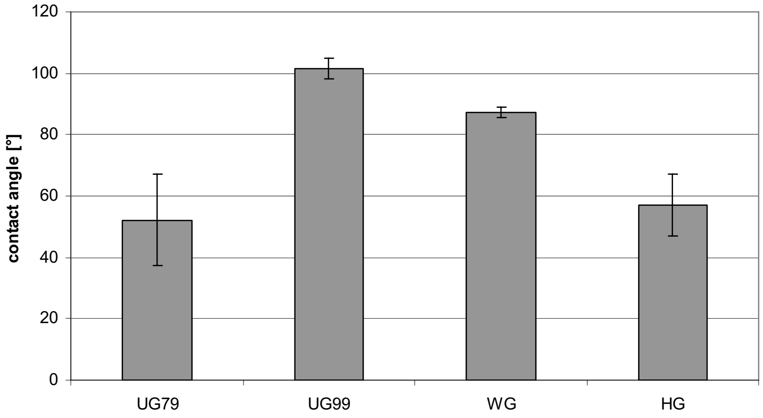

Figure 4.5: Contact angles measured with Wilhelmy plate method, oven dried (40°C) and homogenised samples of the four different grazing intensities (ungrazed since 1979=UG79, ungrazed since 1999=UG99, winter grazing=WG and heavily grazed=HG). Error bars show standard deviation, 4-8 cm depth.

4.4.6 Exemplary modelling results

The above shown results of the laboratory measurements of hydrologic properties and functions show an influence of grazing on the soil water balance. This influence was also revealed by the modelling of one-dimensional water movement in the soil profile. Table 2 displays the modelling results of actual evapotranspiration, transpiration and evaporation during the vegetation periods of the years 2004, 2005 and 2006 based on the HYDRUS-1D model for the UG79 and the HG sites. The modelled actual evapotranspiration is higher on the UG79 site in every year. Also the modelled transpiration of UG79 is always higher than that of HG, whereas the evaporation is always greater on the HG site compared to the UG79 site.

Table 4.3: Results of the HYDRUS-1D modelling of the actual evapotranspiration, transpiration and evaporation for the UG79 and the HG site during the vegetation period of the years 2004, 2005 and 2006.

Parameter	**2004 (Precip.=275mm)**		**2005 (Precip.=147mm)**		**2006 (Precip.=242mm)**	
	UG 79	**HG**	**UG 79**	**HG**	**UG 79**	**HG**
Actual Evapotranspiration [mm]	238.7	189.4	148.3	129.4	236.0	192.8
Transpiration [mm]	126.0	51.0	64.4	33.6	122.1	39.9
Evaporation [mm]	112.7	138.4	83.9	95.8	114.0	152.9

4.5 Discussion

High grazing intensities lead to low amounts of living and dead above ground biomass, thus increased sensitivity to wind erosion (Qian et al., 2007; Zhao et al, 2006; Hesse & Simpson, 2006; Hu et al., 1997). The comparatively high sand content on the HG site can be explained by the fact that bare soil which is not protected by vegetation and litter shows an increased vulnerability to wind erosion and may have resulted in a higher proportion of sand (Shao, 2001; Merril et al., 1999; Moldenhauer et al., 1983). The texture coarsening due to wind transportation of the finer particles is also described by Huang et al. (2007). This can be a reason for the coarser texture on the HG site, because clay and particularly silt particles may have been eroded by wind. This is in agreement with the findings of Huang et al. (2007) for Northern Chinese soils and Horn (1986), who proved that the texture of a grazed mountainous soil is coarser than the control. The sand content of the other sites is lower, possibly because the vegetation that was less sparse there filters saltating and suspended particles out of the air. Another reason for the differences in texture, particularly between the HG and the other sites, can be the distance of about 1000 m between the HG and the other sites, which although the distance is not too far may be affected by relocation processes such as water- and wind erosion and following deposition of soil material depending on wind speed or water flow velocity different to the other sites. The high carbon-contents can be attributed to the climatic conditions (dry, cold) of the region that strongly decelerate the decomposition of organic matter. The total carbon-content is similar on the UG79, UG99 and WG site, while it is depleted by high grazing intensity (HG); this was also described for a Sahelian sandy soil by Hiernaux et al. (1999) and for a steppe soil from Alberta, USA, by Naeth et al. (1991). They found a decrease of organic matter due to increased grazing intensities. It can be attributed to the low amount of remaining living and particularly dead biomass contributing to the C-pool of the site.

