Water use efficiency and management of agro-pastoral landuse systems

in the Mongolian-Chinese Altay

Greta Jordan

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Summary

A changing climate, environmental degradation and increasing resource scarcity are likely to affect particularly small-scaled agricultural production systems in semi-arid areas of the world and make crop and animal husbandry even more challenging in those regions. The intensification of agricultural systems under semi-arid climate conditions can be a key strategy to increase resource use efficiency while maintaining food production and economic development. The present PhD thesis includes three studies of crop and animal husbandry systems in Oman and the Chinese-Mongolian Altay-Dzungarian region where the efficient use of scarce and susceptible resources is of vital importance.

The use of organic fertilizers such as compost and goat manure is an important approach to maintain soil fertility of irrigated agricultural land under the semi-arid climate conditions of Oman. However, high nutrient losses due to leaching and especially gaseous emissions are likely impairing the efficiency of organic substrate applications. Activated charcoal and tannins have the potential to reduce such gaseous losses of carbon and nitrogen. Therefore, gaseous emissions of carbon dioxide (CO_2), ammonia (NH_3) and nitrous oxide (N_2O) were measured by a photo-acoustic infrared multi-gas monitor in two different experiments: (i) carbon and nitrogen emissions from compost were measured after addition of activated charcoal and tannins as a single or mixed application in a field experiment in Oman; (ii) carbon and nitrogen emissions from soil amended with goat manure and additionally mixed with either activated charcoal, tannin or the sum of these both additives were determined in an incubation experiment under greenhouse conditions. Results showed that peaks of gaseous carbon and nitrogen emission were reduced and/or temporally shifted after tannin applications to compost as well as soil. Compared to the unamended compost, application of tannins to compost reduced cumulative gaseous emission for carbon by 2100 g carbon m^{-2} 69 d^{-1} (-36%) and for nitrogen by 6 g N_{total} nitrogen m^{-2} 69 d^{-1} (-40%). Tannins applied directly to soil reduced N_2O (-17%) and in particular NH_3 (-51%) emissions in comparison with the control. In contrast to these results, emissions of all gases increased from compost amended with activated charcoal. Based on these results, tannins appear to be a promising amendment to composts and soils to mitigate gaseous emissions, especially under semi-arid climate conditions.

Transhumance systems in the Altay-Dzungarian region of China and Mongolia are characterized by mixed herds on seasonal grazing sites in the desert, mountain steppe and alpine belt. Chinese governmental interferences and the economic privatization in the 1990s in Mongolia led to modifications of transhumance systems in both countries which are likely to affect the herbage yield and quality. To identify such processes, spatio-temporal mobility patterns of pastoral herds, number and size of utilized pastures, and the herbage offer and its nutritive value were investigated. To this end, one representative goat and cattle was equipped with a GPS collar and herbaceous biomass was determined at 869 sampling locations on the main seasonal pastures. The average cumulative annual lengths of cattle and small ruminant transhumance routes were similar within the respective countries (317 km year^{-1}). Throughout the year, cattle herds spent more time on a specific pasture in Mongolia than in China (108/59 days), whereas, the sojourn of small ruminants was similar in both countries. In the study region the average size of utilized grazing areas ranged from 1 to 77 ha. In China, herbage yields (t DM ha^{-1}) ranged from 0.9 (winter pasture) to 1.7 (summer pasture), whereas the Mongolian herbage yields varied between 0.5 (summer pasture) to 1.2 (spring pasture). In consequence, herbage allowance (kg dry matter per sheep unit^{-1} day^{-1}) ranged in average from 34/17 to 91/95 (China/Mongolia) at the onset of a grazing period, whereby only Chinese spring pastures showed lower values than Mongolian one. Across all seasonal pastures hemicellulose concentration was 1.5 higher in Mongolia than in China; while crude protein and phosphorous concentration were comparable in both countries. It can be concluded that official regulations on animal numbers, timing of pasture utilization and allocation of specific seasonal grazing areas to individual herders in combination with higher amounts of spring rainfall seem to generate higher herbage yields on the Chinese site. On the other hand, enforced regulations may prevent flexible adaptation of herd management to inter-annual climatic variation and extreme climatic events. In Mongolia, increased goat numbers, reduced livestock and thus high seasonal stocking rates in combination with low precipitation until May affect biomass yield and herbage allowance. Increasing the animals' daily grazing radius by active herding of sheep and goats may reduce grazing pressure and improve pasture productivity especially on spring and summer pastures.

Traditionally, land use in Mongolia had been dominated by a well-adopted animal husbandry system, while crop production played a relative minor role. As in other parts of Mongolia, land cover and land use changes are likely to decrease the water availability of river oases. Therefore, a study was conducted to analyze land cover changes between 1972 and 2013 as well as the current prevailing livelihood strategies and farming practices of the river oasis Bulgan *sum* in Western Mongolia. Additionally, the water-use efficiency for different land cover classes was simulated by using the Soil and Water Assessment Tool (SWAT). The comparison of two satellite images of the Bulgan *sum* river oasis indicated a change from natural rangeland to built-up areas and river water receiving sites. Three different livelihood strategy clusters were identified: (i) sedentary households (HHs) practicing field cropping and keeping livestock, both for subsistence needs, (ii) semi-commercial HHs keeping livestock and practicing field cropping for subsistence needs and (iii) HHs keeping livestock for commercial needs and hiring labour for semi-commercial hay production. Overall, an area of 769 ha received irrigation water drawn from the Bulgan River. The application of irrigation water productivity ranged from 1.6 (cereals) and 0.2 (melons) $m^3 kg^{-1}$ fresh matter yield. The precipitation to potential evapotranspiration ratio of 0.1 indicates a high number days with crop water stress. Modelled auto-irrigation as well as auto-irrigation and fertilization management increased the yield by about 46 and 77%, respectively, on average. The water use efficiency of biomass ranged from 11 to 52 kg ha^{-1} mm^{-1} for rangeland and wetland. High evapotranspiration/precipitation ratio values and the potential rise of evapotranspiration, especially due to land cover changes (from an extensive to a more intensive land use management) and a changing climate, underlined the importance the importance of a more efficient use of water in the Bulgan *sum* watershed. Under these conditions biomass productivity per unit water transpired and evaporated need to be improved by changing irrigation practices and management practices.

Zusammenfassung

Ein sich veränderndes Klima, Verschlechterung der Umweltbedieungen und zunehmende Verknappung natürlicher Ressourcen beeinträchtigen voraussichtlich insbesondere kleinbäuerliche Produktionssysteme in semiariden Gebieten. Ackerbau und Viehzucht in diesen Regionen stehen damit vor noch größeren Herausforderungen. Eine mögliche Schlüsselstrategie für eine Steigerung der Ressourcennutzungseffizienz bei gleichzeitiger Beibehaltung der Nahrungsmittelproduktion und ökonomischen Entwicklung ist die Intensivierung solcher landwirtschaftlicher Systeme. Die vorliegende Dissertation beinhaltet drei Fallstudien zu Ackerbau- und Viehzuchtsystemen im Oman und der chinesisch-mongolischen Altai-Dsungarei-Region, in denen eine effiziente Nutzung der knappen und empfindlichen Ressourcen von zentraler Bedeutung ist.

Ein wichtiger Ansatz für den Erhalt der Bodenfruchtbarkeit von bewässerten Landwirtschaftsflächen unter den ariden Klimabedingungen des Omans ist die Nutzung organischer Düngemittel wie Kompost und Ziegendung. Hohe Nährstoffverluste durch Auswaschung und vor allem gasförmige Austräge beeinträchtigen jedoch die Effizienz organischer Substrate. Aktivkohle und Tannine besitzen das Potential, gasförmige Kohlenstoff- und Stickstoffverluste aus dem Boden zu reduzieren. Zwei Experimente maßen darum gasförmige Kohlendioxid- (CO_2), Ammoniak- (NH_3) und Lachgasverluste (N_2O) mithilfe eines photoakkustischen Infrarotmultigasmonitor: (i) Es wurden Kohlenstoff- und Stickstoffemissionen aus Kompost gemessen, dem während eines Feldexperiments im Oman Aktivkohle und Tannine entweder als Einzel- oder Mischanwendung hinzugegeben wurde. (ii) Nach Zugabe von Ziegendung entweder gemischt mit Aktivkohle, Tanninen oder beidem wurden bodenbürtige gasförmige Kohlenstoff- und Stickstoffemissionen während eines Inkubationsversuchs im Gewächshaus bestimmt. Die Ergebnisse zeigen, dass die gasförmigen Emissionsspitzen für Kohlenstoff und Stickstoff nach der Zugabe von Tanninen zum Kompost oder zum Boden reduziert und/oder zeitlich versetzt waren. Im Vergleich zum unbehandelten Kompost reduzierten Tanninzugaben die kumulierten Gasemissionen aus dem Kompost um 2100 g Kohlenstoff m^{-2} 69 d^{-1} (-36%) und 6 g N_{total} Stickstoff m^{-2} 69 d^{-1} (-40%). Im Vergleich zur Kontrolle reduzierten direkt dem Boden applizierte Tannine sowohl N_2O- (-17%) als auch vor allem NH_3-Emissionen (-51%). Die Zugabe von Aktivkohle steigerte dagegen die Emissionen aller Gase aus dem Kompost. Auf Grundlage dieser Ergebnisse erscheint die Zugabe von

Tanninen zum Kompost und Boden vielversprechend zu sein, um Gasemissionen insbesondere unter semiariden Klimabedingungen zu mindern.

Transhumanzsysteme der Altai-Dsungarei-Region in China und der Mongolei sind durch gemischte Herde auf saisonalen Weidegründen in der Wüste, in Bergsteppen und auf alpinen Höhenstufen geprägt. Eingriffe der chinesischen Regierung sowie die ökonomische Privatisierung der 1990er in der Mongolei führten zu Veränderungen dieser Transhumanzsysteme in beiden Ländern. Um eventuelle negative Effekte zu bestimmen, wurden die räumlich-zeitliche Verteilung pastoraler Herden, die Anzahl und Größe der genutzten Weidegründe sowie deren Weidefutterangebot und -nährstoffgehalte untersucht. Stellvertretend wurden hierzu eine Ziege und ein Rind mit einem GPS-Halsband ausgestattet. Die krautige Biomasse wurde an 869 Probenahmestellen der saisonalen Hauptweiden erfasst. Über das ganze Jahr gesehen verweilten Rinderherden in der Mongolei länger auf einem bestimmten Weidegrund als in China (108/59 Tage), wohingegen die Verweildauer der Kleinwiederkäuer in beiden Ländern ähnlich war. Die durchschnittliche Größe der genutzten Weideflächen in der Untersuchungsregion erstreckte sich von 1 bis 77 ha. Der Grünfutterertrag (t DM ha^{-1}) reichte auf chinesischer Seite von 0.9 (Winterweide) bis 1.7 (Sommerweide), wohingegen dieser auf der mongolischen Seite zwischen 0.5 (Sommerweide) und 1.2 (Frühjahrsweide) lag. Folglich lag die Grünfuttervefügbarkeit zu Beginn der Beweidungsperiode (kg Trockenmasse pro Schafeinheit^{-1} und Tag^{-1}) durchschnittlich zwischen 34/17 und 91/95 (China/Mongolei), wobei lediglich die chinesische Frühjahrsweide geringere Werte aufwies als die mongolische. In allen saisonalen Weiden lag die Hemicellulosekonzentration in der Mongolei 1.5 mal höher als in China. Die Rohprotein- und Phosphorkonzentrationen waren in beiden Ländern vergleichbar. Zusammenfassend kann festgestellt werden, dass Vorschriften bezüglich der Tieranzahl, des Zeitpunkts der Weidenutzung und der Zuteilung spezifischer saisonaler Weidegründe in Kombination mit höheren Frühjahrsniederschlägen auf chinesischer Seite zu höheren Grünfuttererträgen führen. Andererseits verhindern konsequent umgesetzte Regularien wahrscheinlich eine flexible Anpassung des Herdenmanagements an zwischenjährliche Klimaschwankungen und extreme Klimaereignisse. In der Mongolei beinträchtigen gestiegene Ziegenbestände, reduzierte Viehbewegungen innerhalb der saisonalen Weiden und eine entsprechend hohe saisonale Besatzdichte in Verbindung mit einem verringerten Niederschlag bis zum Mai die

Grünfutterverfügbarkeit. Eine Steigerung des täglichen Tierbewegungsradius im Zuge einer aktiveren Schaf- und Ziegenhütung könnte den Beweidungsdruck reduzieren und zu einer Verbesserung vor allem der Frühjahrs- und Sommerweidenproduktivität führen.

Die Landnutzung in der Mongolei wurde traditionell von einem gut angepassten Tierhaltungssystem dominiert. Der Anbau von Kulturpflanzen war hingegen nachrangig. Wie auch in anderen Gegenden der Mongolei verringert ein Wandel der Landbedeckung und Landnutzung die Wasserverfügbarkeit in Flussoasen. Daher wurden in einer Untersuchung der Flussoase Bulgan *sum* sowohl die Landbedeckungsänderungen zwischen 1972 und 2013 als auch die gegenwärtig vorherrschenden Lebensunterhaltsstrategien und Ackerbaupraktiken analysiert. Zusätzlich wurde die Wassernutzungseffizienz für verschiedene Landbedeckungsklassen mithilfe des Soil and Water Assessment Tools (SWAT) simuliert. Der Vergleich zweier Satellitenbilder der Bulgan *sum* Flussoase zeigte einen erkennbaren Wandel von natürlichem Weideland hin zu bebauten Gebieten und wassererhaltenden Standorten. Drei verschiedene Cluster von Lebensunterhaltsstrategien wurden identifiziert: (i) sesshafte Haushalte, die Ackerbau und Viehhaltung für den Eigenbedarf betreiben, (ii) Haushalte, die halbkommerzielle Viehhaltung und Ackerbau für den Eigenbedarf betreiben, und (iii) Haushalte, die kommerziell Viehhaltung betreiben und Arbeitskräfte zur halbkommerziellen Heugewinnung einstellen. Insgesamt wurden 769 ha mit Wasser aus dem Fluss Bulgan bewässert. Die Bewässerungswasserproduktivität schwankte zwischen 1.6 (Getreide) und 0.2 (Melonen) m^3 kg^{-1} Frischmasseertrag führte. Das Verhältnis des Niederschlags zur potentiellen Evapotranspiration von 0.1 weist auf eine hohe Anzahl von Tagen hin, an denen Kulturpflanzen unter Wassermangel leiden. In der Modellierung führten eine automatisch angepassten Bewässerung und deren Kombination mit einer angepassten Düngung zu einem Ertragszuwachs um durchschnittlich 46 beziehungsweise 77%. Die Wassernutzungseffizienz für Biomasse schwankt für Weideland und Feuchtgebiete zwischen 11 und 52 kg ha^{-1} mm^{-1}. Hohe Werte des Evapotransipiration-Niederschlag-Verhältnisses und der potentielle Anstieg der Evapotranspiration insbesondere durch Landbedeckungsänderungen (von einem extensiven hin zu einem mehr intensiven Landnutzungsmanagement) unterstreichen die Bedeutung einer effizienteren Wassernutzung im Bulgan *sum* Wassereinzugsgebiet. Die Biomasseproduktivität pro Einheit transpiriertes und evaporiertes Wasser müsste durch veränderte Bewässerungs- und Managementpraktiken verbessert werden.

1. Chapter

General introduction and research objectives

1.1 Intensification of agricultural systems in Oman, China and Mongolia

Increasing global population, globalization, urbanization and changing consumption patterns will alter the demand for food and intensify the pressure on existing food-producing systems and their surrounding environment (Conway and Barbier 2009; Cumming et al. 2014; Delgado 2003; Tilman et al. 2011; Conway et al. 2012; Garnett et al. 2013). Scarcity of water, biodiversity and land and a changing climate pose additional challenges to current agricultural systems (Dombrowsky et al. 2014; Houdret et al. 2014; Hofmann et al. 2015; McIntyre et al. 2016). Against this background, many traditional farming systems largely dependent on natural resources and ecosystem are changed towards more intensified agriculture systems to produce higher outputs of food, feed and fiber (Figure 1, Rudel et al. 2009).

Agricultural intensification can be achieved by increasing the gross output through: (i) input expansion devoid of technological innovation, (ii) alteration towards more valuable outputs and (iii) technical innovation that rises land productivity, or any combination of these (Carswell 1997). Typical examples of an intensified agricultural production are the increase of yields per hectare, livestock intensity (such as faster maturing breeds) and the change of land use from low value crops or commodities to those that receive higher market prices or have higher nutrient content (Baulcombe et al. 2009; Rudel et al. 2009; Pingali 2012; Pretty and Bharucha 2014). However, agriculture intensification has not only economic or nutritional benefits; land use change and more intensive use of existing cropland and rangeland have led to numerous environmental impacts and tradeoffs around the globe such as land clearing, habitat fragmentation, an increase in global greenhouse gases, land degradation, salinization of irrigated areas, over-extraction of groundwater, the build up of pest resistance, loss of biodiversity and harming of marine, freshwater, and terrestrial ecosystems by fertilizer use and livestock excretion (Tscharntke et al. 2012; Garnett et al. 2013; Pretty and Bharucha 2014). Agricultural production systems in semi-arid areas are especially vulnerable to such impacts and tradeoffs (Fischer and Turner 1978; Hall et al. 1979; Drechsel et al. 2015). These systems were often threatened by the mining of nutrients, high gaseous losses of carbon and nitrogen, soil organic matter decline, salinization and the degradation of rangeland, which lead to natural resources degradation (Predotova et al. 2010; Buerkert et al. 2010; Goenster et al. 2014; Drechsel et al. 2015). Additionally, these regions with low rainfall face several water problems, such as excessive usage of surface water, groundwater depletion and a competition for scarce water resources (Molden 2013). Increasing demands for water by industrial and urban users, changing climate and land cover are likely to exacerbate the competition (Rockstrom et al. 2007; Fraiture et al. 2010; Rockstrom et al. 2016). Therefore, an increased use of water is a questionable response to an increase of water scarcity in semi-arid environments to produce more food, higher income and better livelihoods (Deng et al. 2006; Molden 2013; Li et al. 2015).

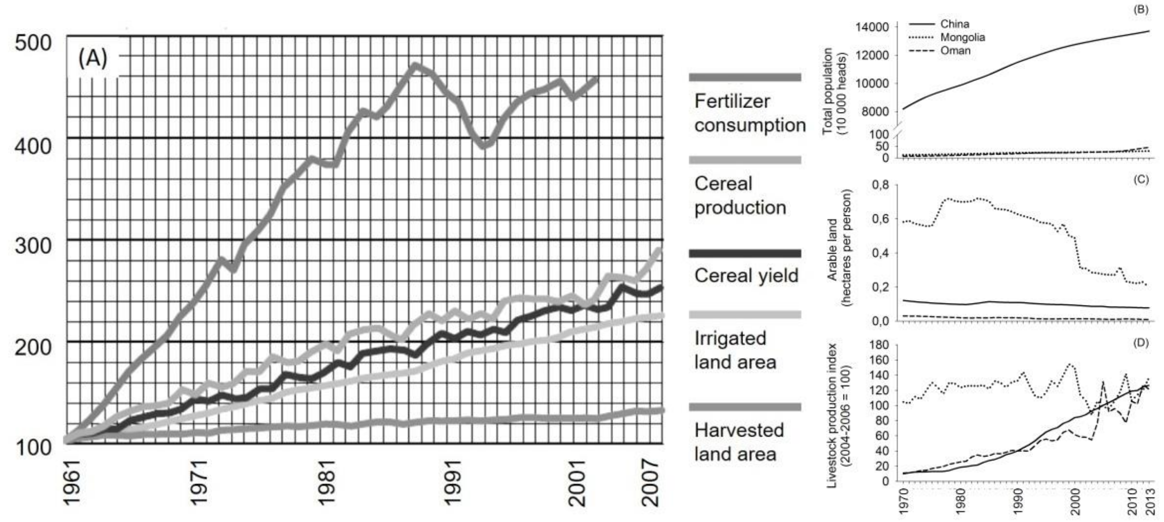

Figure 1. (A) Indicators (fertilizer consumption, cereal production, cereal yield, irrigated land and harvested area) of global crop production from 1961-2007 (Index 1961=100, Source: Collette 2011), (B) total population (counts of all residents regardless of legal status or citizenship), (C) arable land (hectares per person includes land under temporary crops, temporary meadows for mowing or for pasture, land under market or kitchen gardens, and land temporarily fallow) and (D) livestock production index (includes meat and milk from all sources, dairy products such as cheese, and eggs, honey, raw silk, wool, and hides and skins 2004-2006=100) in China, Mongolia and Oman from 1970 to 2013 (Source: The World Bank Group 2016).