Comparing the water retention curves of UG79 and HG, it can be stated that the total pore volume is decreased due to grazing. The decrease of the van Genuchten parameters θr and θs at the very high grazing intensity supports the result; grazing at very high intensities (HG) causes θs and especially θr to decrease. The differences among the ungrazed and WG site are not as pronounced as between HG and the other sites. The results indicate decreasing soil porosity especially at high grazing intensities. Furthermore increasing sand content of the soil leads to lower n and m values, but it should be taken into consideration that α, n and m are regressive values from the analytical model and have no actual physical meaning. In agreement with our results relating to the water retention characteristics are the findings of Martinez and Zinck (2004), who stated that the total porosity of a pasture soil decreases with increasing duration of pasture use and Vilamil et al. (2001), who proved a loss of total porosity and a change of water retention due to the loss of macropores and increase of the meso pore fraction for a soil from southern caldenal area in Argentina. The changes of water retention between grazed and ungrazed soils allow drawing the conclusion that porosity increases again with increasing time of protection from grazing. As already shown by Krümmelbein et al. (2006), the saturated hydraulic conductivity decreases with increasing grazing intensity. The high values on the HG site that represents the exception to this trend can be explained by the higher sand content of this site which prevents saturated hydraulic conductivity from a decrease as distinct as on the finer textured sites.

This is in agreement with the results of Proffitt et al. (1995), who found out that soils under pasture are able to recover relatively rapidly their soil physical conditions and with Wiermann and Horn (2000), who showed that a loess-derived Luvisol exhibited distinct signs of regeneration after a single compaction event, e.g. in terms of increasing macro porosity at 10 cm depth. Horn (2004) furthermore proved, that if the wheeling was always restricted to values smaller than the precompression stress, it resulted in a time dependent recovery of soil structure. Furthermore, Werner and Werner (2001) also found that a Chernozem derived from loess and was wheeled twice with 2.5 t showing structure homogenisation had conformed again to the structural state before wheeling within 3 years.

Despite the coarser texture on the HG site, which normally leads to a higher porosity, greater coarse pore fraction and air capacity (Scheffer & Schachtschabel, 2002), the air capacity is reduced to about 50% of the air capacity of the other sites along with a decrease of total pore volume is also decreased. These results concerning pore size distribution are in agreement with the results of Singleton and Addison (1999) for a cattle-grazed New

Zealand soil and the findings of Vilamil et al. (2001) for an overgrazed Argentinean soil. The values of permanent wilting point correspond with the sand content of the sites. UG79 and HG have higher sand contents and show lower permanent wilting points than UG99 and WG, the permanent wilting point is negatively correlated to the sand content (Scheffer & Schachtschabel, 2002). The decrease of saturated hydraulic conductivity with increasing grazing intensity, particularly in the first soil depth, that was found by Singleton and Addison (1999) and for the particular study area by Krümmelbein et al. (2006) can be attributed to the decrease of coarse pores.

The repellency indices are quite similar at all grazing intensities and at both -30 kPa and 40°C equilibration, although, because of the lower carbon-content of HG, also a lower repellency index could be expected. A weak trend of decreasing values with increasing grazing intensity can be seen, this trend supports the modelling result of rising evaporation with increasing grazing intensity. The height of water repellency is not only depending on the amount (Chenu, 2000), which is underlined by own results concerning the carbon-content, but also on the composition of organic substances (Capriel, 1997). Because the calculated contact angles are calculated from the repellency indices, the differences among them are as small as the differences among the values of repellency index. The contact angles measured using the Wilhelmy plate method differ from the calculated ones. The contact angles decrease with increasing grazing intensity, except on UG79, where the measured contact angle is in the same range as on HG. One reason for the different values compared to the calculated contact angles is the pretreatment of the samples, which are air dried (40°C) and homogenised before the measurement. It is possible that due to soil aggregating processes the hydrophobic components can be found on the surface of aggregates as alredy shown by Jasinska (2006) for soils from southern Germany. When the soil is homogenised, the hydrophobic components become distributed in the material and are not concentrated at the surface anymore. This can be a reason for the smaller measured contact angles of UG79 and HG compared to the calculated ones. The water repellency, hence the contact angle, is also depending on the particle size and texture, respectively. The water repellency increases with decreasing particle size (McHale et al., 2005; de Jonge et al., 1999). That is also an explanation for the low values of the measured contact angles of UG79 and HG, having a similar texture classified as sandy loam (FAO).