Traditional agricultural systems in Oman, China and Mongolia could not evade the above mentioned external influences and aim for higher productivity through intensification (Figure 1). The millennia old Omani oases prove that this traditional agro-pastoral system is highly adapted to the prevailing harsh environment conditions (Buerkert and Schlecht 2008). The highly sophisticated irrigation systems and the high application rates of manure, plant material and soil contributed to the sustainability of the multi-storey cultivation of perennial and annual species in Omani oases (Al-Marshudi 2001; Siebert et al. 2007; Dickhoefer et al. 2010). However, since the 1970s Oman has undergone a rapid economic and social modernization which also had an impact on traditional oasis systems (Buerkert and Schlecht

2008). The subsequent import of cheap agricultural products lowered the competitiveness of oasis farmers with the consequence that many oases have been abandoned and migration into cities reduced significantly the number of farmers. As an economic response, intensified large scale agricultural systems were established particularly near the coast, and relied on ground water irrigation and chemical fertilizer application (Siegfried et al. 2013). These changes caused major problems regarding soil and water salinity, depletion of soil fertility and overuse of water resources in Oman (Al-Marshudi 2001; Siebert et al. 2005; Siebert et al. 2007; Luedeling and Buerkert 2008; Dickhoefer et al. 2010). In addition, the resource use efficiency of these systems is limited by high decomposition rates of organic matter leading to substantial gaseous and leaching losses under the Omani irrigated arid conditions (Wichern et al. 2004; Buerkert et al. 2010; Siegfried et al. 2011; Siegfried et al. 2013). Research is needed to reintroduce organic fertilizer to improve and maintain soil fertility of the predominantly sandy soils of the coastal areas.

Activated charcoal and tannins attract increasing attention as promising amendments to reduce nutrient losses from soil-applied organic fertilizers, as they are known to retain nutrients and to slow rates of nutrient mineralization (Glaser et al. 2002; Kraus et al. 2003; Steiner et al. 2007; Ingold et al. 2015a). For this reason, activated charcoal and/or tannin amendments to compost and manure were tested to enhance the nutrient use efficiency by reducing emissions of carbon dioxide, nitrous oxide and ammonia (Chapter 2).

Another transformation of traditional agricultural systems was observed in China and Mongolia (Figure 1). Rangeland under semi-arid environmental conditions is highly variable in terms of productivity and quality, which ultimately define the area that can be used by livestock at a specific time period (Milner-Gulland et al. 2011). Mobility (long-distance movements, frequency of movements and daily movement pattern) determines animal growth and reproduction under the highly variable resource dynamics (Humphrey and Sneath 1999; Adriansen 2005; Fernández-Giménez and Le Febre 2006; Milner-Gulland et al. 2011). Pastoralists in the Chinese-Mongolian Altay Mountains have traditionally managed a grazing system that is characterized by a high degree of mobility and opportunistic grazing, allowing for an adaptation to the seasonally highly variable environmental conditions (Fernández-Giménez and Le Febre 2006; Milner-Gulland et al. 2011; Reid et al. 2014). At presents, the transhumance system in the Altay Mountains is subjected to considerable transformation due to socio-political shifts (increasing interventions by local and national governments, privatization of the formerly state-owned livestock and transition from nomadic to sedentary lifestyle) and changes of climate (increased temperatures and reduced summer rainfall) and land use (expansion of cropland and mining activities; Janzen 2005; Lise et al. 2006; Sternberg 2008; Kreutzmann 2013; Liu et al. 2013; Fan et al. 2014; Hilker et al. 2014; Martin et al. 2014). This transformation is accompanied by a loss of traditional knowledge and the alteration of traditional rangeland management, including changes in herd size and composition (more Cashmere goats) and a diminished spatial distribution of livestock, which are likely to affect the rangeland productivity in the Chinese-Mongolian Altay Mountains (Briske et al. 2003; Addison et al. 2012; Kreutzmann 2013; Hilker et al. 2014; Khishigbayar et al. 2015). For this reason, the spatio-temporal mobility patterns of pastoral herds and herbage offer and its nutritive value on the main seasonal pastures were studied in this region (Chapter 3).

Before the 1990s, formerly state managed farms were supported with agricultural inputs (such as fertilizers, pesticides and seeds), infrastructure, processing facilities and guaranteed marketing possibilities. This dependence led to a decline of Mongolia’s agriculture sector after the communist period as farms were no longer profitable (Priess et al. 2011; Hofmann et al. 2016). With the introduction of the market economy the majority of farmers reverted back to their nomadic traditions and the farming sector faced a period of land abandonment (Priess et al. 2011; Priess et al. 2015). Recent national land use policies are targeting a re-intensification of agricultural land use and aim at the independence of food imports (Regdel et al. 2012; Pederson et al. 2013). Cropping is predominantly practiced by small scale agro-pastoral households along river valleys, except for the large scale production sites across Mongolia’s ‘breadbasket’ in Central Mongolia (Pederson et al. 2013; Saladyga et al. 2013). Traditionally, transhumant pastoralism coupled with agriculture has been and is continued to be practiced as a response to increased uncertainty or extreme weather events in arid and semi-arid environments which might act as an insurance buffer (Humphrey and Sneath 1999; Milner-Gulland et al. 2011; Reid et al. 2014). However, it is unclear to what degree these livelihood diversification strategies are maintaining crop and pastoral production or perhaps rather competing with each other. The Mongolian cropping sector is challenged by short growing seasons, cold winters, high wind velocity during spring (causing the drying out of top soil and serious wind erosion before and after seeding), limited water availability (especially at seeding and during early crop establishment), high potential evaporation and lack of financial resources for agro-chemicals, irrigation equipment and agricultural machinery (Hickmann 2006; Priess et al. 2011). Additionally, farmer fields are often managed by inexperienced land users leading to, for example, in-adequate fertilizer application, late weed removal, low plant densities, irregular application of irrigation water and no crop rotation (Hickmann 2006; Hofmann et al. 2016). This results not only in an inefficient use of fertilizer (when used) and labor but particularly in a low use efficiency of water which needs to be considered critically in these low input and low output systems (Hickmann 2006). Rising water demands coupled with land use and cover changes may in the future deplete water resources and reduce water availability (Malsy et al. 2012; Dombrowsky et al. 2014; Hofmann et al. 2015; Karthe et al. 2015). The (re)intensification of abandoned crop land calls for a responsible handling of scarce resources in particular of water. For this reason, the water use of agro-pastoral livelihood systems in the Bulgan river watershed was investigated (Chapter 4).

1.2 Research areas and objectives and study outline

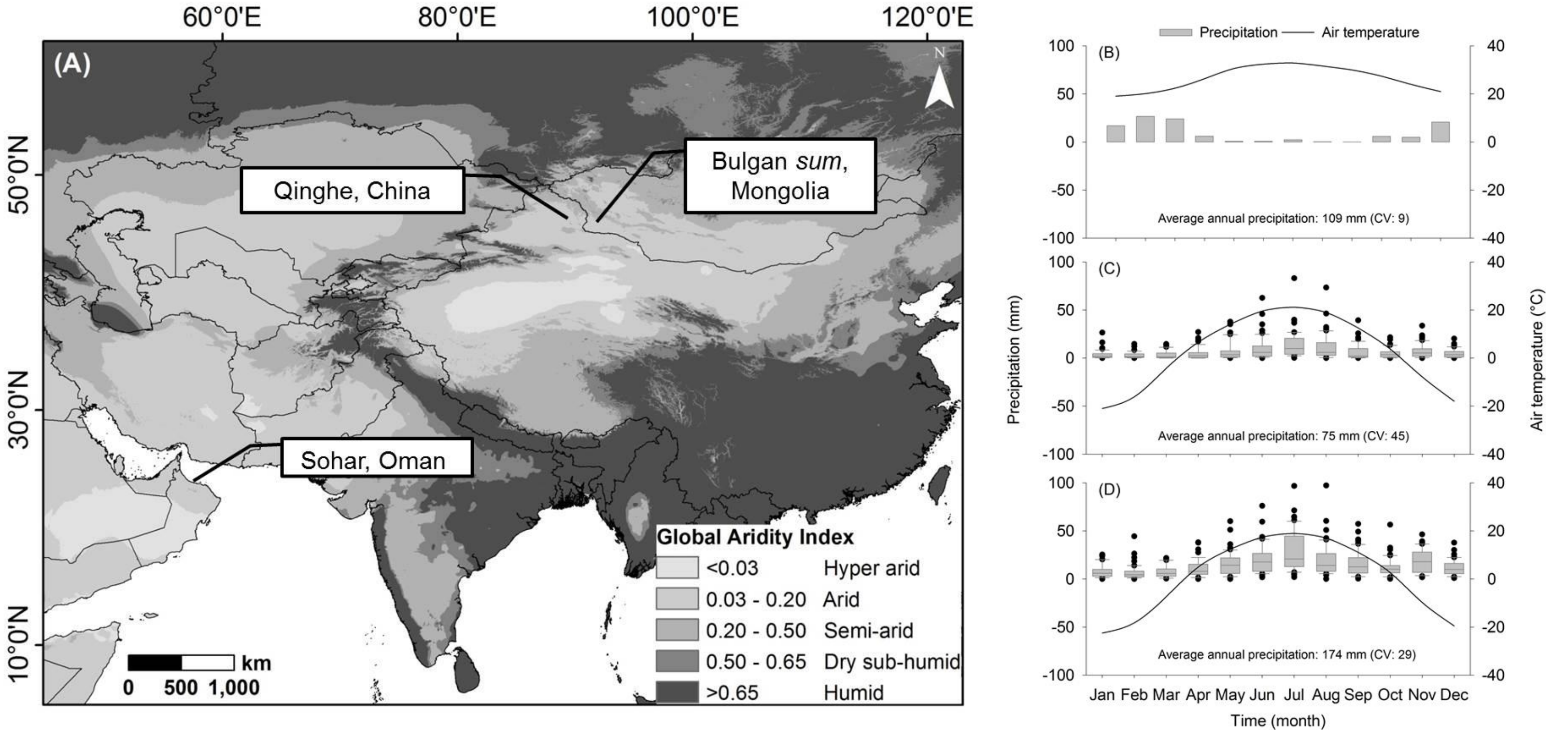

Figure 2. On the left (A), spatial distribution of the average annual aridity index (aridity is expressed as a generalized function of precipitation, temperature and potential evapotranspiration) from 1950-2000 (Data source: Trabucco and Zomer 2009) and on the right, average monthly precipitation (mm) and air temperature (°C) of Sohar, Oman (B, 1986-2009, source: WMO 2016), Bulgan sum, Mongolia (C, 1963-2014, source: National Statistical Office of Khovd) and Qinghe, China (D, 1958-2007, source: Statistical Office of Qinghe), CV: coefficient of variance.

All three study locations are located in arid or semi-arid environments (Figure 2). These regions are characterized by rainfall variable in space, time, quantity and duration. Soils in arid environments are often weakly developed, shallow and skeletal (except in lowlands/flood plains which feature soils developed as a result of colluviation and alluviation) and are mainly influenced by physical weathering (Weil and Brady 2016). Arid soils require irrigation as rain-fed agriculture is constrained due to scarce and unpredictable rainfall; therefore the predominant land use is extensive grazing (Reid et al. 2014).

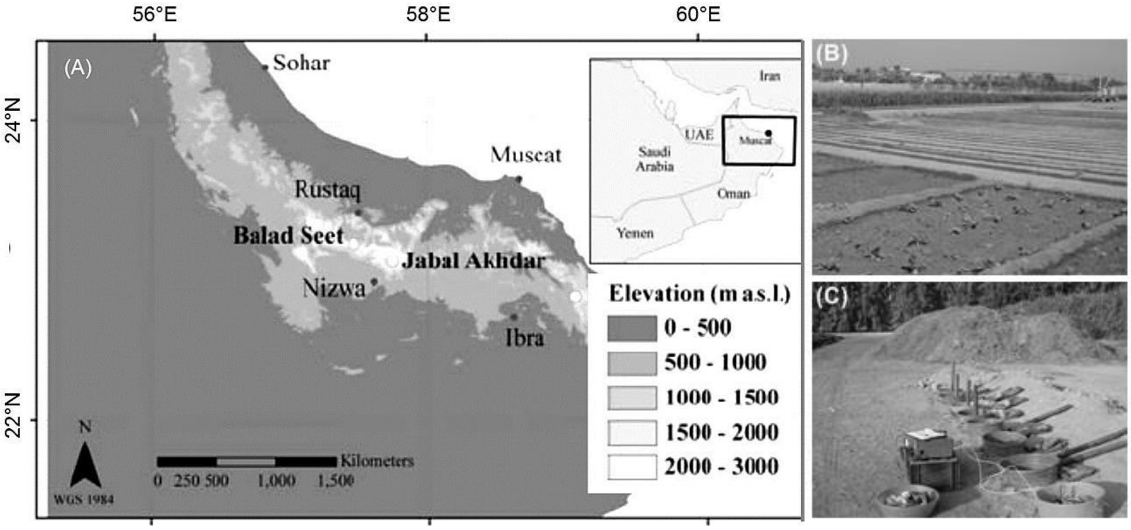

Figure 3. Map of Oman including the study location of Sohar (A, source: Gebauer et al. 2007), a picture of an agricultural site in the coastal plain near Sohar (B) and of a compost experiment (C).

A field experiment to investigate the ‘Effects of activated charcoal and tannin added to compost and to soil on carbon dioxide, nitrous oxide and ammonia volatilization’ (Chapter 2) was conducted on a private farm in the coastal Al Batinah Plain, near Sohar, Northern Oman (24°N, 57°E, 4 m a.s.l., Figure 3). At this location the average annual temperature was 27°C, while average minimum/maximum air temperatures were reached in January/June (14/37°C, WMO 2016, Figure 2). The average annual precipitation averaged 109 mm with a coefficient of variance of 9% (WMO 2016). Nowadays, the coastal plains serve as the main agricultural areas and have replaced mountain oases. The typical growing season in the Al Batinah plain lasts from September to May, whereas the remaining part of the year is characterized by high air and soil temperatures which prevent economic crop cultivation in open fields. The objective and hypothesis of this study were:

Objective:	Investigating whether the addition of even small amounts of activated charcoal and/or tannin to composting material or soil improves the application efficiency of organic fertilizers by reducing gaseous losses of carbon and nitrogen, in particular of carbon dioxide, dinitrogen oxide and ammonia.
Hypothesis:	Amending compost or soil with tannins leads to a stabilization of organic matter and reduces the turnover of these amendments.

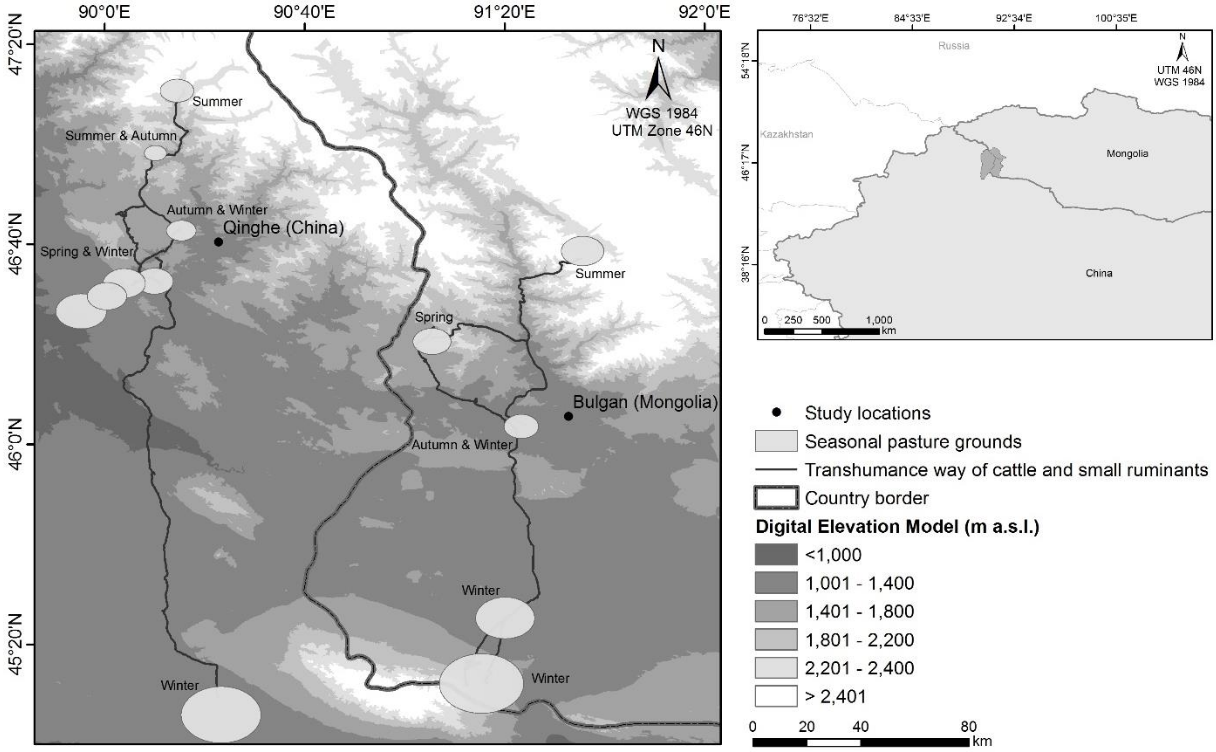

Figure 4. Study area in China and Mongolia (right) and seasonal pasture grounds and transhumance way of cattle and small ruminants including a digital elevation model.

The study on ‘Spatio-temporal patterns of herbage availability and livestock movements - A cross-border analysis in the Chinese-Mongolian Altay’ (Chapter 3) was conducted in the Altay Mountains and the Dzungarian Desert in Western China and Mongolia (45-47°N, 89-91°E, Figure 4 and 5). In the floodplains, the average annual air temperature was 1°C (Qinghe, China) and 3°C (Bulgan *sum*, Mongolia, Figure 2), respectively. The average annual precipitation was 174/75 mm with a coefficient of variance of 29/45 (China/Mongolia, Figure 2).

During the study period (2013-2014) the annual air temperature averaged 3/4°C with a mean annual precipitation of 162/50 mm (China/Mongolia) in the floodplains. However, in the alpine belt (3097 m a.s.l.) an average annual air temperature of -1/-5 °C and average annual precipitation of 160/305 mm (2013-2014, China/Mongolia) were recorded.

Figure 5. Cattle (A and B), small ruminant herd (C and D) and transhumance route (E and F) in the study region in China and Mongolia.

The study area is traditionally characterized by pastoral systems, to be more specific, by classical mountain transhumance with seasonal migration between pasture sites representing a decreasing altitude gradient (max: 3097 to min: 1031 m a.s.l., Figure 4 and 5) and aridity from the alpine belt to the desert steppe. The spring (April to July) and autumn pasture (September to November) were located in the transition from upper desert steppe to mountain steppes and floodplains. The alpine belt was used during the summer months (July to September), whereas the winter pasture (November to March) was located in the desert steppe of the Dzungarian Desert plains. Against this background, the objectives and hypothesis of this study were:

Objectives: (i) Examining the spatio-temporal mobility patterns of pastoral herds including long-distance transhumance routes and daily grazing itineraries, number of utilized pastures and size of pastures, and (ii) monitoring the herbage offer and its nutritive value on the main seasonal pastures in both countries.