The results of the HYDRUS-1D modelling show that actual evapotranspiration and transpiration is higher on the UG79 site than that on the HG site. In contrast to this, the evaporation on HG exceeds the evaporation on UG79. Parameters that influence modelling results are water retention curve, hydraulic conductivity, vegetal cover, root density and weather conditions, of which the latter one is the same for all grazing intensities, while the other parameters have been shown to depend amongst others on the grazing intensity. Evapotranspiration decreases with increasing grazing intensity due to the grazing induced changes of water retention characteristics, pore size distribution and water repellency. The HG site shows higher soil water storage due to decreasing root water absorption, greater amounts of surface runoff due to decreasing vegetal cover and possibly an enhanced drainage after heavy rainfall due to low water repellency and a low water holding capacity. On the other hand the amount of evaporation increases due to slightly reduced hydrophobicity. The transpiration is higher on the UG79 site, because the vegetation is more dense there compared to that on the HG site. This is also the reason for higher evaporation on the HG site. On the UG79 site only very small areas are not covered by living or dead biomass that holds off wind and solar radiation and thus protects the soil from evaporating water. The modelling results are in agreement with the findings of Li et al. (2007) and Chen et al. (2007), who investigated steppe soils in central Mongolia and with Bremer et al. (2001), who showed the effect of cattle grazing on a prairie soil in north-eastern Kansas, USA.

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5 General discussion and conclusions

5.1. General

The research articles presented in this work demonstrate that grazing has an influence on soil mechanical and hydraulic properties and functions, predominantly in the upper 10 to 15 cm. This result is in agreement with the findings of various authors who investigated grazing- and trampling effects, respectively of different animals on soils around the world (Krümmelbein et al., 2006; Brye & West, 2005; Drewry, & Paton, 2005; Martinez & Zinck, 2004; Greenwood& McKenzie, 2001; Zhang & Horn, 1996). Analogous to the results presented here Pietola et al. (2005), Horn, (2004, 2003) and Ferreras et al. (2000) proved mechanical and hydraulic soil properties and –functions to be interlinked with each other. Thus, changing mechanical properties also influence the hydraulic features of a soil. The compressive behaviour of the soil was shown to be not only dependent on the grazing intensity, but also on the kind of loading path during determination.