Hypothesis: Despite similar natural conditions, the differences in recent socio-political and socio-economic developments on the Chinese and Mongolian side of the border have a large impact on the local transhumance systems in the Altay-Dzungarian region and on rangeland utilization as indicated by herbage offer and quality.

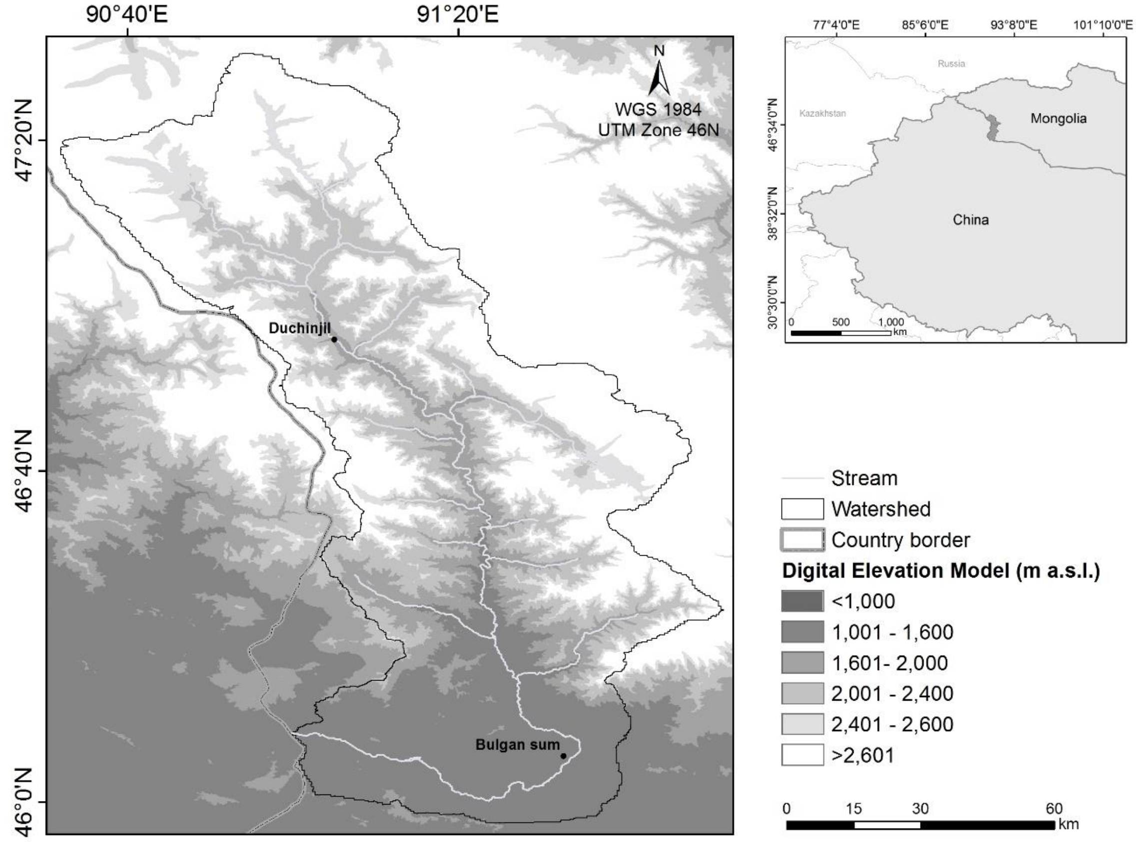

Figure 6. Study area within Mongolia (right) and the Bulgan *sum* watershed including a digital elevation model (left).

The third study ‘Water use of agro-pastoral livelihood systems in the Bulgan river watershed of the Altay Mountains, Western Mongolia’ (Chapter 4) was conducted in the Bulgan river watershed which stretches from the Altay Mountains towards the river oasis Bulgan *sum*, Mongolia (Figure 6). Areas at higher altitude feature slightly higher precipitation and lower temperatures compared to the lowlands (average annual precipitation of 128/75 mm and average annual minimum air temperatures of -35/-21°C, Figure 4). The alpine belt, desert and mountain steppes are predominantly used as rangeland; however, the floodplain and river valley are used additionally for irrigated crop, hay and fruit tree production (Figure 7). The growing season in the floodplain lasts from May to September, because in the remaining part of the year cropping is not possible due to low temperatures. Therefore, the study objectives and hypothesis were:

Objectives: (i) Describing the land cover change between 1972 and 2013, (ii) characterizing the current prevailing livelihood strategies and farming practices (such as management, irrigation systems and water use) in the river oasis Bulgan *sum*, Western Mongolia and (iii) simulating water-use efficiency for different land cover classes with the 'Soil and Water Assessment Tool' in the Bulgan River watershed.

Hypothesis: Land cover changes and current farming practices lead to increasing stress on scarce water resources in the Bulgan River watershed.

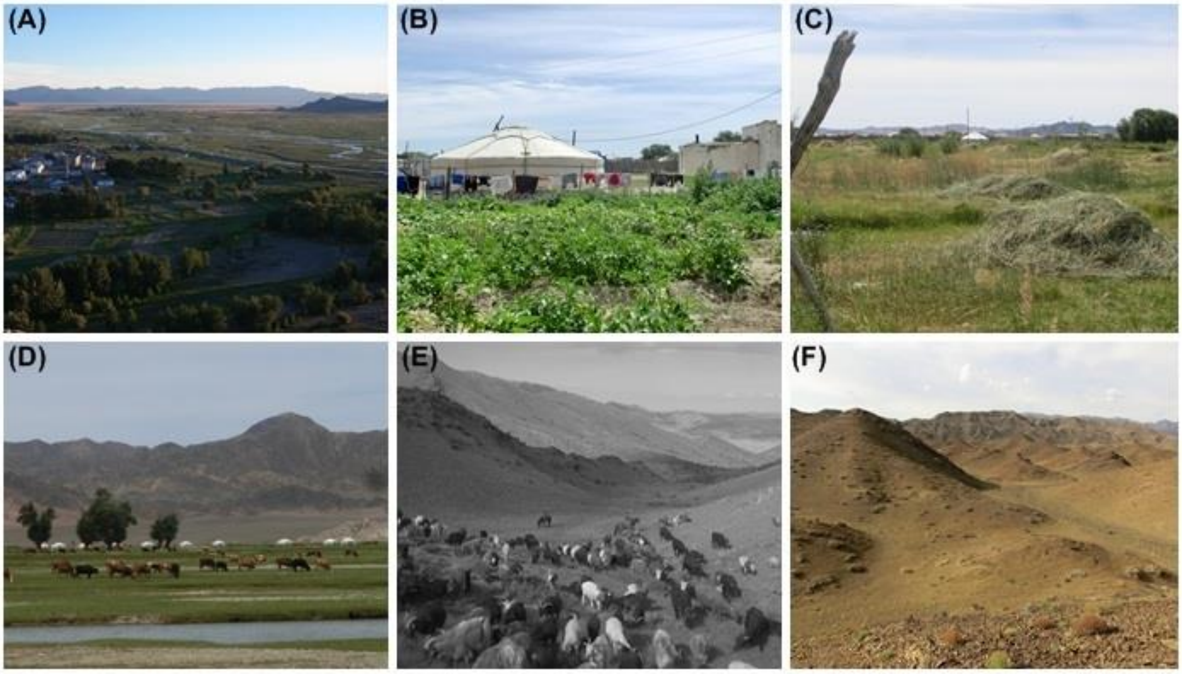

Figure 7. Predominant land cover types of the Bulgan *sum* district, Mongolia (A) Bulgan *sum* river oases, (B) irrigated vegetable and (C) hay production, (D) Bulgan river meadow, (E) rangeland and (F) mountainous area.

Following the introduction, this dissertation is composed of three stand-alone manuscripts positioned in the Chapters 2, 3 and 4. In Chapter 5 the main findings and conclusions are discussed. Finally, in Chapter 6 the overall conclusions and recommendations are presented.

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2. Chapter

Effects of activated charcoal and tannin added to compost and to soil on carbon dioxide, nitrous oxide and ammonia volatilization

This chapter has been published in Journal of Plant Nutrition and Soil Science:
Jordan, G., Predotova, M., Ingold, M., Goenster, S., Dietz, H., Joergensen, R. G., Buerkert, A. (2015): Effects of activated charcoal and tannin added to compost and to soil on carbon dioxide, nitrous oxide and ammonia volatilization. Journal of Plant Nutrition and Soil Science 178, 218–228.

Abstract

Given high mineralization rates of soil organic matter addition of organic fertilizers such as compost and manure is a particularly important component of soil fertility management under irrigated subtropical conditions as in Oman. However, such applications are often accompanied by high leaching and volatilization losses of N. Two experiments were therefore conducted to quantify the effects of additions of activated charcoal and tannin either to compost in the field or directly to the soil. In the compost experiment, activated charcoal and tannins were added to compost made from goat manure and plant material at a rate of either 0.5 t activated charcoal ha^{-1}, 0.8 t tannin extract ha^{-1}, or 0.6 t activated charcoal and tannin ha^{-1} in a mixed application. Subsequently, emissions of CO_2, N_2O, and NH_3 volatilization were determined for 69 d of composting. The results were verified in a 20 d soil incubation experiment in which C and N emissions from a soil amended with goat manure (equivalent to 135 kg N ha^{-1}) and additional amendments of either 3 t activated charcoal ha^{-1}, or 2 t tannin extract ha^{-1}, or the sum of both additives were determined. While activated charcoal failed to affect the measured parameters, both experiments showed that peaks of gaseous CO_2 and N emission were reduced and/or occurred at different times when tannin was applied to compost and soil. Application of tannins to compost reduced cumulative gaseous C emissions by 40% and of N by 36% compared with the non-amended compost. Tannins applied directly to the soil reduced emission of N_2O by 17% and volatilization of NH_3 by 51% compared to the control. However, emissions of all gases increased in compost amended with activated charcoal, and the organic C concentration of the activated charcoal amended soil increased significantly compared to the control. Based on these results, tannins appear to be a promising amendment to reduce gaseous emissions from composts, particularly under subtropical conditions.

2.1 Introduction

Under irrigated, subtropical conditions high temperatures lead to high turnover rates of soil organic C (SOC), thus contributing to its rapid decline (Buerkert et al., 2010; Siegfried et al., 2013). Although the intensively manured traditional oasis systems in Oman have been sustainable production environments for centuries (Buerkert et al., 2005), high turnover rates of C and N have been detected (Wichern et al., 2004; Buerkert et al., 2010). Recent studies show that under such conditions annual gaseous losses from agricultural fields may range from 5 to 30 t C ha^{-1} and 43 to 92 kg N ha^{-1} (Predotova et al., 2010; Siegfried et al., 2011; Goenster et al., 2014). During the last decade, biochar/charcoal and tannins have attracted increasing attention as a promising option to improve soil properties (Glaser et al., 2002; Kraus et al., 2003; Spokas et al., 2012). Studies have shown that biochar/activated charcoal has great potential to retain nutrients due to its high specific surface and low bulk density resulting in a substantial adsorption capacity (Glaser et al., 2002; Woolf et al., 2010; Ippolito et al., 2012; Spokas et al., 2012). Applications of coconut charcoal to compost and soil resulted in a significant reduction of N-losses through ammonia adsorption (Hua et al., 2009; Spokas and Reicosky, 2009). Aside from these positive effects, at high application rates biochar/charcoal may also have a negative environmental impact such as the loss of wood from kilting, heavy metal accumulation, decrease in plant growth and raising soil pH (Van Zwieten et al., 2010; Zimmerman et al., 2011). The use of activated charcoal seems to be particularly promising given its larger effective surface and a higher C content compared to biochar/charcoal (Spokas and Reicosky, 2009; Spokas et al., 2011). Based on these advantages even low application rates of activated charcoal could be sufficient for significant soil improvements and, thus, reduce possible negative environmental effects of biomass conversion into biochar/charcoal.

There is evidence that tannins can contribute to the long-term immobilization of soil-N through the formation of tannin-protein complexes and the inhibition of enzyme activity in soils (Joanisse et al., 2007; Mutabaruka et al., 2007). Organic material with a high tannin concentration tends to decompose slowly, resulting in low rates of nutrient mineralization (Palm and Sanchez, 1990; Bradley et al., 2000). However, in contrast to charcoal experiments, studies on the effects of tannin applications to soils are rare and mainly focused on forest ecosystems (Kraus et al., 2003; Halvorson et al., 2012). In order to fill this knowledge gap, we investigated whether the addition of even small amounts of activated charcoal and/or tannin to composting material or soil improves the application efficiency of organic fertilizers by reducing gaseous losses of C and N, in particular of CO_2, N_2O, and NH_3.

We hypothesized that amending compost or soils with tannins leads to a stabilization of organic matter (OM) and reduces the turnover of these amendments.

2.2 Material and methods

2.2.1 Compost experiment

The compost experiment was conducted on a private farm in the coastal Al Batinah Plain, near Sohar, N Oman (24.2°N, 56.8°E, 4 m asl) in the 2010/11 winter season. According to Koeppen's climate classification, the study site is located in the hot arid, winter dry climate zone (BWh; Peel et al., 2007), characterized by a mean ambient temperature of 33°C, a mean relative humidity of 73%, and an average annual rainfall of 108.5 mm (data from 1971 to 2000; FAO, 2006). During the study period, a Watchdog® weather station (Spectrum Technologies Inc., Plainfield, IL, USA) was used to record climate data: mean ambient temperature was 25°C, mean relative humidity was 64%, and no precipitation was recorded during the experimental period.

In the compost experiment in Oman, a mixture of 30% Rhodes grass hay (Chloris gayana Kunth.) and 70% farm yard manure (contained 18.2% C, 0.9% N) from North Omani Goats of the Al Jabal Al Akhdar region were aerobically composted in 80 L PVC buckets with a basal area of 0.28 m^2 sunk into 0.70 m deep holes dug in the ground. Buckets rested on top of a gravel layer and had holes pierced in to the bottom to insure proper drainage. To ensure aerobic conditions in the buckets, a perforated plastic pipe of 0.06 m inner diameter was inserted vertically into the centre of the bucket. The four treatments used in the experiment consisted of a control compost made from manure and hay (TM), compost amended either with 3% (w/w), equivalent to 0.5 t activated charcoal ha^{-1} (TMC), with 4% (w/w), equivalent to 0.8 t tannin extract ha^{-1} (TMT), or with both 1.5% (w/w) activated charcoal and 1.5% (w/w) tannin (TMCT), equivalent to 0.6 t ha^{-1}. The charcoal powder was manufactured from coconut shells followed by steam activation (AquaSorb® CP1, Jacobi Carbons Service GmbH, Premnitz, Germany). During the production process, the coconut shells pass three phases physically located in different zones of the furnace (zone 1: 900–950°C, zone 2: 870–920°C, and zone 3: 780–850°C), in which residence time varies from 18–40 h. The activated charcoal of our study contained 92.1% C, 0.1% N, 0.03% P, 0.8% K, and had a pH of 9.1. The physical properties of the activated charcoal were characterized by a particle size of 44 µm, a surface area of 1,050 $m^2 g^{-1}$ and a total pore volume of 0.62 $cm^3 g^{-1}$.

Condensed tannins of *Schinopsis balansae* heartwood was supplied by Silvateam S.p.A. (Buenos Aires, Argentina). The tannin powder contained 52.8% C, 0.1% N, 0.01% P, 0.09% K, and had a pH of 4.7. To amend the respective compost treatments, activated charcoal and tannin powder were suspended / dissolved in tap water and mixed with the compost material. Over the first 9 d of incubation the temperature in the compost buckets ranged from 24 to 38°C. To adjust the C/N ratio to 21, OM (15% green Rhodes grass and 5% Rhodes hay) was added 11 d after incubation (DAI), which resulted in temperatures rising to between 50 and 53°C. To ensure equal distribution of moisture and the exchange of gases involved in microbial respiration (O_2 and CO2), the compost was turned daily for the first 25 DAI, and every 48 h from 26 to 50 DAI according to local practice. At the same time, the moisture content was adjusted to 40 to 60% water-filled pore space (WFPS) by adding the necessary amount of water. At day 50, the compost was left to mature without further watering and turning for another 19 d. The four treatments were arranged in a completely randomized design with two replications per treatment. It was assumed that high temperatures in the compost pile generated an upward airflow and most gases are thus emitted through the top of the compost pile from the top 15 cm of material (chimney effect), where the airflow is released to the atmosphere (Boldrin et al., 2009).

Gaseous emissions of CO_2, N_2O and volatilization of NH_3 were measured using a dynamic closed chamber system. This consisted of a cuvette and a photo-acoustic infrared multi-gas monitor (INNOVA 1312–5, LumaSense Technologies A/S, Ballerup, Denmark; Predotova et al., 2009; 2010; Siegfried et al., 2011). The multi-gas monitor and measurement cuvette were connected by two 80 cm long standard Teflon® tubes (3 mm diameter) as inlet and outlet. The cuvette consisted of a 30 cm wide and 11 mm high PVC ring combined with a 30 cm wide and 6 cm high fitting ring made of PVC that was pushed 3–5 cm into the compost material. During measurements, air humidity and temperature in the cuvette were recorded using an air-tight installed thermo-hygrometer (PCE-313 A, Paper-Consult Engineering Group, Meschede, Germany; Siegfried et al., 2011). The system was closed for an accumulation time of 3 to 3.5 min. Between measurements the cuvette was lifted and ventilated for 2 min to reduce unwanted feedback on gas emissions due to high cuvette air moisture and temperature (Predotova et al., 2009). Previous experiments showed that during such accumulation times non-condensing moisture conditions prevailed and measurements were reliable for CO_2 and, as long as and the instrument was properly calibrated, also for NH_3, and N_2O, but inaccurate for CH_4 (Predotova et al., 2011; Iqbal et al., 2012; Rosenstock et al., 2013).

In Oman, gaseous C- and N-emissions from compost buckets were measured 33 times during the 69 d composting process. Measurements were conducted daily until gaseous emission peaks dropped at 17 DAI, as observed from direct readable photo-acoustic data. As of 17 DAI, measurements were conducted less regularly since lower emissions rates were assumed (Predotova et al., 2010). The moisture of composting material at 6 cm depth was determined using a TDR soil moisture meter (Theta Probe Sensor attached to an Infield7b datalogger, UMS, Munich, Germany).

2.2.2 Soil incubation experiment

Following the compost experiment in North Oman, a soil incubation experiment under controlled greenhouse conditions was carried out in Germany in 2012 to study more closely the relationships between C and N emissions and the applications of activated charcoal and tannins to soil or compost. The climatic conditions in the greenhouse chamber were set to an air temperature of 24°C and a relative humidity of 36%. In both experiments ambient air temperature and humidity were recorded by a HOBO® U23 Pro v2 data logger (Onset Computer Corporation, Bourne, MA, USA).

A N- and P-poor C horizon soil with 77% silt, 12% sand, and 10% clay was air-dried and sieved to < 2 mm. Subsequently, the substrate was mixed with silica sand (mixture 2:1, 0.93% C, 0.01% N, pH 8.1) to obtain soil texture conditions similar to those in Oman. Eight kg of the oven-dried soil-silica mixture was filled into 30 cm wide and 15 cm high PVC pots. All treatments, except a zero control (00), were amended with goat manure (7.38 t manure ha^{-1}, equivalent to 135 kg N ha^{-1}; TM) and additionally mixed with either 3 t activated charcoal ha^{-1} (TMC), 2 t tannin extract ha^{-1} (TMT), or the sum of both additives (TMCT). To do so, 2 cm of top soil were removed, mixed with the amendments and then placed back into the pot. The manure came from Boer goat and was collected in bags (Schlecht et al., 2007) followed by deep freezing at –17°C. The substrate in the pots was watered to 80% water holding capacity (WHC) at the beginning of the experiment, to 50% WHC at 9 DAI and to 35% WHC at 17 DAI.

During the soil incubation experiment, the emissions of CO_2, N_2O, and volatilization of NH_3 were measured as described for the compost experiment. The closed chamber system was maintained for 2 to 2.5 min. Gaseous C and N emissions from soil were measured 14 times during the 20 d of incubation. Measurements were conducted daily for the first 7 DAI during which time gaseous emission peaked, and as of 8 DAI, measurements were conducted every second day as emissions decreased substantially. During the soil incubation experiment, soil temperature was measured using a digital penetration thermometer (Carl ROTH GmbH + Co, Karlsruhe, Germany) inserted into the soil three times to a depth of 3 cm after gas measurement. The soil water content was determined gravimetrically by weighing the pots daily.

2.2.3 Data processing and analysis

Emission flux rates were calculated by dividing the difference of gas concentrations after the first and the 123rd second of the measurement period by the elapsed time period (122 s). Negative emission rates of NH_3 and N_2O were set to zero (Predotova et al., 2009). The increase of gas concentrations in the cuvette was assumed to be linear (Conen and Smith, 2000). This assumption was supported by high Pearson correlation coefficients which were used as a measure of the linear relationship between accumulation time and gas concentration and calculated exemplarily for 200 measurements during the composting experiment (CO_2: R = 0.99, standard error (SD) = 0.07; NH_3: R = 0.86, SD = 0.19, and N_2O: R = 0.96, SD = 0.10).

The reference area was up-scaled from the cuvette surface to one m^2 ($mg\ m^{-2}\ h^{-1}$). For accumulated gaseous losses from the composting process, data of each measurement were multiplied by the time span to the next measurement event and summed up to the end of the incubation period. To compare accumulated gaseous C and N losses with total C and total N in the compost material and soil as well as further C and N fluxes via other pathways, samples were taken from the compost and from the soil at the beginning and at the end of experimental incubation (69 and 20 DAI). Samples were analyzed on a dry weight basis using a C/N analyzer (RC-412 and FP-329, Leco; Mönchengladbach, Germany). The WFPS in percent of the total pore volume of the composting material was calculated as described by Goenster et al. (2014).

2.2.4 Statistics

All data were processed with SPSS 19.0.0.1 (IBM Inc., Armonk, NY, USA). Arithmetic means of CO_2, NH_3, and N_2O fluxes are presented. In addition, the accumulated CO_2, NH_3, and N_2O fluxes were tested for normal distribution with the Shapiro-Wilks test. Pearson correlation analysis was used to investigate the relationship between flux rates of emitted CO_2, NH_3 and N_2O, temperature and WFPS in compost and soil as well as the linearity of chamber flux data.

One-way ANOVA with t- and LSD-test was conducted to analyze group differences. A significance level of $P \leq 0.05$ was used for the statistical tests.

2.3 Results

2.3.1 Compost experiment

During the compost experiment, the WFPS at 6 cm depth ranged between 40 and 60%, and the temperature in the top 25 cm of the substrate from 21 to 52°C. The temporal curve showed the typical mesophilic, thermophilic, and cooling composting phases (Figure 1). The pH of the compost material ranged between 7.6 and 7.9 at the beginning of the experiment and between 7.9 and 8.2 at 69 DAI. As a result of the microbial degradation of organic substances the dry matter (DM) declined in all treatments over the composting period (Table 1). The OM concentration of the mature compost was lowest for TMC and TMCT and highest for TMT. The final loss in total C ranged from 30% in TMT to 45% in TMCT and the loss in total N mass losses varied around 17.5%. Total N mass loss in relation to the initial mass was lowest for TMT (11%) and highest for the control treatment (23%). The remaining total N was highest in compost amended with tannins (TMT) and lowest in the control. The C/N ratio declined most strongly in compost amended with activated charcoal, while in tannin amended compost, the C/N ratio remained almost constant (Table 2).

In all compost treatments, emission rates of CO_2 were bimodally distributed. The first maxima were observed 2 DAI, ranging between 3.84 g C m^{-2} h^{-1} in TMT and 6.60 g C m^{-2} h^{-1} for the control. The second peak, likely a consequence of the additional N-input was reached 11 DAI. At 25 DAI, the respiration in all treatments decreased to <1 g C m^{-2} h^{-1} and declined continuously from then on. In general, CO_2 emission rates were lowest for TMT. Gaseous CO_2 losses were lowest during the thermophilic phase from 10 to 19 DAI (Figure 1).

Gaseous NH_3 and N_2O losses peaked shortly after the start of the composting process. In TMT, TMC, and TMCT, NH_3 volatilization peaked at 1 DAI (16.0, 24.9, and 36.3 mg N m^{-2} h^{-1}, respectively), while in TM the peak of 27.4 mg N m^{-2} h^{-1} was reached at 3 DAI. At 12 DAI, flux rates of NH_3 for all treatments dropped below 1.9 mg N m^{-2} h^{-1} (Figure 1).

N_2O flux rates were highest during the first days when temperatures were ≤ 36°C and at 47 DAI when temperatures dropped to 25°C. However, at 1 DAI emission rates declined rapidly and varied between 15.7 and almost 0 mg N m^{-2} h^{-1} in the following period.

Table 1. Organic matter mineralization and losses of carbon and nitrogen in a 69-d composting experiment in Oman (2010). Data show means (n = 2).

DAI	Composting stages	DM pile mass (kg)	OM (g kg^{-1})	C_t (g kg^{-1})	N_t (g kg^{-1})	C/N ratio
Pure compost						
0	Initial	19.3	338.0	167.1	8.2	20
69	Mature	14.7	276.0	128.9	8.3	16
Compost amended with activated charcoal						
0	Initial	19.3	347.0	204.9	9.0	23
69	Mature	15.5	258.0	139.8	9.3	15
Compost amended with tannin						
0	Initial	19.3	370.0	185.0	9.5	20
69	Mature	15.7	320.0	159.6	10.3	15
Compost amended with activated charcoal and tannin						
0	Initial	19.3	321.0	183.7	8.3	22
69	Mature	15.6	258.0	147.0	8.4	17

DAI= days after incubation, DM= drymatter, OM= organic matter, C_t= total carbon, N_t= total nitrogen

Only after the second application of grass and hay at 9 DAI there was a small increase in N_2O for all treatments noted. Furthermore, in TMC and TM short, small peaks (5.00 and 1.97 mg N m^{-2} h^{-1}, respectively) were recorded at 47 DAI.

During the 69 d of composting, CO_2 dominated emissions from all compost treatments with values ranging from 2.07 to 3.45 kg C m^{-2} 69 d^{-1} in TMT and TMC (Figure 1). Total CO_2 emissions were reduced by 40% in TMT and by 4% in TMCT. Total NH_3 was also lowest in TMT and highest in TMC with 2.3 and 5.1 g m^{2} 69 d^{-1}, respectively, resulting in a reduction of 39% for TMCT and to 50% for TMT. Total N_2O emission varied between 3.6 g N m^{-2} 69 d^{-1} in TMCT and 5.7 g N m^{-2} 69 d^{-1} in TMC. The addition of tannins additions lowered total emissions by 13% in TMT and 22% in TMCT.

Cumulative losses of CO_2, NH_3, and N_2O were highest for activated charcoal amended compost accounting for 25% and 2% of the initial C and N contents in the compost material.

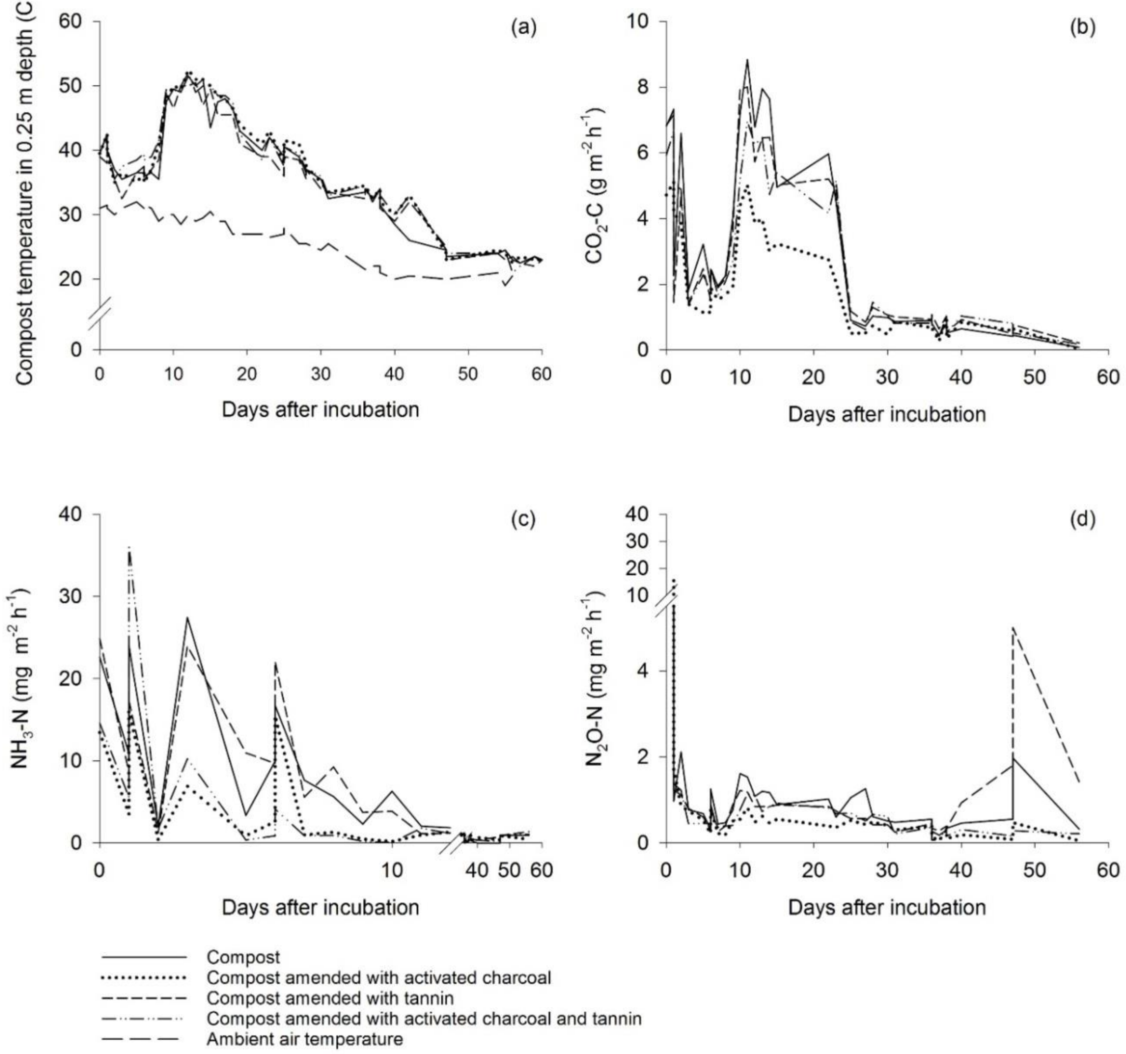

Figure 1. (a) Ambient air temperature and temperatures in compost treatments at 0.25 m depth, (b) fluxes of CO_2-C, fluxes of (c) NH_3-N and (d) N_2O-N during the composting process in Sohar, Oman (2010). Data show means (n = 2); TM = compost, TMC = compost amended with activated charcoal, TMT = compost amended with tannin, TMCT = compost amended with activated charcoal and tannin.

Compared to the cumulative gaseous CO_2 in the control treatment, this represented a decrease of 9%. However, NH_3 and N_2O losses were similar to the control. Cumulative losses of CO_2, NH_3 and N_2O were smallest in tannin-amended compost accounting for 17% of initial C and 1% of initial N. Here, addition of tannins led to a decline of about 50% for C and 44% for N losses compared to the control. For the mixed application of activated charcoal and tannins, the reduction of gaseous CO_2 losses amounted to only 12%, while total gaseous N losses declined by 39% as compared with a single application of tannins.

Table 2. Carbon and nitrogen losses during a composting experiment in Oman (2010; n = 2) and a soil incubation experiment in Germany (2012; n = 5).

Compost experiment treatments	Carbon			Nitrogen				
	(kg m^2 69 d^{-1})	(% of inital content)	(g kg^{-1} in material after incubation)	(g m^2 69 d^{-1})	NH_3-N (%)	N_2O-N (%)	(% of inital content)	(g kg^{-1} in material after incubation)
TM	3.4	30.1	128.9	9.8	47.4	52.6	1.8	8.3
TMC	3.5	24.7	139.8	10.8	47.2	52.8	1.8	9.3
TMT	2.1	16.4	159.6	6.3	36.3	63.7	1.0	10.3
TMTC	3.3	26.4	147.0	6.4	43.8	56.2	1.1	8.4
Soil experiment treatments	Carbon			Nitrogen				
	(g m^2 21 d^{-1})	(% of inital content)	(g kg^{-1} in material after incubation)	(mg m^2 21 d^{-1})	NH_3-N (%)	N_2O-N (%)	(% of inital content)	(g kg^{-1} in material after incubation)
OO	2.5 a	0.2 a	9.9 a	51.5 ab	33.4 ac	66.6 a	0.5 abe	0.1 a
TM	16.8 bc	1.2 b	12.5 b	90.2 bcd	55.3 bd	44.7 a	0.4 abce	0.3 b
TMC	18.0 c	1.0 c	19.8 d	73.0 abc	52.0 abcd	48.0 a	0.3 bcd	0.3 b
TMT	15.0 bc	1.0 de	14.3 c	57.7 ab	42.2 ac	57.8 a	0.2 cd	0.3 b
TMCT	15.2 b	0.8 e	20.9 d	112.9 cd	50.8 bcd	49.3 a	0.4 abe	0.3 b

2.3.2 Soil incubation experiment

The average soil temperature in the top 5 cm was 24°C, while the soil water content varied from 8–20%. Soil pH was 8.1 at the beginning of the experiment and ranged from 8.2–8.5 at 21 DAI. Total C concentration in the pots declined during the soil incubation experiment for all treatments; final C concentration was lowest for the zero control (9.92 g kg^{-1}) and the control (12.54 g kg^{-1}). Activated charcoal seemed to reduce the C decline over the course of the experiment (TMC 19.77 and TMCT 20.92 g kg^{-1}). Total C losses were reduced by 37% in TMC ($P<0.001$) and by 40% in TMCT ($P<0.001$) compared to the control. However, no significant differences in total N content were noted between treatments (differed between 0.25 to 0.27 g kg^{-1}), except for the zero control (0.14 g kg^{-1}), in which total N was significantly lower ($P<0.001$, Table 2).

For all treatments, the emission rates of CO_2 were distributed polymodally (Figure 2). The CO_2 emission reached a first maximum 1 d after the second irrigation event (12.4% water content) with values of 56.9 and 54.2 mg C m^{-2} h^{-1} (201 h after incubation, HAI) for TM and TMC, respectively, and thereafter declined with diminished water content. Volatilization maxima of NH_3 were observed at 106 HAI in TM (0.47 mg N m^{-2} h^{-1}) and TMC (0.36 mg N m^{-2} h^{-1}), at 19 HAI in TMT (0.16 mg N m^{-2} h^{-1}) and already at 18 HAI in TMCT (0.18 mg N m^{-2} h^{-1}). In N_2O emission maxima ranged from 0.15-0.24 mg N m^{-2} h^{-1} for TMC and the control, respectively.

Emissions of N_2O tended to decline as water content declined over the course of the experiment.

CO_2 emissions ranged from 2.52 to 17.26 g C m^{-2} 21 d^{-1} in the zero control and in TMC, respectively. Cumulated NH_3 volatilization varied between 17.2 and 57.9 mg N m^{-2} 21 d^{-1} in the control and TMCT, respectively. N_2O values were within the same range, with accumulations varying between 33.70 and 55.60 mg N m^{-2} 21 d^{-1} in TMT and TMCT, respectively (Figure 2). The addition of tannins in TMT reduced total emission of all measured gases compared to the non-amended control, while in TMCT only CO_2 emissions were reduced. Total CO_2 emissions were reduced by 11% in TMT and by 15% in TMCT. Reduction of NH_3 volatilization was 24% in TMC and 51% in TMT ($P=0.049$) and tannin additions lowered cumulative N_2O emissions by 13% in TMC and 17% in TMT. In contrast, activated charcoal and tannin mixture increased emissions of all gases (for N_2O by 44% and NH_3 20% compared with the control) except for CO_2. For the control and TMT, a shift from NH_3 volatilization to N_2O emissions was observed.

Gaseous C losses were orders of magnitude higher than N losses. Charcoal additions significantly increased the remaining C concentration in soil ($P<0.001$), whereas the addition of tannin led to a C decline of approx. 17% ($P=0.039$) and an approx. 37% decline of N ($P=0.044$) compared with the control.

2.4 Discussion

Our data suggest that the most important driver of gaseous emissions was the compost's temperature with its positive effects on microbial activity (Paillat et al., 2005). The temperature curve during composting was similar to curves of CO_2 emissions from other substrates, demonstrating the interdependence of temperature and CO_2 emissions (Tiquia et al., 2002; Paillat et al., 2005). Compared with the composting experiment, most of the emissions in the soil incubation experiment were released earlier that is directly after manure application, under moist conditions. Total C-losses were lower than those reported from other composting studies (Tiquia et al., 2002; Paillat et al., 2005). This may be due to the relatively small size of the compost containers, which limited temperature development and uniformity during the thermophilic phase. The maximum recorded temperature was 52°C,

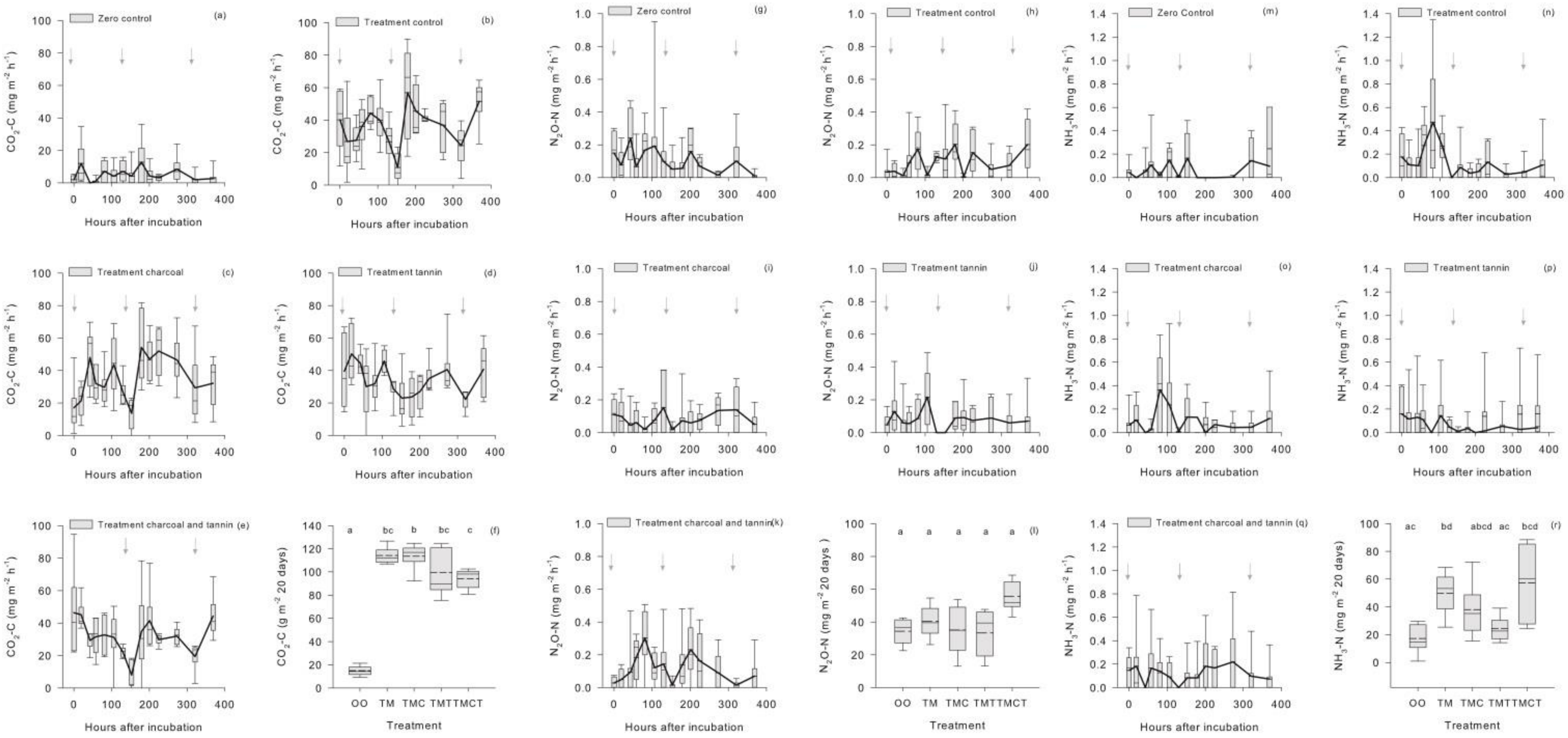

Figure 2. Flux rates and accumulated gaseous emissions of CO$_2$-C (a–f), N$_2$O-N (g–l) and NH$_3$-N volatilization (m–r) during a soil incubation experiment in Germany (2012). Data show means (n = 5), arrows indicate water application to soil. OO = zero control, TM = control, TMC = soil amended with activated charcoal, TMT = soil amended with tannin, TMCT = soil amended with activated charcoal and tannin.

while in larger compost piles temperatures typically reaches 60–70°C (Eghball and Power, 1999). Cumulative CO_2 emissions during composting varied between 15 and 44% of the initial C content, which is similar to what Paillat et al. (2005) and Predotova et al. (2009) reported for manure composting. Conversely, during the soil incubation experiment, cumulative CO_2 emission values were lower than in other studies (Buerkert et al., 2010; Siegfried et al., 2011; Goenster et al., 2014). This may be explained by the low initial C and SOM concentration of the sandy soil used in our experiment.