5.2 Grazing effects on soil mechanical properties

The results reveal that grazing leads to increasing values of precompression stress on the grazed sites, particularly in the upper soil layer. This indicates a grazing induced compaction of the soil, along with increasing soil strength against compressive forces and an increasing bulk density. A commonly used method to determine the mechanical strength of a soil is the determination of precompression stress under static loading conditions in oedometer tests (Arvidsson & Keller, 2004; Keller et al., 2004; Hartge & Horn, 1992). It is frequently stated however, that the static determination of precompression stresses is not realistic, because soils are often not loaded statically under field conditions but repeatedly with a sequence of short intermittent loading-unloading-reloading events or with a high number of loads over time (Peth & Horn, 2006). Accordingly, in this study the precompression stress was determined under static and cyclic loading conditions. The static determination of precompression stress revealed the greatest differences among the various grazing intensities and the lowest values, representing minimal soil strength. This is in agreement with the results of Lebert et al. (1989), because the rearrangement of soil particles, along with an increasing number of particle contacts (Hartge & Horn, 1984) is most pronounced, when the load application is statically and allows redistribution and drainage off of soil water, thus reaching final settlement. The cyclic loading of the soil revealed in general lower values of precompression stress than the static loading, with a dependence of precompression stress on the number of loading cycles. If the first loading cycle is considered for determining the precompression stress, a situation as balanced as after static loading is not reached. With increasing number of loading cycles and accordingly loading time, the particle rearrangement and possibly redistribution and drainage off of soil water becomes more complete and settlement becomes more pronounced. This process, which is partly responsible for the similarity of the values of precompression stress of all grazing intensities after one loading cycle, is schematically shown in figure 5.1. After 20 loading cycles the precompression stress values of the ungrazed sites decrease and approach those determined statically, because of the increasing loading time, and the further advanced rearrangement of soil particles. The better rearrangement can partly be attributed to the weakened inner soil strength due to positive pore water pressure during loading (fig. 5.1). The differences of matric suction/pore water pressure during loading and unloading can furthermore induce a pumping effect which is able to transport soil water to the pore space affected by loading and unloading. The maceration of the soil structure therefore is endangered to become more intense due to cyclic loading processes. The grazed sites do not reveal a higher sensitivity to cyclic loading processes due to their mechanical history, which determines the soil's mechanical behaviour (Koba & Stypulkowski 1980). The grazed sites have been trampled, thus cyclically loaded before; the rearrangement of soil particles is far advanced, as there are no significant differences between the precompression stress after one and after 20 loading cycles and the statically determined values. In contrast to that, the ungrazed sites that have been fenced and protected from grazing and reveal increasing precompression stress values from static determination over 20th and to the first loading cycle of cyclic determination which can be interpreted as a sign for structural soil recovery. This result is supported by the smaller angles of internal friction, by the changing anisotropy of saturated hydraulic conductivity from horizontal (grazed) to vertical (ungrazed) accentuation and by decreased total and coarse pore volume of the grazed compared to the ungrazed sites. Structural recovery of mechanically loaded soils was formerly shown by Werner and Werner (2001) for a loess-derived Chernozem compacted by wheeling within three years, by Wiermann and Horn (2000) for a loess-derived Luvisol after a single compaction event (e.g. increasing macro porosity and gas permeability at 10 cm depth) and by Mekuria et al. (2007) for a Northethopian soil formerly degraded by grazing and then excluded from grazing by fencing.

The soil structure deterioration is not only pointed out by decreasing strength against compressive forces, but also by decreasing angles of internal friction with increasing grazing intensity. The angle of internal friction is a measure for the structural development of a soil; the greater the angle of internal friction, the further advanced is the structural formation of the soil (Silva et al., 2004, Horn et al., 1994). It is characterized e.g. by swelling and shrinkage processes and biological activity of plant roots and soil inhabiting animals, leading to rearrangement of particles and resulting in the formation of aggregates of higher densities than the bulk soil and the surrounding interaggregate pore system. The more pronounced the soil aggregation is and the more stable the aggregates are, the stronger is the increase of the shear resistance with increasing normal stress, thus the greater is the angle of internal friction. Aggregate stabilising processes are for instance age hardening effects, organic (humic substances, micro-organisms) or mineral (calcium-carbonate) binding agents, which stabilise the contacts between soil particles, and enmeshment of aggregates by fine roots. The cohesion is determined by the capillary cohesion of the soil and the greatest drying event the soil has experienced before. Repeated mechanical loading combined with shearing forces as applied by grazing animals adversely affects the structure of the grazed sites along with diminishing angles of internal friction and a decrease of the total and coarse pore volume. This in turn affects the pore water pressure and the occurrence and orientation of water menisci, which in dry states are concave, thus stabilising. Due to the compression of coarser pores, stabilising water menisci develop in newly created finer pores, this can induce a higher cohesion on the grazed sites at a sample equilibration to -30 kPa compared to the coarserpored ungrazed sites. If due to the compression of coarse pores the hydraulic conductivity of the soil becomes too low to remove excess soil water from the pore system, soil compaction leads to less negative and sometimes even positive pore water pressure during loading, resulting in convex, thus mechanically destabilising menisci according to the Bishop's equation. With incomplete drainage off of excess soil water soil strength can be severely decreased as to be seen in figure 5.1:

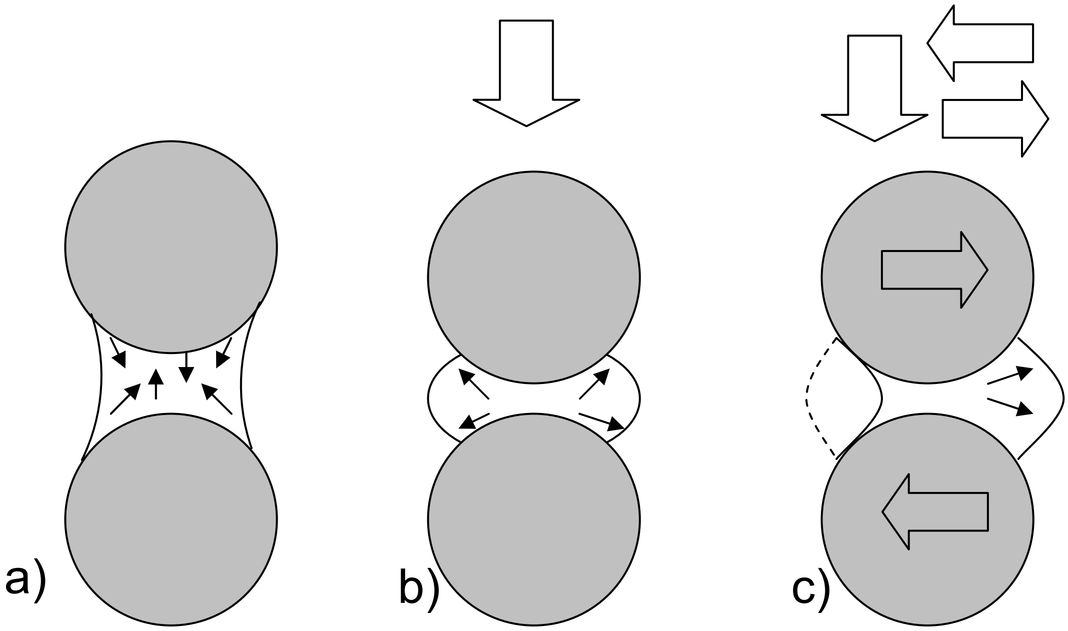

Figure 5.1: Schematic: water menisci between soil particles. a) original state with stabilising, concave water menisci; b) under compression, the water menisci become convex, thus destabilising; c) application of compressive and shearing force, due to the orientation of water menisci particle mobility is enhanced.

Concave menisci as to be seen in figure 5.1 a) allow the angle of internal friction to stay relatively high. During loading the menisci become convex, thus destabilising; the angle of internal friction decreases. Under natural conditions not only compressive but also shearing forces are applied, these shearing forces also lead to changes of the menisci shape (figure 5.1 c)) and can induce a breakdown of the menisci, followed by a soil structural breakdown. The differences of pore water pressure during the loading test are highly dependent on the unsaturated hydraulic conductivity of the soil. It can also be expected that while being loaded cyclically, the pore water pressure changes during loading and unloading furthermore induce a distinct pumping effect which increases the risk of kneading deforming processes and severe structure deterioration of the soil (Figure 5).

Although in the studied soils at the given predrying conditions this complete structure and pore functioning deterioration could not be shown, it has to be kept in mind as an option because heavy rainfall events occur regularly with precipitation of more than 100 mm within 1 day which than leads to water contents near saturation of the uppermost centimetres of the soil profile, especially on the grazed sites. If under those conditions the cyclic loading through trampling occurs, not only a weakening via deterioration of the aggregates and their arrangement in the soil but also through the frequent changes in the menisci forms (concave to convex and vice versa) can be expected and as a consequence also the hydraulic fluxes and intensity as well as their directions affect the landscape stability, erosion dynamic in the lowland and the sustainability of the steppe.

5.3 Grazing effects on soil hydraulic properties and functions

The structural change due to grazing is also reflected by decreasing values of vertically oriented saturated hydraulic conductivity with increasing grazing intensity and particularly by the anisotropy of the saturated hydraulic conductivity. As it can be seen from the results, the change of pore function and pore size distribution and the decreased total pore volume was proven by own data, which shows the decrease of the coarse pore fraction along with the creation of finer pores due to compaction. Figure 5.3 schematically shows the stress-dependent modification of the water retention curve with a decrease of the total and coarse pore volume.