CO_2 formation in soils results mainly from oxidation of easily degradable C compounds in OM through the activity of microorganisms (Smith et al., 2003). Biochar/charcoal seems to have an opposite effect on CO_2 emissions, which can be explained either by differences in the soil properties, by differences in charcoal/biochar source materials and processing, or by a combination of these conditions (Spokas and Reicosky, 2009; Spokas et al., 2012). Further, the adsorption of OM onto biochar/charcoal either rendered it unavailable for decomposition (Zimmerman et al., 2011; Aguilar-Chávez et al., 2012) or for positive priming effects (Scheer et al., 2011), both of which impact on CO_2 emissions. Steiner et al. (2010) reported a significant increase in CO_2 respiration rates from poultry litter amended with 28% biochar. The porous structure of biochar/charcoal, the decay of the more labile compounds within it, and the increase in pH associated to its presence in the substrate are thought to provide optimal living conditions for microorganisms (Jones et al., 2011; Lehmann et al., 2011). Our observations support these findings; even low application levels of activated charcoal increased microbial respiration, particularly during composting. This can be explained with the higher total C content and up to 10 times higher surface area of activated charcoal in comparison with biochar/charcoal (Spokas and Reicosky, 2009). In contrast to activated charcoal, tannin amendments reduced CO_2 emission, reflecting a potential decline in microbial activity (Kanerva et al., 2006; Mutabaruka et al., 2007; Kraal et al., 2009; Norris et al., 2011). Palm et al. (2001) suggest a critical tannin level of 40 g kg^{-1} above which the respiration rate is negatively affected. However, in the present compost experiment changes in C-release patterns in tannin-amended treatments were observed even after the application of only 0.4 g tannin kg^{-1} substrate. These effects were presumably caused by enzyme inhibition, toxic effects on microorganisms (Palm et al., 2001; Schweitzer et al., 2005), and substrate deprivation (Kraus et al., 2003). Such a reduction of microbial activity based on CO_2 emissions was also observed for the treatment with a combination of activated charcoal and tannins, though to a lesser extent than when only tannins were added. Possible causes may be either the lower tannin extract application rates (1.5% vs. 4% w/w) in our study or the potential of biochar to inhibit the effect of tannins on microbial activity (DeLuca et al., 2006). About 16–77% of the initial N can be lost during composting, in particular through volatilization (Martins and Dewes, 1992; Tiquia et al., 2002). The N losses in the compost and soil incubation experiment were relatively low compared with other studies (Martins and Dewes, 1992; Tiquia et al., 2002; Predotova et al., 2010; Goenster et al., 2014). This could be either due to the relatively high initial C/N ratio, which may have reduced the potential N-losses due to ammonia volatilization, or due to major N-losses from fresh manure, which may have occurred immediately after excretion and/or during storage of goat manure (Predotova et al., 2009).

In our compost experiment, cumulative gaseous NH_3 losses of initial N were in the range reported for dung stored in Niger (Predotova et al., 2009). As previously reported by Predotova et al. (2010), NH_3 volatilization in the soil incubation experiment peaked shortly after amendment application. The values for cumulative soil gaseous NH_3 were similar to those recorded in semi-arid environments (Buerkert et al., 2010; Siegfried et al., 2011; Goenster et al., 2014). The increase of NH_3 volatilization observed during composting in response to activated charcoal applications contradicts the findings of our soil incubation experiment and of other studies (Spokas et al., 2011; Aguilar-Chávez et al., 2012). It is widely assumed that, because of its sorption capacity due to its large specific surface, biochar/charcoal acts as a buffer for soil NH^{+4}, thereby reducing NH_3 volatilization losses (Steiner et al., 2010; Woolf et al., 2010). Stark and Hart (1997) reported that biochar may decrease NH_3 volatilization by increasing nitrification, demonstrating that the transformation of NH^{+4} to NO^{-3} can occur at a high rate and is determined by rapid microbial assimilation of NO^{-3}. This may explain the observed reduction of NH_3 volatilization in our soil incubation experiment. As opposed to activated charcoal, tannins are believed to reduce OM degradation and N mineralization to NH^{+4} (Bradley et al., 2000; Kraus et al., 2003; Halvorson et al., 2012).

Tannins are also known to reduce microbial activity by forming complexes with proteins and eventually inhibiting enzymes (Grant, 1976) and sequestering organic N sources (Kraus et al., 2003). These properties of tannins reduce the pool of NH^{+4} and consequently lower the possibility of NH_3 volatilization, as detected in the current study. This observation was more pronounced towards the end of the experiment, probably due to longer incubation periods. Whether as a result of biological denitrification under anaerobic conditions (McNeill and Unkovich, 2007) or due to autotrophic and heterotrophic nitrification processes, N-emissions increase under aerobic conditions (Beck-Friis et al., 2000). The low N_2O fluxes in the present composting study might be explained by the inhibited activity of nitrifying microorganisms during thermophilic conditions as nitrifying bacteria are sensitive to high temperatures (Dalias et al., 2002). Another reason could be the largely aerobic conditions caused by regular aeration of the compost (Smith et al., 2003) and the small size of the compost containers (Fukumoto et al., 2003). In the soil incubation experiment most of the N_2O was released shortly after amendment application, when high percentages of WFPS caused anaerobic conditions. The addition of activated charcoal to compost potentially increases bioavailable C, which is needed for denitrification (Lehmann et al., 2003; Steiner et al., 2007). This stimulation of denitrification may explain the observed increase of N_2O emissions during composting. In the soil incubation experiment the lower N_2O emissions observed may be due to higher application rates of activated charcoal and a lower N concentration in the soil. Other researchers have observed similar contradictory effects of activated charcoal/biochar on N_2O emissions (Yanai et al., 2007; Lehmann and Joseph, 2009; Cheng et al., 2012). Especially polyphenols are known to shift the pathway of N-cycling (Fox et al., 1990). The observed potential of tannins to reduce N mineralization was shown in several studies (Fox et al., 1990; Palm and Sanchez, 1990). Tannins may reduce N_2O emission due to their ability to form complexes with proteins, resulting in insoluble N and the consequent reduction of available N (Grant, 1976; Mutabaruka et al., 2007). Additionally, tannins may bind to soil microbial enzymes lowering or inhibiting their activity (Fox et al., 1990; Palm and Sanchez, 1990; Haettenschwiler and Vitousek, 2000). DeLuca et al. (2006) found that in combination with tannins activated charcoal stimulated nitrification by removing inhibitory tanninic compounds.

In our experiment low rates of activated charcoal were applied (0.5 and 3 t ha^{-1}) compared with rates up to 150 t C ha^{-1} used by Rondon et al. (2006) and Van Zwieten et al. (2010). The authors are well aware that activated charcoal from coconut shells is not a viable option for large-scale application of charcoal in Oman. However, for experimental purposes this material is fairly uniform and, thus, allows to better understand the soil effects of charcoal application under field conditions. The low rates were chosen since the availability of unused biomass in farming systems such as in Oman is very limited. Hitherto neglected biomass of date palm branches, date kernels and immature, not marketable dates may provide a resource which could be tested for charcoal/biomass production and/or as tannin-rich compost ingredients in these systems (Sait et al., 2012; Martín-Sánchez et al., 2014). However, the amount of activated charcoal tested in our experiment may not have reached the threshold above which the C and N cycling is significantly affected.

2.5 Conclusions

Our study shows that (1) activated charcoal amendments increase biological activity during composting, whereas tannins reduce it, (2) activated charcoal amendments increase cumulative CO_2 emissions and show a similar effect on N emissions, in contrast to tannins, which reduce gaseous losses in all treatments. Consequently, our initial hypothesis, which stated that amending compost or soils with tannins leads to a stabilization of OM and a reduced turnover of organic amendments, was largely confirmed. However, the hypothesis could not be confirmed for activated charcoal, even if as a soil conditioner applied at low rates the latter may improve soil physical properties. Tannins, in contrast, seem to be a promising additive to reduce nutrient losses from soil-applied organic fertilizers although their effects on plants at the field scale need to be better understood.

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3. Chapter

Spatio-temporal patterns of herbage availability and livestock movements

A cross-border analysis in the Chinese-Mongolian Altay

This chapter has been published in Pastoralism:

Jordan, G., Goenster, S., Munkhnasan, T., Shabier, A., Buerkert, A., Schlecht, E. (2016): Spatio-temporal patterns of herbage availability and livestock movements: A cross-border analysis in the Chinese-Mongolian Altay. Pastoralism 6, 1-17.

Abstract

Due to increasing population and the recent implementation of policies to intensify the use of land and water resources, the transhumant pastoral systems in the Chinese-Mongolian Altay-Dzungarian region are rapidly changing, leading to modifications of herd size, herd composition and spatial distribution of livestock grazing. This may have major consequences for the supply and quality of rangeland biomass. Despite similar topographic settings, the socio-political framework for Chinese and Mongolian pastoralists differs significantly, leading to differences in rangeland utilization. To substantiate these claims, the long-distance transhumance routes, frequency of pasture changes, daily grazing itineraries, and size of pastures were recorded by means of GPS tracking of cattle and goats on 1535 (China) and 1396 (Mongolia) observation days. The *status quo* of the main seasonal pastures was captured by measuring the herbage offer and its nutritive value in 869 sampling spots.

In the Altay-Dzungarian region small ruminant herds covered up to 412 km (Mongolia) and grazed on up to 9 pastures per year (China). In Mongolia, the herds' average duration of stay at an individual pasture was longer than in China, particularly in spring and autumn. Herbage allowance at the onset of a grazing period (kg dry matter per sheep unit and day) ranged from 34/17 to 91/95 (China/Mongolia). Comparing crude protein and phosphorous concentrations of herbage, in China highest concentrations were measured for spring and summer pastures, whereas in Mongolia highest concentrations were determined for autumn and winter pastures.

Based on our data we conclude that regulation of animal numbers and access to pastures seemingly maintained pasture productivity in China, especially at high altitudes. However, this policy may prohibit flexible adaptation to sudden environmental constraints. In contrast, high stocking densities and grazing of pastures before flowering of herbaceous plants negatively affected rangeland productivity in Mongolia, especially for spring and summer pastures.

3.1 Introduction

In the Chinese and Mongolian Altay-Dzungarian region, the prevailing harsh continental climate with its periodic severe winters, called *dzud* in Mongolian language, is considered to be a major challenge for local herders, and lead over centuries to a well-adapted animal husbandry system characterized by a high degree of herd mobility and herder flexibility in both countries (Morrison 1999; Behnke et al. 2011; Reid et al. 2014; Liao et al. 2014b; Middleton et al. 2015). While the topographic conditions of the Altay-Dzungarian region are similar on both sides of the Mountain range, the social and economic context of Chinese and Mongolian pastoralists could hardly be more different. This reflects the different historical-cultural background as well as the significant political and economic transformation processes of the last decades, which severely challenge the transhumance system in both countries (Angerer et al. 2008; Liu et al. 2013; Liao et al. 2014b; Martin et al. 2014; Hilker et al. 2014).

During the last decades in the Chinese part of the Altay-Dzungarian region, laws and policies were implemented to intensify livestock production while reducing the rate of land degradation (Brown et al. 2008; Conte and Tilt 2014; Hua and Squires 2015; Gongbuzeren et al. 2015). Measures directly affecting the transhumance systems included state-sponsored fencing programs and regulations on herd management such as herd size and duration of pasture utilization (Brown et al. 2008; Yeh 2009). Other political programs aimed at the settlement of pastoralists (Harris 2010; Hua and Squires 2015). Besides such planned interventions in the transhumance system, increasing urban expansion, intensified cropping and local mining activities progressively hamper the accessibility of rangeland (Squires et al. 2009; Kreutzmann 2013a; Conte and Tilt 2014; Liao et al. 2014b).

In the Mongolian part of the Altay-Dzungarian region, privatization of the formerly state-owned livestock triggered an increase in livestock numbers and a change in herd composition (Lise et al. 2006; Lkhagvadorj et al. 2013a; Lkhagvadorj et al. 2013b; Saizen 2013). Additionally, the transition from a centrally planned to a market economy put considerably more responsibility on individual herders for careful use of pasture resources, access to markets, maintenance of infrastructure for seasonal movements and watering places and preparation of winter fodder (Janzen 2005; Fernández-Giménez and Le Febre 2006; Zhen et al. 2010). Nevertheless, informal/traditional norms allow Mongolian pastoralists to use pastures flexibly to cope with climate hazards (Upton 2010; Fernández-Giménez et al. 2011; Addison et al. 2013: Saizen 2013).

Recent rangeland studies in both countries mainly focused on different interacting drivers of declining herbage yields and herbage quality such as increasing livestock numbers, changes in livestock species, reduction of livestock mobility, reduction of affordable and good quality winter fodder, privatization of rangeland, alteration of traditional rangeland management, rural labor outmigration to cities and changing climate either in China or in Mongolia (Glindemann et al. 2009; Kakinuma et al. 2013; Liu et al. 2013; Yamamura et al. 2013; Bruegger et al. 2014; Hilker et al. 2014; Ma et al. 2014; Khishigbayar et al. 2015). Despite marked differences between China and Mongolia, both countries struggle with designing effective rangeland strategies, policies and programs that allow to sustain rangeland productivity on the basis of fine-tuned pasture management and planning for disaster mitigation (Sasaki et al. 2012; Schönbach et al. 2012; Addison et al. 2012; Kreutzmann 2013a; Wang et al. 2013; Hilker et al. 2014; Khishigbayar et al. 2015).

To the best of our knowledge the present case study is the first to undertake a three-year long comparison of rangeland utilization strategies between China and Mongolia by means of GPS tracking of herds and concomitant determination of herbage offer and quality. We hypothesized that, despite similar natural conditions, the differences in recent socio-political and socio-economic developments on both sides of the border have a large impact on the local transhumance systems in the Altay-Dzungarian region and on rangeland utilization as indicated by herbage offer and quality. To test this hypothesis, the present case study aimed at (i) examining the spatio-temporal mobility patterns of pastoral herds including long-distance transhumance routes and daily grazing itineraries, number of utilized pastures and size of pastures, and (ii) monitoring the herbage offer and its nutritive value on the main seasonal pastures in both countries.

3.2 Materials and Methods

3.2.1 Study area and pastoral system

The study was conducted in Qinghe county, Xinjiang Uyghur Autonomous Region, China (area: 15,760 km^2; inhabitants: 64,300; livestock number: 286,500; 2011), and in Bulgan county, Khovd province, Mongolia (area: 8,105 km^2, inhabitants: 9,018; livestock number: 154,058; 2012), which are only about 100 km apart. Both comprise parts of the central Altay Mountains and the Dzungarian Desert Basin (45°-47°N, 89°-91°E). In the administrative centers of both counties, which are located in the transition zone between the mountain range and the basin, long-term average minimum/maximum annual air temperatures of -34/24°C for China (1958-2007, Qinghe 46°40’28 N, 90°22’59 E, 1253 m) and -32/26°C for Mongolia (1963-2014, Bulgan, 46°05’19 N, 91°32’41 E, 1182 m) were recorded. The average rainfall per year amounts to 174 mm (standard deviation (SD) 50) and 75 mm (SD 34), respectively, with a coefficient of variation of 29% and 45%. During the study period (2013-2014), the annual air temperature and the annual rainfall averaged 3°C and 162 mm in Qinghe compared to 4°C and 50 mm in Bulgan. In contrast to the drier conditions in the desert steppe, the relative wetter climate at the alpine belt was characterized by an average minimum/maximum annual air temperature of -33/26°C in China (C) and -40/23°C in Mongolia (M) and an average annual rainfall of 160 mm (C) and 305 mm (M) at an altitude of 2121 m (C) and 2432 m (M), respectively (Figure 1).

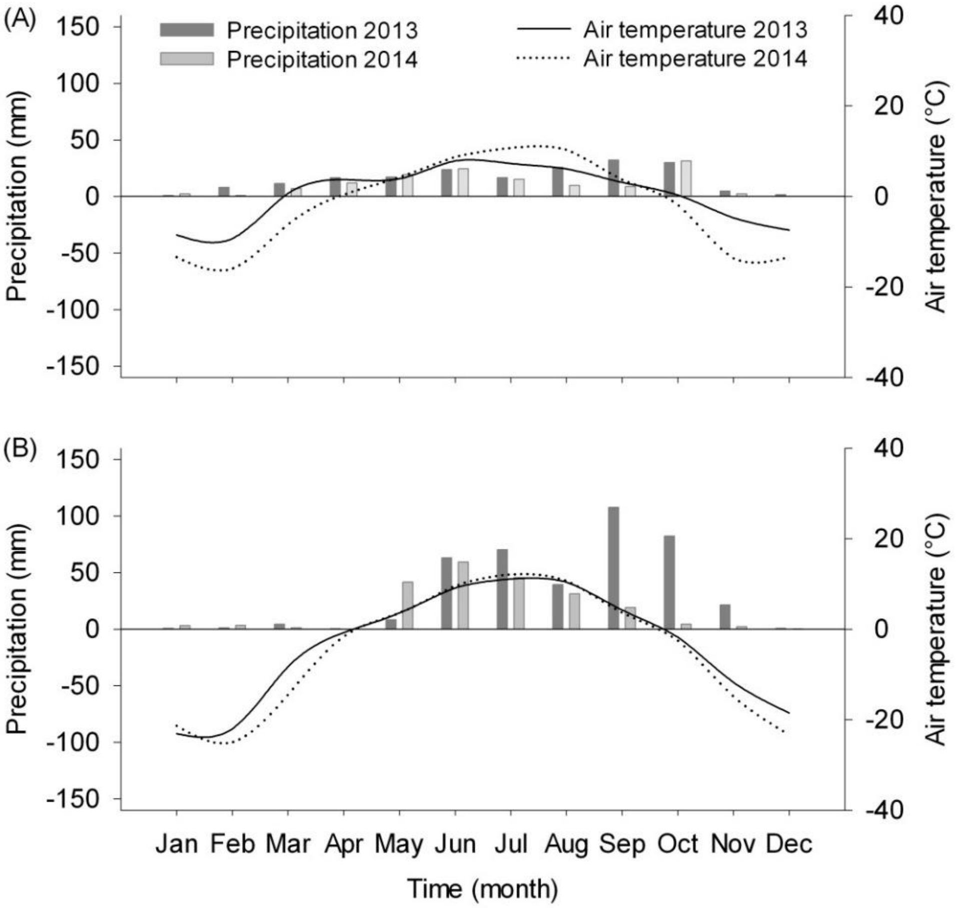

Figure 1. Average monthly precipitation amount (mm) and air temperature (°C) of the Chinese (A, at an altitude of 2121 m) and the Mongolian summer pasture (B, at an altitude of 2432 m) in the alpine belt of the Altay Mountains in 2013 and 2014.