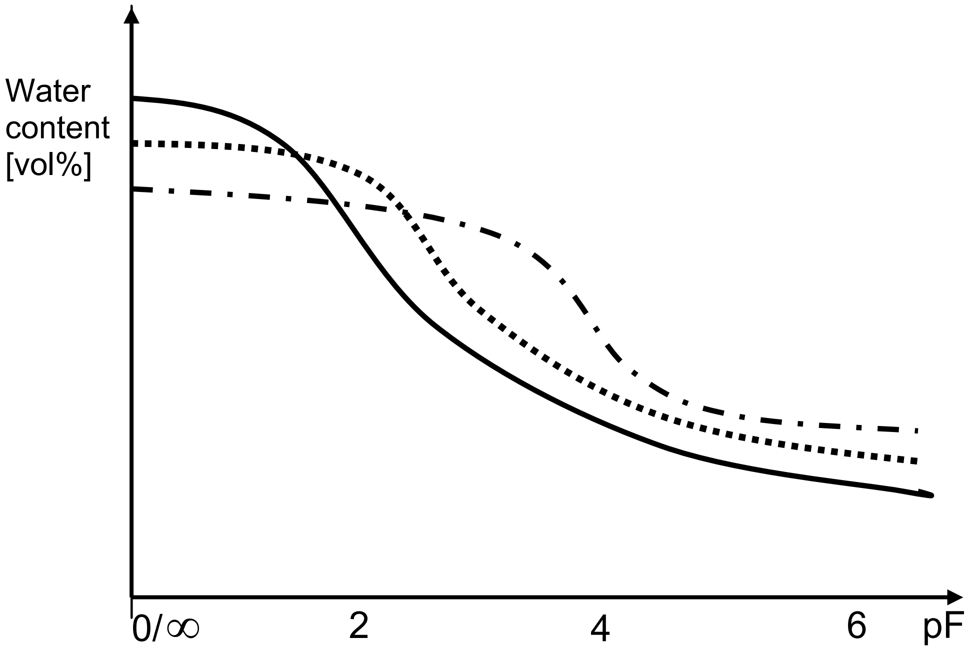

Figure 5.2: Schematic: Changes of water retention curve in dependence of the applied stress. Solid line: original water retention curve before stress application, dotted line: after medium stress application, dashed line: after high stress application

According to the Hagen-Poiseuille law, the flux Q is depending on the pore radius with the 4th power, which results through the reduction of coarser pores in an enormous decrease of the total flow of water or gases per pore in the soil. Decreased water flow due to grazing is revealed by own results concerning saturated hydraulic conductivity, which is in general lower on the grazed compared to the ungrazed sites and which, due to grazing induced compaction, hence formation of a platy structure (Doerner & Horn, 2006; Martinez & Zinck, 2004; Horn et al., 2003) becomes higher in the horizontal compared to the vertical direction. At the ungrazed sites the saturated hydraulic conductivity is higher in the vertical direction due to vertical crack formation following former homogenising processes (Janssen et al., 2006; Peng et al., 2005) and macropores created by soil fauna and plant roots (Schrader et al., 2007; Joschko et al., 2006; Krück et al., 2006; Scheffer & Schachtschabel, 2002). Roots not only form continuous vertical pores (root channels) by exerting mechanical stresses on the soil, they also take up water, followed by more intense and more frequent wetting and drying cycles, which create a higher pore water suction (according to the Bishop equation) and induce crack formation close to the roots. Besides the saturated hydraulic conductivity also other hydraulic features, e.g. water retention characteristics of the soil, are modified due to grazing and grazing-based soil structure deterioration. Comparing the UG79 and the HG site, the total pore volume as well as the coarse pore volume is decreased, even though on the HG site the texture is sandier, which normally leads to greater amounts of coarse pores. Along with the reduction of coarse pores, the field capacity of the grazed site rises according to the coarse pores that have been compressed to pores of smaller diameters (figure 5.2).

At very high grazing intensities (HG), the amount of living and dead biomass remaining on the site is reduced (Qian et al., 2007; Zhao et al, 2006; Hesse & Simpson, 2006; Hu et al., 1997). This leads, as own results indicate, to a sandier texture on the grazed sites due to the wind erosion of clay and particularly silt particles from the unprotected soil surface (Shao, 2001; Merril et al., 1999; Moldenhauer et al., 1983), as also proven by Huang et al. (2007) for northern Chinese soils. While the HG site can be characterised as erosion site, the other sites, especially the ungrazed sites, are capable of catching solid particles out of the air and act as deposition sites for the wind eroded soil particles. The grazing induced changes from deposition- to erosion site at a very high grazing intensity moreover decrease the ability of the soil to recover from degradation, because of the continuing mechanical disturbance and the export of soil organic matter and nutrients. Another reason for the sandier texture on the HG site can be the distance of about 1000 m to the other sites. Possibly the landscape that is shaped by relocating processes of wind- and water erosion implies such textural changes within relatively small distances. The export of biomass by grazing animals furthermore not only influences wind erosion and deposition processes, but it has also consequences for the water repellency of the soil.