Since millennia, the environmental conditions of the study area shaped a pastoral system that can be described as classical mountain nomadism with seasonal transhumance between pastures in the desert steppe (C: from 1194 m to 1366 m; M: from 1528 m to 1938 m -

winter), mountain steppe (C: from 1432 m to 1576 m; M: from 1603 to 2025 m - spring; C: from 1031 m to 1328 m - autumn), floodplains of the Bulgan river in Mongolia (from 1133 m to 1161 m - autumn) and the alpine belt (C: from 1981 to 2943 m; M: from 2392 m to 3097 m - summer). To facilitate comparison between years and countries, respectively, each season's length was set at three months.

In China the spring and autumn pastures are characterized by the *Stipa caucasica* and *Anabasis brevifolia* community, the *Halimodendron halodendron* and *Convolvulus gortschakovii* community. The *Agropyron cristatum* community, the *Festuca ovina*, *Festuca altaica* and *Phlomis tuberosa* community and the *Juniperus sabina* and *Larix sibirica* community prevail in the summer pasture. Whereas the *Stipa caucasica* and *Anabasis brevifolia* community and the *Nanophyton erinaceum* community are predominant in the winter pasture. In Mongolia, the *Caragana leucophloea* community prevails on the spring pasture, the summer pasture is characterized by the *Agropyron cristatum* community and the *Festuca altaica* community, and the autumn pasture by the *Salix turanica*, *Caragana spinosa* and *Populus laurifolia* community and *Phragmites australis* community. The *Stipa caucasica* and *Anabasis brevifolia* community dominates on the winter pasture. Transhumant pastoralism in the Chinese as well as in the Mongolian Altay-Dzungarian region is characterized by resembling consistent sequence of seasonal pastures and comparable soil properties (Jordan et al. 2015). Beside similar geographic settings, the Chinese and Mongolian study region is also characterized by a similar sequence of seasonal pastures, spatially fixed since generations. The spring pastures in desert steppes or at mountain foothills are of major importance for the herds' reproduction. In summer the animals graze at the alpine meadows. At the summer pastures higher precipitation amounts and soils richer in organic carbon and nutrients favors higher herbage yields and quality, which is of importance to fatten the animals and for dairy production. Decreasing temperatures in autumn force herds to move back to flood plains and desert steppes which play an important role for building up further body reserves for the winter. Winter pastures at the desert steppes feature relatively low biomass yields, but its accessibility is ensured due to relatively low snow cover, nevertheless late winter and early spring are known as bottlenecks of animal nutrition.

Even though the agro-ecological environment is similar, the political context could not be more different. In the Chinese Altay-Dzungarian region the start date for transhumance movements to any seasonal pasture (pastures used only in a specific season i.e. spring, summer, autumn and winter), the duration of stay on a pasture, location and size of a household's pastures and the animal numbers per household are defined by the local government (Squires et al. 2010). A (household's) pasture is always in state ownership, and in the study region is normally an unfenced but clearly delimited rangeland management unit for grazing assigned to an individual herder household; in the whole of Qinghe county there was only one fenced winter pasture for cattle. Representatives of the local government followed the herders year-round to ensure their compliance with the mentioned regulations. However, the prescribed dates of transhumance movements to the seasonal pastures were often circumvented by sending un-herded livestock ahead (especially cattle, horses and camels). In Mongolia, in contrast, the timing of transhumant movements is determined by social and environmental factors (start of school holidays, weather conditions, herbage yield and water availability). The compliance with regulations of traditional rangeland utilization and number of animals kept are largely self-controlled by the individual herder and a communally nominated 'major' herder elected by the local herders itself (Upton 2010).

In the study region most livestock herds consist of sheep and goats complemented by cattle, horses, and sometimes by camels or/and yaks. Bovids on both sides of the border are of the same types, namely fat-tail sheep, cashmere goats and Turano-Mongolian cattle. Each livestock species grazes separately, except for sheep and goats. None of these animals are actively herded; only sheep and goats are sporadically checked to assure the utilization of assigned (on the basis of governmental or traditional regulations) pasture and to avoid mixing of different herds. In the early evening sheep, goats and cattle return to the herder's camp. During winter the livestock herds are separated into cattle herds and other livestock (goats, sheep, horses and camels). The cattle stay in the floodplains in the vicinity of villages, whereby in China some of them grazed in a fenced plot, and receive additional fodder in form of hay, while the remaining livestock is moved far into the desert plain.

3.2.2 Livestock related data collection

From a previous baseline survey covering >150 herder households in each country (Munkhnasan et al. 2014), it appeared that groups of 30 to 50 or even more families utilized the same seasonal pastures and connecting tracking routes. From the baseline survey households' one typical herder family per country was chosen and asked for its willingness to participate in the current study. This family practiced the classical seasonal transhumance between lowland and mountain pastures and its herd was of average size and country-specific species composition. From May to September its pastoral movements were personally accompanied. The study herder in China was of Kazakh ethnicity (as all other herders in the study region), whereas in Mongolia the study herder was Mongolian (Torguud tribe, the predominant ethnicity in the study region). Between 2012 and 2014, the herd studied in China averaged 428 sheep units (SU) with a SD of 43 (cattle= 125, goats= 21, sheep= 242, horses= 40, camels= 0) and that in Mongolia 1004 SU (SD 117; cattle= 342, goats= 173, sheep= 190, horses= 263, camels=37), whereby one cattle equals 5 SU, one goat 0.9 SU, one sheep 1 SU, one horse 5 SU and one camel 7 SU (Zizhi and Degang, 2011). Differences between both countries were particularly large for the number of sheep (C: n= 242; M: n= 190) and goat heads (C: n= 23; M: n = 192).

Given the importance of cattle and goats for the provision of food and income to the herder families, and their major economic and social value, GPS tracking of livestock was limited to these two species. Butt (2010) and Moritz et al. (2012) reported that one GPS-tracked animal per herd may be sufficient to study the general movements and grazing patterns of the entire herd over long periods of time. Therefore, per herd one representative female cattle and male goat, respectively, both of middle social rank, were equipped with a GPS Collar (GPS PLUS Globalstar, VECTRONIC Aerospace GmbH, Berlin, Germany) to record the herd´s temporal and spatial mobility. Date, time, altitude, longitude and latitude were stored at one minute intervals from May to September and at 16 minute intervals from October to April in the years 2012, 2013 and 2014. From May to September each animal was carrying the collar for a minimum of three days per seasonal pasture, whereas from September to May the collared animals were tracked continuously. In addition, the transhumance routes between the seasonal pastures were tracked. This resulted in a total track number of n_{Cattle}= 602 and $n_{\text{Small ruminants}}$= 933 in China and n_{Cattle}= 644 and $n_{\text{Small ruminants}}$= 752 in Mongolia. The difference in track numbers between both countries and species is explained by accidental discharge of battery before the end of an observation period, and the temporary loss of one GPS collar. For the calculation of the length and duration of transhumance movements and the duration of stay on pastures, missing GPS data were substituted by herder’s information. During the first year of study, a brief survey on animal numbers, way of transportation to seasonal pastures and course of transhumance routes was conducted along the main transhumance axis on each side of the border.

3.2.3 Sampling and chemical analysis of aboveground herbaceous biomass

At each seasonal pasture herders were asked (with the help of satellite images) to which pasture they would move next, subsequently the pasture was visited for herbage sampling before the herders' actual movement. Prior to herders' arrival at each seasonal pasture, the initial aboveground herbaceous biomass was determined. At each seasonal pasture, a regular grid of 500 m x 500 m and a list of the GPS coordinates of each grid point (=sampling point) was created in QGIS 1.4 (Quantum GIS Development Team, 2010, QGIS Geographic Information System, Open Source Geospatial Foundation Project). At each of these sampling points, which in the field were located by a hand-held GPS device (HOLUX M-241, Holux Technology Inc., Hsinchu, Taiwan), a spot with representative herbaceous cover and composition was chosen within a radius of 4 m. Then a sampling frame (50 cm x 50 cm) was placed on the ground and the aboveground herbaceous vegetation was clipped to 1 cm above soil surface, whereby dead plant material was excluded. Additionally, further spots were sampled at every 500 m along the itinerary of the GPS-collared cattle and goat. The number of sampled spots per pasture was set on the basis of the herbage heterogeneity of each pasture. In total 869 spots (C: n= 359, M: n= 510) were sampled for the main spring, summer, autumn and winter pastures. Whereas the measurements on the pastures took place from 2012 to 2014, those along the animals' itineraries were restricted to 2013 and 2014. Due to logistic constraints, measurements at the winter pastures took place in September, although pastures were not grazed until November/December; all other measurements were made during the utilization period of the respective pasture. At each spot the vegetation and stone cover, mean vegetation height (n= 3) and occurrence of functional plant groups (grasses, herbs and shrubs) were assessed. However, these parameters are not considered in the current study. In addition, environmental variables (altitude, aspect) and the GPS position were measured. After the total fresh weight of herbaceous biomass was determined directly in the field (portable electronic balance, range 0.1 to 1000 g, precision 0.1 g), the samples were dried at 60°C until constant weight to determine the dry weight of aboveground biomass; this mass (available at the start of the grazing season) is further referred to as 'herbage offer' (Allen et al. 2011). Following grinding to 1 mm particle size (FOSS sample mill, CyclotecTM 1093, Haan, Germany), all samples were read with a XDS-Rapid Content Analyzer NIRsystem (FOSS NIRsystems, Hillerod, Denmark). The concentrations of dry matter (DM) after drying to weight constancy at 105°C, of organic matter (OM) after combustion at 550°C, of phosphorus (P) and calcium (Ca) were determined in a subset of 290 samples following standard procedures (Naumann and Bassler 2004). Using a semi-automated Ankom 200 Fiber Analyzer (Ankom Technology, Macedon, NY, USA), a subset of 179 samples were measured for the concentration of neutral detergent fiber (NDF) and acid detergent fiber (ADF) according to van Soest et al. (1991) following the procedure of Schiborra et al. (2010). Carbon (C) and nitrogen (N) concentrations were determined by a CN-Analyzer (Vario MAX CN; Elementar Analysensysteme GmbH, Hanau, Germany). On the basis of a calibration model (NDF: R^2= 0.87, standard error of cross-validation (SECV)= 43 g kg^{-1} DM; ADF: R^2= 0.90, SECV= 31 g kg^{-1} DM; N: R^2= 0.94, SECV= 1.5 g kg^{-1} DM; OM: R^2= 0.88, SECV= 21 g kg^{-1} DM; P: R^2= 0.72, SECV= 30 g kg^{-1} DM, Ca: R^2= 0.95, SECV= 25 g kg^{-1} DM) the concentration of the respective chemical fractions was predicted in the remaining samples (Reddersen et al. 2013). The concentration of crude protein (CP) was calculated based on the N concentration (CP= N x 6.25, Allen et al. 2011). The above mentioned parameters were used for the evaluation of the nutritive value of the vegetation ('herbage quality').

3.2.4 Data processing and statistical analysis

All GPS raw data obtained from the tracked animals were corrected for outliers (GPS positions estimated from only 3 satellites) as well as failed GPS readings (GPS positions were estimated from < 3 satellites) and were subsequently merged per season (spring, summer, autumn and winter) and animal species. All data were processed using the software packages ArcGIS 9.2 (ESRI Corp, Redlands, CA, USA) and QGIS; coordinates were converted to UTM grid projection (WGS 1984, 46°N). The horizontal distance covered in long distance transhumance movements was calculated using the Hawth's Analysis Tools extension for ArcGIS. For the calculation of the 'daily walked distance' the horizontal distance was divided by the number of tracking days. On the basis of the GPS tracks the number of utilized pastures was counted and duration of stay (time between date of arrival and departure) was determined. A buffer with a 50 m width to both sides of the collared animal's itinerary was placed along the merged tracks. The surface of the resulting area was calculated and defined as 'theoretical utilized pasture area' for the entire small ruminant and cattle herd, respectively (Feldt and

Schlecht 2016). The theoretical utilized pasture area was divided by the herd´s duration of stay to determine the ‘theoretical utilized pasture area per day’. The herbage offer and selected herbage quality data (NDF, CP and Ca:P ratio) were spatially interpolated by the Inverse Distance Weighting Method in QGIS 1.4 using a distance coefficient of three. Selected properties of the seasonal pastures as well as of the species-specific theoretical utilized pasture area were extracted from the interpolated herbage offer and herbage quality map.

On the basis of SU in a given theoretical utilized pasture area the ‘herd-related stocking density’ (SU ha^{-1}) was calculated. For estimations of stocking densities/stocking rates, the livestock of other herders were neglected, due to the fact that either grazing areas were far off each other or herders confirmed their exclusive utilization of assigned pastures. For the calculation of the ‘herd-related stocking rate’ (SU*season ha^{-1}) the SU were divided by the summed theoretical utilized pasture area and subsequently multiplied by the length of season (three months). The ‘daily herbage allowance per SU’ was calculated based on the herbage offer at the pasture divided by the number of SU and duration of stay at the pasture. For the estimation of herbage allowances autumn and winter data were combined to compare small ruminants and cattle, since cattle stayed on the same pasture during autumn and winter. To assure comparability of the calculation of stocking density and stocking rate as well as herbage allowance across the two countries, the SU of sheep and goats were summarized and defined as ‘small ruminants’ as they were continuously herded and managed together.

All resulting data were compared between locations (China, Mongolia), species (cattle and goat for GPS-tracks; cattle and small ruminants for herbage-related data) and seasons (spring, summer, autumn and winter). To assess the statistical relations between herbage offer and quality data and GPS-tracked data, the non-parametric Spearman's rank correlation coefficient (r_S) was calculated. Statistical analyses were performed with RStudio Inc. (Version 0.98.1103, Boston, MA, USA); differences were viewed as statistically significant at $P \leq 0.05$.

3.3 Results

3.3.1 Seasonal herd movements and pasture utilization

The altitude range captured within the seasonal transhumance movement varied between 1031 m and 2943 m (China) and between 1122 m and 3097 m (Mongolia). The overall annual distances covered by seasonal movements were similar between the countries whereas across countries differences were observed between cattle and small ruminant herds due to different management practices. The average (2012-2015) annual length of transhumance routes serving the movements between the seasonal pastures of cattle amounted to 219 km (SD 5.1, n= 29, China) and 244 km (SD 10.4, n= 8, Mongolia), whereas small ruminants covered a transhumance distance of 395 km (SD 136.2, n= 28, China) and 412 km (SD 97.0, n= 23, Mongolia).

The number of utilized pastures differed between countries and species, particularly for cattle herds. While the cattle herd in China visited up to nine pastures over the year, only four pastures were visited in Mongolia, mainly due to different numbers of autumn pastures. In contrast to that, a similar pattern of seasonal pasture use was observed for the two small ruminant herds (Table 1). Throughout the year the herds spent more time on a specific pasture in Mongolia than in China which applied in particular to cattle and was mainly due to longer sojourn of the Mongolian herd at the spring and autumn pastures. The sojourn of the two small ruminant herds on the individual pastures followed a similar pattern in both countries. Their average duration of stay at a pasture was shorter than for cattle due to a higher number of pastures grazed by small ruminants in autumn and winter (Table 1). Additionally, in China, the herds' sojourn (small ruminants and cattle) was longer at places with lower herbage allowance (r_s= -0.75, P< 0.001). In China the duration of sojourn (arrival as well as departure date) was regulated by the local government. Nevertheless, information gathered from herders about arrival and departure dates of their animals deviated by 3 to 112 days from the official dates during the study period.

Generally, the daily walked distance differed numerically between seasons; longer distances were observed during spring (China) and summer (Mongolia) and shorter ones in autumn and winter. The annual average for the daily walked distance of cattle was 5 km day^{-1} in China compared with 12 km day^{-1} in Mongolia. For small ruminants similar average daily walked distances were observed in China and Mongolia (10 km and 9 km, respectively; Table 1). The daily walked distance was mainly influenced by herbage offer and for the cattle was slightly negatively correlated with the latter variable (r_s= -0.40, P= 0.005) across both countries, whereby this inverse relationship was stronger on the Mongolian side of the Altay (r_s= -0.62, P= 0.001).

Table 1. Average number of utilized pastures, duration of stay at an individual pasture, grazed area per day, daily walked distance and herd-related stocking rate of cattle and small ruminants/goats at the main seasonal pastures in China and Mongolia between 2012 and 2014. Given values are mean values with the corresponding one standard deviation (SD) and number of samples as specified for each variable (n).

			China				Mongolia			
			Spring	Summer	Autumn	Winter	Spring	Summer	Autumn	Winter
Pastures (n)	Cattle	Mean	2	2	4	1	1	2	-	1
		SD	1.0	0.0	0.5	0.0	0.0	0.0	-	0.0
		n	4	4	7	2	2	4	-	2
	Small ruminants	Mean	3	2	3	1	2	2	1	3
		SD	1.5	0.0	0.8	0.0	0.0	0.0	0.0	0.0
		n	5	6	9	3	4	4	3	5
Duration of stay per pasture (days)	Cattle	Mean	21	38	11	167	45	32	-	247
		SD	0.2	0.8	1.9	16.8	19.3	5.4	-	14.3
		n	55	102	72	334	38	47	-	412
	Small ruminants	Mean	28	43	23	140	42	32	77	57
		SD	1.3	7.1	1.7	42.9	11.4	0.0	23.2	18.5
		n	124	135	198	411	190	126	84	269
Daily pasture area (ha)	Cattle	Mean	22	6	77	1	8	22	-	4
		SD	15.2	3.1	11.0	0.6	3.9	3.1	-	0.7
		n	70	101	72	334	38	47	-	416
	Small ruminants	Mean	36	18	68	63	66	25	8	73
		SD	26.8	2.0	13.6	41.4	20.6	2.8	2.3	40.4
		n	110	135	149	482	190	126	100	269
Daily walked distance (km)	Cattle	Mean	6	6	5	3	11	15	-	8
		SD	2.0	1.3	0.8	0.6	2.3	3.6	-	2.2
		n	70	101	72	334	38	47	-	416
	Small ruminants	Mean	12	9	10	9	11	12	6	8
		SD	1.8	1.6	2.6	3.3	3.2	3.0	0.4	1.6
		n	110	135	149	482	190	126	100	269
Stocking rate (SU*season ha^{-1})	Cattle	Mean	1.3	2.1	0.4	1.7	3.5	1.6	-	0.8
		SD	1.1	1.2	0.1	0.9	0.7	0.5	-	0.0
		n	70	101	72	334	38	47	-	416
	Small ruminants	Mean	1.1	1.5	0.5	0.3	0.6	1.3	2.1	0.3
		SD	1.1	0.7	0.2	0.3	0.3	0.3	0.8	0.1
		n	110	135	149	482	190	126	100	269

Considering the size of the utilized pastures throughout the year, the theoretical utilized pasture area per day of the Chinese cattle herd (73 ha day^{-1}) was more than twice of that in Mongolia (34 ha day^{-1}), whereas the theoretical utilized pasture size of Chinese small ruminants was only slightly larger (+18%) than of small ruminants in Mongolia. In contrast, the theoretical utilized pasture area during autumn and winter in China was about 19 times larger for the cattle herd and 9 times larger for the small ruminant herd than in Mongolia. Comparing the different species within China and Mongolia, respectively, the theoretical utilized pasture area of cattle was always smaller than that of small ruminants, especially during winter, except for the autumn pastures. The largest differences were observed for the winter pastures of cattle which were 44 and 17 times smaller than the ones of small ruminants in China and in Mongolia (Table 1). Herbage offer was an important driver for the theoretical utilized pasture area: The area used per day was negatively correlated with the average herbage offer at the pasture site across all species (r_s= -0.43, P= 0.013), whereby the correlation was higher if only cattle were considered (r_s = -0.53, P= 0.044).

Seasonal (3-months) stocking rates (SU ha^{-1}) ranged from 0.32 and 0.31 for Chinese and Mongolian small ruminants during winter to 3.48 for Mongolian cattle during spring. Comparing both countries, seasonal stocking rates of cattle were lower in the Chinese spring and autumn pastures, whereas stocking rates of small ruminants were only lower in the Chinese autumn pastures. Particularly Mongolian spring pastures evinced high cattle stocking rates, while for small ruminants high rates were observed during summer (China) and autumn (Mongolia). Comparing stocking rates of cattle and small ruminants within each country, Chinese and Mongolian cattle pastures featured always higher stocking rates over the course of the year, with the exception of the Chinese autumn pastures of cattle (Table 1).

3.3.2 Quantity and quality of herbage

The herbage offer ranged from 847 (winter pasture) to 1685 kg DM ha^{-1} (summer pasture) in China. At the Mongolian sites a wider range of herbage offer from 535 (summer pasture) to 1868 kg DM ha^{-1} (autumn pasture; Table 2) was recorded. Compared with Mongolia, Chinese pastures were characterized by a higher herbage offer with the exception of the autumn pastures; the largest difference was observed for the summer pastures where herbage offers were three times higher on the Chinese side (Table 2). Considering all seasonal pastures, overall average herbage offer was about 18% higher in China than in Mongolia. Comparing average herbage offers available to each livestock species between both countries, Chinese cattle utilized pasture areas with lower herbage offers (-14%) than those utilized by cattle in Mongolia, whereas herbage offers on pasture areas utilized by Mongolian small ruminants were 29% lower than the respective Chinese values. Comparisons between livestock species within each country indicated lower herbage offers on pasture areas utilized by cattle than by small ruminants (-24%) in China, whereas in Mongolia cattle utilized pasture areas with 22% higher yields than areas utilized by sheep and goats (Figure 2).

Yearly average herbage allowances (kg DM SU day^{-1}) amounted to 20 (Mongolia) and 50 (China) for cattle and 52 (Mongolia) and 65 (China) for small ruminants (Figure 3). The herbage allowance on all seasonal pastures was higher in China compared with Mongolia, except for the spring pasture of small ruminants, where the Chinese value was 33% lower. Despite the high herbage offer in the summer season, the lowest herbage allowance was determined for the summer pastures, while high herbage allowances prevailed at spring and autumn/winter pastures.

Comparisons of herbage allowances between livestock species within each country showed higher values for Chinese cattle than for small ruminants, except for the autumn pasture on which herbage allowance for cattle was considerable lower than for small ruminants. In contrast, in Mongolia, all pastures of cattle were characterized by a lower herbage allowance than for the pastures of small ruminants. Across both species, stocking density was slightly negatively correlated with herbage allowance in Mongolia (r_S= -0.74, P< 0.001), but not in China.

Herbage quality varied between countries, seasons and utilized pasture areas of different livestock species. Concentrations of CP and P were low on autumn and winter pastures, whereas high concentrations were measured on spring pastures. Comparing the quality parameters of pastures between livestock species, difference was largest for the CP concentration in herbage from the autumn/winter pastures; the Chinese cattle/small ruminant pastures showed -10%/-21% less CP than in Mongolia. The lowest NDF and ADF concentrations were measured for the summer pasture in China and for the winter pasture in Mongolia, whereby overall concentrations were lower for the Chinese than for the Mongolian pastures (Table 2).

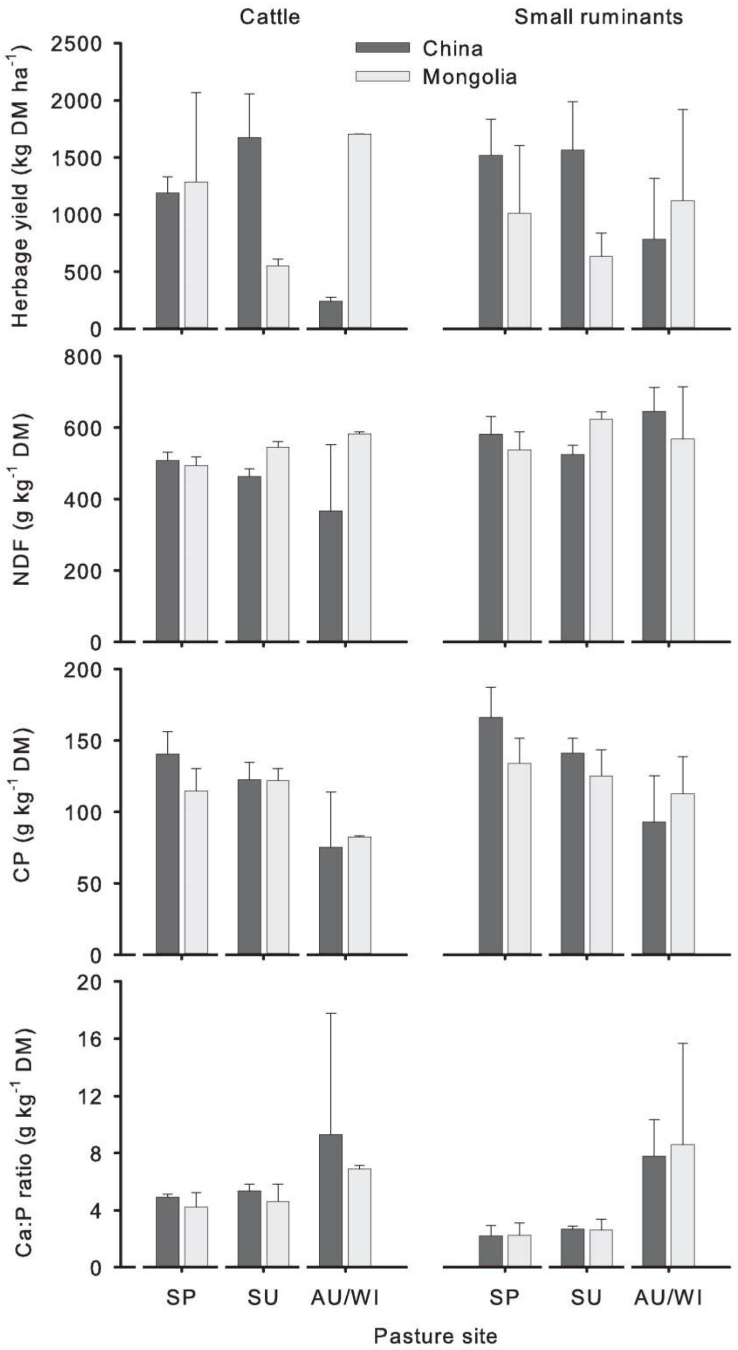

Figure 2. Herbage offer and concentrations of neutral detergent fiber (NDF), crude protein (CP), Calcium:phosphorus ratio (Ca:P) for herbage at the main spring (SP), summer (SU) and autumn/ winter (AU/WI) cattle (A to D) and small ruminants (E to H) grazing grounds in China and Mongolia (collected between 2012 and 2014). Bars represent mean values; whiskers show one standard deviation (SD).

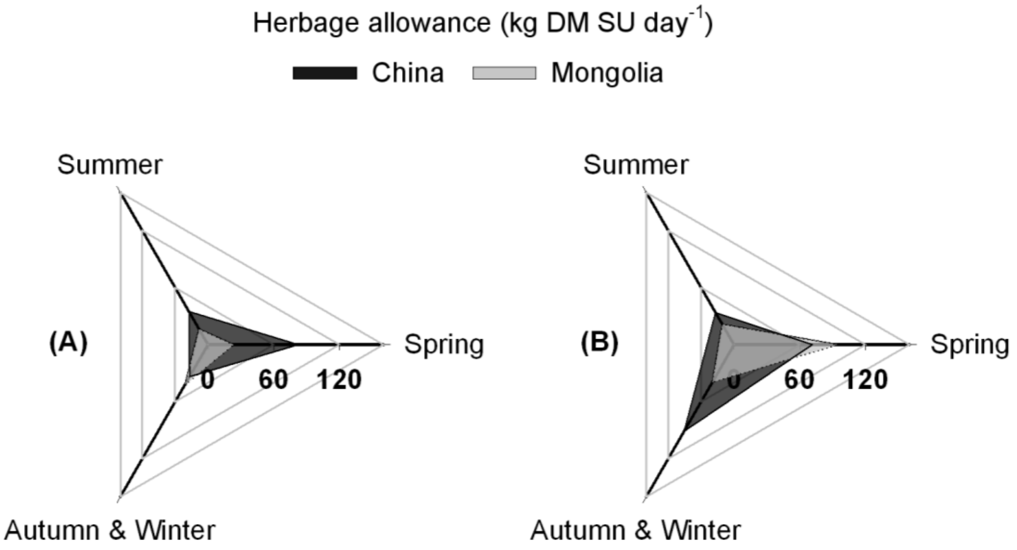

Figure 3. Average herbage allowances at the main seasonal pastures of cattle (A) and small ruminants (B) in China and Mongolia between 2012 and 2014. Values given are mean values.

Comparing herbage NDF concentrations for livestock species and countries, maxima on cattle pastures were determined in spring (China) and autumn/winter (Mongolia), whereas maxima on small ruminant pastures were measured during autumn/winter (China) and summer (Mongolia). On both sites of the border, Ca concentrations were highest for the winter pastures in the desert areas. Given the relative low P concentrations, Ca:P ratios varied between 4:1 (Chinese spring pasture) and 28:1 (Mongolian autumn/winter pasture). On all seasonal cattle pastures, lower Ca:P ratio were measured than on small ruminant pastures, particularly for the Chinese (-68%) and Mongolian (-150%) autumn/winter pasture (Figure 3).

The herbage offer of a respective pasture was positively related to herbage quality, as pasture sites with higher herbage offers showed also higher CP concentrations (r_s= 0.35, *p*= 0.044) with a particularly high correlation determined for the Chinese pasture areas utilized by cattle (r_s> 0.52, P= 0.033).

3.4 Discussion

3.4.1 Mobility pattern

Pastoralists in semi-arid and arid environments strongly depend on herd mobility to optimize forage availability for their animals and utilize pastures sustainably (Humphrey and Sneath 1999; Fernández-Giménez and Le Febre 2006; Behnke et al. 2011).

Table 2. Duration of stay at the seasonal pasture as well as average yield and concentrations of dry matter (DM), organic matter (OM), neutral detergent fiber (NDF), acid detergent fiber (ADF), crude protein (CP), phosphorus (P) and calcium (Ca) for herbage at the main seasonal pastures in China and Mongolia between 2012 and 2014. Given values are mean values with the corresponding one standard deviation (SD) and number of samples (n).

		China				Mongolia			
		Spring	Summer	Autumn	Winter	Spring	Summer	Autumn	Winter
Duration of stay (days)	Mean	25	43	18	154	43	32	77	135
	SD	1.1	7.0	3.8	16.3	3.1	0.0	23.2	70.0
	n	179	237	270	745	227	173	84	680
Herbage yield (kg DM ha^{-1})	Mean	1418	1685	1121	847	1201	535	1868	555
	SD	896.5	747.2	864.6	656.2	820.7	419.3	835.1	338.0
	n	44	219	31	65	60	326	28	96
DM (g kg^{-1} FM)	Mean	449	359	447	428	513	571	384	386
	SD	131.3	129.5	93.5	89.8	127.2	159.4	59.6	116.9
	n*	44	194	30	56	57	290	22	91
OM (g kg^{-1} DM)	Mean	853	891	822	869	917	891	891	811
	SD	35.9	26.9	59.8	34.1	22.3	33.3	22.5	67.9
CP (g kg^{-1} DM)	Mean	136	121	71	85	118	108	83	111
	SD	26.6	17.2	27.5	23.5	19.6	30.8	14.9	18.1
NDF (g kg^{-1} DM)	Mean	528	467	586	525	470	552	586	410
	SD	64.9	44.6	98.5	64.3	87.4	53.3	53.1	88.1
ADF (g kg^{-1} DM)	Mean	360	325	397	367	286	298	339	239
	SD	54.6	38.3	92.3	43.2	44.2	46.8	33.9	69.5
P (g kg^{-1} DM)	Mean	2.1	2.0	1.2	1.3	1.7	1.3	1.2	1.3
	SD	0.3	0.2	0.4	0.5	0.4	0.3	0.2	0.4
Ca (g kg^{-1} DM)	Mean	8.0	10.5	15.3	17.8	8.1	7.1	7.9	31.1
	SD	5.3	2.9	10.8	8.7	3.9	3.6	3.3	14.8

* for the following quality parameters numbers (n) are equal in the corresponding column; FM=Fresh matter

This implies seasonally and annually flexible adaptation of long-distance transhumance routes, frequency of pasture changes and daily grazing itineraries (Saizen et al. 2010; Kakinuma et al. 2014). As in other transhumant systems of the world, livestock mobility in the Altay-Dzungarian region is mainly influenced by the seasonal variability of herbage quantity, quality and palatability, access to water, weather conditions (precipitation, snow depth, temperature and wind) and prevalence of pests and predators (such as mosquitos, horseflies and wolfs), topographic features, traditions, infrastructure and political and social framework but also by individual human decisions (Angerer et al. 2008; Tsui 2012; Kakinuma et al. 2014).

We observed that as decisions were taken, pastoralists were assessing the benefits of specific herding strategies against potential risks. Yet, the two cooperating herders largely managed their animals and pastures according regional practices which comprised in the Chinese Altay the use of transhumance routes of up to 640 km per year including 33 changes of pastures (Morrison 1999; Squires et al. 2010). However, increasing population density, rising economy and governmental interference with the transhumance system (such as regulation of mobility and animal numbers, state-sponsored fencing programs, clearance of 'degraded' rangeland, expansion of irrigated agricultural land and mandatory forced resettlement of herders) changed the traditional local herding system in the Chinese Altay (Yeh 2005; Brown et al. 2008; Squires et al. 2009; Yeh 2009; Squires et al. 2010; Tsui 2012). The transhumance system in the Mongolian Altay, in contrast, remained largely unregulated by the distant government, but is currently also changing due to a shift from camels to trucks for the transportation of families, mobile homes (yurts) and weak animals, and changes in people's way of living such as year-round grazing near the villages due to a rising demand for social and health services and generation of supplementary income. This was also described by other studies conducted in Mongolia (Lise et al. 2006; Okayasu et al. 2007; Kamimura 2013; Lkhagvadorj et al. 2013b; Bruegger et al. 2014). Despite these altered social and political circumstances, the long-distance movements (particularly of small ruminants) in the Chinese and Mongolian Altay were longer compared with distances reported for other regions in China (Xinjiang Autonomous Region, Altay prefecture) and Mongolia (the Mongolian Plateau and Ugtaal sum) ranging from 90 km to 190 km (Morrison 1999; Lise et al. 2006; Zhen et al. 2010; Kreutzmann 2013b). The remoteness from markets and the high altitudinal gradient of the Altay-Dzungarian region may explain the relatively high degree of mobility (Lkhagvadorj et al. 2013a; Liao et al. 2014b). Regardless of the different framework conditions across our study region, long-distance movement patterns were similar. During the period of our on-site measurements, the transhumance routes of Chinese small ruminants changed from long-distance movement to the desert steppe in 2012 to pasture sites closer to the settlements (in 2013 and 2014) due to low herbage availability on the remote pastures. The latter was triggered by an expansion of irrigated agricultural land and mining activities directly within the autumn and winter pasture areas during the last two years of this study. The frequency of changes of individual pasture areas within a seasonal pasture and the duration of long-distance movements in our study region was within the range of values reported in other studies of similar ecological context (Lise et al. 2006; Behnke et al. 2011; Liao et al. 2014a), in which the number of utilized pastures and duration of stay ('sojourn') varied between three and eight times and 1.5 and 3.5 months, respectively. The higher number of movements and consequently shorter duration of stays in China compared with Mongolia largely reflected governmental regulations.

A further integral component of herd mobility and use of pasture in accordance with the environmental conditions is the exploitation of seasonal pastures. Grazing itineraries and the resultant theoretical utilized pasture area are determined by a variety of factors such as meteorological conditions, topographic features, the spatial expansion of the pasture, herbage yield and quality, animals' dietary preferences, distance to water, land use rights and management strategies such as daily herding practices (Baumont et al. 2000; Lin et al. 2011; Askar et al. 2013). The average daily walked distance in the study area was slightly lower (particularly during autumn and winter) than reported by studies of transhumance systems in sub-Saharan Africa (Turner et al. 2005; Schlecht et al. 2006; Butt 2010; Raizman et al. 2013). Environmental conditions such as low temperature, snow cover and strong wind as well as the herd-release strategy (small ruminants) or absence of active herding (cattle) likely reduced the length of daily grazing itineraries (Vetter 2005; Schlecht et al. 2006; Squires et al. 2010). This assumption is substantiated by a comparison with daily itineraries tracked under similar management conditions in Inner Mongolia, Mongolia and Tibetan plateau, which closely matched the data of the current study and ranged between three to 13 km per day (Kawamura et al. 2005; Joly et al. 2013; Ding et al. 2014). The cross-country comparison of daily grazing itineraries revealed larger distances covered by cattle in Mongolia than in China, likely caused by lower herbage offers in Mongolia on the one hand, and the Chinese regulation of animal numbers per pasture on the other hand. However, differences in daily distances and thus in sizes of theoretical utilized pasture areas between species may be explained by their different foraging preferences and accessibility of pastures. As various authors reasoned, in particular topographic features such as steep slopes and high stone cover at the pastures may limit the grazing radius of cattle (Zemmrich et al., 2010; Fujita et al., 2013; Turner et al., 2014) as it was also observed in the Altay-Dzungarian region. The relatively short distances of Chinese cattle covered during the winter are a result of restricted pasture grounds (pastures near the village and partly fenced pastures) and additional fodder supply in form of hay.