The water repellency index R, which is depending on the amount (Chenu, 2000) and composition (Capriel, 1997) of organic matter revealed similar values on all investigated sites and can be classified as subcritically water repellent with a weak trend of decreasing values with increasing grazing intensity. The repellency index R is measured on the surface of soil aggregates, while the Wilhelmy plate method measures contact angles of homogenised soil material. The different methods showed the amount of hydrophobicity particularly of the UG79 site to be dependent on the pretreatment of the samples; the UG79 site has similar repellency indices as the other sites, but the contact angles measured with the Wilhelmy plate method are as low as on the HG site. Probably the aggregates of UG79 have, due to age hardening effects and biological activity, developed an organic coating that is destroyed and mixed into the soil material during its homogenisation. The contact angle is not only determined by the organic matter, another influencing factor is the particle size and soil texture, respectively. Additionally, the water repellency increases with decreasing particle size (McHale et al., 2005; de Jonge et al., 1999), which is another reason for the small contact angles determined with the Wilhelmy plate method on the UG79 and the HG site, where the texture is sandier than on the other sites.

Grazing induced changes in soil physical properties and functions were also shown to influence parameters used to model water movement in the soil profile. The HYDRUS 1-D modelling of evapotranspiration and its components transpiration and evaporation resulted in greater actual evapotranspiration and transpiration on the UG79 site compared to the HG site. In contrast to this, the evaporation on HG exceeds the evaporation on UG79 due to removal of living and dead vegetation, thus prevention from transpiration and bare soil which is exposed to solar radiation and wind impact. Furthermore, the unsaturated hydraulic conductivity function of the HG site is enhanced because of the conversion of coarse into finer pores which longer contribute to water transport processes with increasing matric suction of the soil and increases evaporation compared to the ungrazed site. The modelling results are in agreement with the findings of Li et al. (2007) and Chen et al. (2007), who investigated steppe soils in central Mongolia and with Bremer et al. (2001), who showed management effects on steppe soils in Inner Mongolia and north-eastern Kansas, USA, respectively.

5.4 Conclusions

In this study it could be shown that the soil's properties and functions are modified by grazing and trampling animals, mostly in the upper soil layer. It could also be shown that soil mechanical and soil hydraulic characteristics cannot be considered separately, because they are closely interlinked with each other. A change in mechanical properties was proven to have extensive impact on hydraulic features and vice versa. Apart from the negative effects that have already been addressed, e.g. wind- and water erosion and accordingly loss of nutrients and of water which otherwise could be stored in the soil or used by plants, animals and human beings and air pollution problems in the whole northern part of China, (over-) grazing can imply far-ranging consequences locally, regionally and globally. Slight management alterations, e.g. increasing stocking rates or variation of the size of grazed areas can seriously change soil properties and functions and consequently productivity of grassland and grazing animals, thus living conditions of the farmers and finally agricultural economy. Furthermore it will not only have a local impact, but sometimes dust storms from the Northern grasslands of the country reach and paralyse the Chinese Capital Beijing; also global change processes can be affected due to modifications of the carbon cycle and air pollution with particulate matter. Recapitulating it can be stated that

- Grazing was shown to adversely affect the mechanical stability of the soil against compressive and shearing forces and the soil water balance, hence productivity and ecological functioning.
- Grazing induced changes of soil mechanical and hydraulic properties lead to increased sensitivity of the soil against water-and wind erosion.
- The changes in mechanical and hydraulic properties and functions were proven to be strongly interrelated with each other.
- A different behaviour of the variously grazed soil under cyclic and static loading conditions was encountered due to different mechanical loading history of the sites.
- The steppe soil in Inner Mongolia shows distinct signs of recovery from grazing caused damages on the fenced, grazing-protected sites in hydraulic as well as mechanical aspects.

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7 Lebenslauf

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