The stocking density and stocking rate differed between the two countries due to the above-discussed differences in livestock mobility patterns such as the number of movements and duration of stay but also livestock numbers and daily herding strategies. In particular during spring and summer, the observed stocking rates were relatively high in both countries compared with similar regions in Inner Mongolia and Mongolia (Kawamura et al. 2005; Lise et al. 2006; Chen et al. 2007; Sugita et al. 2007; Glindemann et al. 2009; Lkhagvadorj et al. 2013a; Bösing et al. 2014; Liao et al. 2014a). Governmental regulation of animal numbers and duration of stay on pastures seemed to lower the stocking densities particularly in the Chinese Altay. However, the non-compliance with administratively prescribed arrival and departure dates for pasture sites by most of the herders (own data, unpublished) disclosed the limited reach of strict regulation in a highly fragile environment (Banks et al. 2003; Campbell et al. 2006; Lee et al. 2015). Mongolian pastures, in contrast, are currently subjected to rising grazing pressure due to increasing livestock numbers (especially before the 2009/2010 dzud) and particularly increasing numbers of cashmere goats, as well as possibly reduced livestock mobility (Saizen et al. 2010; Saizen 2013; Hilker et al. 2014). These phenomena were also observed in Bulgan county (personal communication, Bulgan *sum* governor), where from 1999 to 2014 the goat and sheep population in the Mongolian study region increased by 51% and 9%, with peaks of 114% and 14%, respectively, reached in the pre-dzud year 2008 (Appendix 1). Furthermore, our 3-year data of long distance movements and complementary information from the baseline survey indicate a decline of long-distance movements to the desert steppes (winter) and alpine belts (summer) in favor of year-round grazing of pastures near the settlement. The localized high grazing pressure resulting from these developments is exacerbated by a declining number of active herders and a concurrent increase of herd sizes which is partly the result of an increased number of herders who are in charge of additional livestock of other herders in return of payment, which has also been observed elsewhere (Humphrey and Sneath, 1999; Saizen, 2013).

In addition, active daily herding was often lacking, which reflects labour scarcity, loss of traditional knowledge and absence of an effective coordinating authority at the pastures which intensified the grazing pressure in both countries (Brown et al. 2008; Addison et al. 2012; Yamamura et al. 2013).

3.4.2 Quantity and quality of herbage

The harsh continental climate with its high inter-annual rainfall variability and short growing period limits the rangeland productivity in the Chinese-Mongolian Altay (Chen et al. 2007; Saizen et al. 2010). These circumstances may aggravate according to climate change predictions for the Altay-Dzungarian region that foresee an increase in the average annual temperature, more frequent and prolonged summer droughts and temporal shifts of precipitation from summer to winter (Angerer et al. 2008; Lkhagvadorj et al. 2013a; Hilker et al. 2014; Liao et al. 2014a). Moreover, herd management such as daily herding practices and grazing duration, livestock numbers and herd composition are known to affect the occurrence, frequency, distribution and growth of grassland species and thus herbage yield and its nutritive value (Briske et al. 2003; Schönbach et al. 2012; Kreutzmann 2013a; Lkhagvadorj et al. 2013b; Hilker et al. 2014). The spatio-temporal variability in herbage yield and quality challenges grazing management decisions as both parameters are the main determinants of animal performance in transhumant livestock systems (Behnke et al. 2011). Hence, long-distance moves (temporary relocation of herds) and selective feeding strategies of individual livestock species are of importance in the quest for the best possible forage exploitation for animal growth and production (Baumont et al. 2000; Vallentine 2001; Behnke et al. 2011; Yoshihara et al. 2013; Liao et al. 2014a). In accordance with literature (Ni 2004; Angerer et al. 2008) Chinese-Mongolian pastures feature a wide range of aboveground biomass yields (30 to 20,210 kg^{-1} DM ha) depending on the ecotype and season. At the same time, high standard deviations indicate a high variability within each pasture due to varying topography and variability of rainfall. Nonetheless, the observed herbage offers were relatively low compared with studies in similar climatic contexts elsewhere (Sankey et al. 2009; Behnke et al. 2011; Sasaki et al. 2012; Tao et al. 2013), whereas the nutritive values were relatively high and constant throughout the studied years. Especially the latter observation is surprising as in Central Asia the nutritive value of natural vegetation varies strongly with season and has been reported to be particularly low during winter and early spring (Yoshihara et al. 2008; Glindemann et al. 2009; Olson et al. 2010; Sasaki et al. 2012; Schönbach et al. 2012; Müller et al. 2014; Bösing et al. 2014; Ding et al. 2014; Ma et al. 2014).

It may therefore be concluded that the herd mobility patterns observed in the Altay-Dzungarian region balanced for the seasonal variability in herbage quality (Yoshihara et al. 2013). With values of approximately 0.05 to 2.5 kg DM of aboveground herbaceous biomass per kg live weight and day the herbage allowance in the study region was at the lower end of values reported for pastures in Inner Mongolia (0.7 to 26.4 kg DM per kg live weight; (Schönbach et al. 2012; Bösing et al. 2014). According to Lin et al. (2011) who categorized herbage allowances (kg DM kg^{-1} live weight), the values obtained in our study correspond to the classes 'heavy grazing' and 'very heavy grazing' during all seasons.

In the present study interactions between stocking density and stocking rate on one hand and herbage yield on the other were observed, especially at the Mongolian sites. Other studies pointed to a reduction of above ground biomass yield at stocking densities >0.4 sheep ha^{-1} in Mongolian grasslands (Chen et al. 2007; Sugita et al. 2007). Most stocking densities on the studied pastures exceeded 0.4 SU ha^{-1} and thus indicated a high grazing pressure. Additionally, grazing duration which is a decisive factor for rangeland productivity (Glindemann et al. 2009; Ma et al. 2014), was negatively (China) and positively (Mongolia) correlated with herbage allowance. These contradictory tendencies may be explained by strict regulations in China that forced herders to stay at pastures with relatively low herbage allowance (Banks et al. 2003), whereas Mongolian herders could flexibly adapt the length of their stay depending on the circumstances (Fernández-Giménez and Le Febre 2006).

Although cattle and small ruminant herds mostly grazed on spatially different rangelands in the study region, no significant differences in herbage offer and quality were observed on the sites visited by the two livestock groups, with the exception of the winter pastures. Besides environmental characteristics of a pasture such as slope, exposition, stone cover and density of woody vegetation, factors such as land use rights are likely to prevail over species-specific diet preferences (Ganskopp and Bohnert 2009), together with high stocking rates and absence of active herding, leading to broad dietary overlap (Vallentine 2001; Yoshihara et al. 2009). However, as herbage allowance was negatively correlated with the size of the area visited per day and the daily walked distance (in particular for cattle), it can be assumed that grazing cattle were hampered by topographical features (Ganskopp and Bohnert 2009) and animals therefore walked further distances per day, which inevitably increased their theoretical utilized pasture area, but not necessarily the herbage allowance. This relationship seemed to be more pronounced on the Mongolian side which may be explained by an increased competition between livestock species for the same fodder resources (Vallentine 2001).

Climatic conditions vary with latitude and altitude resulting in different ecological zones, that is desert and mountain steppe and alpine meadows, in the Altay-Dzungarian region. Increasing latitude and altitude usually correspond with an increased biomass production, but not necessarily with a higher nutritional quality of the pastures (Fernández-Giménez and Allen-Diaz 2001; Zemmrich et al. 2010). The spring pastures at the fringes of desert and mountain steppes are of particular importance for the herds' reproduction (Kerven 2003). In accordance with literature (Fryxell 1991; Yoshihara et al. 2008; Fujita and Amartuvshin 2013), the highest CP and P concentrations were determined on the spring pastures in newly sprouting protein-rich forbs and shrubs of the genera Stipa, Caragana and Achnatherum. At the summer pasture high herbage yields and nutritive values allow the fattening of livestock and the maintenance of milk production (used for processing cheese and butter for the winter; Behnke et al. 2011). The summer pastures at the alpine belt are characterized by a delayed snow melt which retards vegetation growth and therefore prolongs the availability of young vegetation, similar in quality to the spring pastures (Bauer et al. 2011). In addition, the Umbrisols prevailing at the summer pastures in both countries are relatively rich in organic carbon and nutrients, favoring high herbage yields and high CP concentrations (Fernández-Giménez and Allen-Diaz 2001; Schönbach et al. 2012), which was particularly true for the Chinese summer pasture. Marked herbage offer differences were observed between the Chinese and Mongolian summer pasture. Compared to the Mongolian summer pasture, higher water availability due to higher amounts of snow melt water and spring precipitation were likely to foster plant growth on the Chinese summer pasture during the late spring, the period immediately preceding summer pasture utilization. For 2013 and 2014, the average cumulated precipitation before summer pasture utilization amounted to 71 mm in China and 32 mm in Mongolia (Figure 1). These data imply that the Mongolian summer pasture suffered from low soil moisture contents in the late spring/early summer season; in addition, very low average daily air temperatures before the utilization period was of -11°C in Mongolia as compared with only -2°C in China (Figure 1) was delaying vegetation growth (Yiruhan et al. 2014). Additionally, strict regulations at the Chinese summer pasture (that is limited animal numbers and restricted access to the pastures until the end of the main flowering period) may have favored herbage production. Despite the high herbage offers, herbage allowances were lowest on the summer pastures as a result of the relatively high density of herds during summer, leading to high stocking rates. The herbage quality at the summer pastures was relatively high primarily due to the occurrence of *Allium* sp. and *Polygonum alpinum* at the Chinese site and *Artemisia* sp. at the Mongolian site. At the Mongolian summer pasture, the high occurrence of grazing weeds (such as *Carex duriuscula*) indicated a strong anthropo-zoogenic influence as a result of intense pastoral utilization (Fernández-Giménez and Allen-Diaz 1999, 2001; Fujita and Amartuvshin 2013). The data from the Mongolian summer pasture revealed that both quality and quantity of herbage were not sufficient to adequately fatten livestock and help them recover from live weight losses experienced during winter. This highlights the importance of the Mongolian autumn pasture for livestock production and health.

During autumn high quality fodder is needed to boost the nutritional status of herds before breeding and to build up sufficient fat reserves for the winter (Behnke et al. 2011; Yoshihara et al. 2013). The herbage offer of the autumn pastures was relatively high, but the high concentration of structural carbohydrates and relative low concentration of crude protein of the then dry standing biomass (especially *Achnatherum splendens*) may have reduced herbage digestibility (Fryxell 1991; Yoshihara et al. 2008). Compared with the Mongolian autumn pasture, lower herbage offer and quality were observed on the Chinese mountain steppes grazed in autumn. In Mongolia the autumn pasture was located in the flood plains of the Bulgan River which are characterized by a favorable water availability allowing for high herbage yields and ensuring high herbage availability throughout the year (Zemmrich et al. 2010). In China flood plain areas were mainly used for irrigated crop and hay production or were inaccessible to livestock due to urbanization and political regulation which was also reported by (Squires et al. 2009; Dittrich et al. 2010). Consequently, during autumn and winter, Chinese livestock had to shift to less productive pasture sites outside the fertile floodplains that are the mountain and desert steppes.

The late winter and early spring pastures are known as bottlenecks to animal nutrition since livestock then has to rely on the mature standing biomass which may be partly snow-covered (Fryxell 1991; Wehrden and Wesche 2007; Yoshihara et al. 2008). During the winter months, small ruminants accessed low-altitude areas in the desert steppe (ranging from 1194 m to 1366 m in China and 1528 m and 1938 m in Mongolia) which are normally less subjected to dense snow cover. The relative high nutritional quality of herbage at the winter pasture may be attributed to the occurrence of nutritious plants (especially *Anabasis brevifolia*), particularly in Mongolia (Vetter 2005). However, due to infrastructure limitations herbage was sampled already in September in the present study, and a decline of herbage quality until the arrival of the herds in December cannot be ruled out (Olson et al. 2010; Ding et al. 2014). In addition the observed wide Ca:P ratios in winter pasture herbage may favor P deficiency and in the longer term can lead to infertility, non-infectious abortions, anemia and bone abnormalities (van Soest 1994; Olson et al. 2010; Yoshihara et al. 2013). In contrast to small ruminants, cattle remained in the vicinity of villages (China) and on the autumn pastures (Mongolia) during the winter. During this period, the herders provided supplementary feed such as hay, cereals and crop residues, mainly to cattle, which is also reported from Central Asia and North-Eastern Asia (Kerven et al. 2004; Kreutzmann 2013b, 2013a). Moreover, on the Chinese side, cattle were partly fenced on agricultural land that in summer was irrigated and on which only a few crop residues, if any, remained. This may explain the relatively low herbage allowance and lower nutritive value of herbage compared with Mongolia. Furthermore, it can be assumed that cattle herds staying in the vicinity of villages locally foster rangeland degradation due to high stocking rates on both sites of the border (Lise et al. 2006; Addison et al. 2012; Bruegger et al. 2014).

To address our initial hypothesis, it can be stated that for cattle differences in the Chinese and Mongolian transhumance system were observed, whereas for small ruminants results from both sides of the border were similar despite the different socio-political and socio-economic framework conditions. Whereas for herbage quality no substantial divergence was observed between both countries, herbage offers clearly differed on the summer pastures. Since number of utilized pastures was higher and theoretical utilized pasture area was larger in China, herds in general spent less time on a specific pasture. In consequence, the herbage allowance on all seasonal pastures was higher in China compared with Mongolia, except for the spring pasture of small ruminants.

3.5 Conclusions

In the Altay-Dzungarian region, a highly mobile and flexible transhumance strategy is of major importance for pastoral herds to cope with the seasonal and spatial variability in quality and quantity of pasture vegetation. Regulation of animal numbers, a larger number of utilized pastures and the control of prescribed dates of transhumance movements (especially of small ruminants) to the summer and autumn pasture seem to maintain herbage yield and quality in China. Nevertheless, changes of the transhumance routes of small ruminants (triggered by expansion of irrigated agricultural land and mining activities) may hamper these positive regulation effects. On the other hand, these restrictions are likely to prevent flexible reaction of herders to the high inter- and intra-annual variation of precipitation and sudden adverse weather conditions. In Mongolia, however, high stocking densities (particularly due to a high number of goats), a diminished frequency of pasture changes (especially at the spring and winter pasture which are characterized by low precipitation) and grazing of the summer pasture before flowering of herbaceous plants seem to decrease the herbage offer. The introduction of access dates and the reduction of stocking densities and/or the duration of herds' sojourn in particular areas may be promising to improve herbage offer and sustain animal production.

On both sides of the border the introduction of active daily herding strategies may be promising to optimize the exploitation of the entire rangeland and consequently reduce high stocking rates. Nevertheless, to maintain large-scale mobility as a core feature of the transhumance system in the Altay-Dzungarian region, amenities should be provided to herders even at remote pasture locations, such as mobile shops and medical services, public transport between the pastures and regular visits of livestock and milk-product, wool and livestock traders as it is partly done in China.

In years with average to good precipitation, active herding and fine-tuned pasture management can sustain herbage yield and quality and thus enhance animal performance at a longer term. To justify the increased work load and economic cost of active herding, the development of niche markets for clean, green and maybe even organic products in urban demand centers of China and Mongolia is an important prerequisite.

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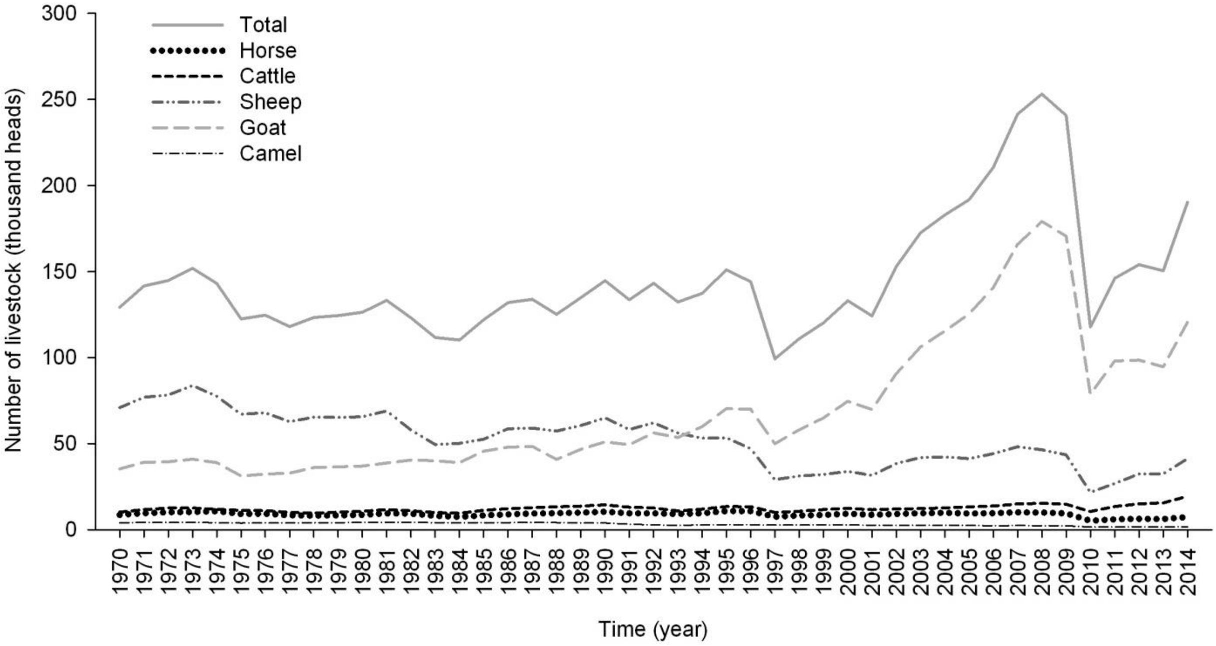
3.7 Appendix



Appendix 1. Changes in the number of total livestock, horses, cattle, sheep, goats and camels (thousand heads) in Bulgan *sum*, Mongolia, from 1970 to 2014 (data source: Livestock account, National Statistical Office of Mongolia).

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4. Chapter

Water use in agro-pastoral livelihood systems within the Bulgan River watershed of the Altay Mountains, Western Mongolia

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Abstract

Watersheds in the arid and semi-arid regions of Mongolia are especially vulnerable to the effects of climate and land cover changes, which will likely exacerbate the disparity between water availability and demand. This study was conducted to describe land cover changes between 1972 and 2013 and to characterize the currently prevailing livelihood strategies and farming practices in the river oasis Bulgan *sum*, Western Mongolia. The Soil and Water Assessment Tool (SWAT) was used to simulate the water-use efficiency for the concerned Bulgan River watershed.

The comparison of the two land cover maps (1972 and 2013) of the Bulgan *sum* river oasis showed an apparent change from natural rangeland to mostly built-up areas (+288%) and river water receiving sites (+594%). In 2013 the prevailing livelihood strategies in Bulgan *sum* were: (i) sedentary households (HHs) practicing field cropping and keeping livestock, both for subsistence needs, (ii) HHs keeping livestock for subsistence needs and practicing semi-commercial field cropping and (iii) HHs keeping livestock for commercial needs and hiring labour for semi-commercial hay production. The Bulgan River watershed covered an area of 7409 km^2 and the Bulgan River featured a long-term annual average discharge of 9.53 m^3 s^{-1}. Overall, an area of 769 ha was under irrigation from the Bulgan River. A total withdrawal of 555,461 m^3 irrigation water was estimated, 86% of which was applied to hay fields. Water application ranged from 657 (hay) to 2762 (vegetable) m^3 ha^{-1} $year^{-1}$ leading to an irrigation water productivity ranging from 1.64 (cereals) to 0.18 (melons) m^3 kg^{-1} fresh matter yield and an average income per unit applied water of 2.94 Euro per m^3. The SWAT model simulated an average evapotranspiration of 100 mm and potential evapotranspiration of 993 mm per year. The water-use efficiency ranged from 11 to 52 kg ha^{-1} mm^{-1} for rangeland and wetland. Auto-irrigation and fertilization management simulated by the SWAT model increased yields (of irrigated crops, vegetable, hay and fruit trees) by about 46 and 77% on average. To enhance biomass productivity per unit water transpired and the income per unit applied water, improved irrigation technologies and management practices are needed.

4.1 Introduction

Watersheds in the arid and semi-arid regions of Mongolia are especially vulnerable to the effects of climate and land cover changes, which will likely exacerbate the disparity between water availability and demand in the near future (Lioubimtseva and Henebry 2009; Malsy et al. 2012; Pederson et al. 2013; Malsy et al. 2015). Hence, water scarcity is an increasing threat in the Bulgan River watershed of Western Mongolia. In other parts of Mongolia, a rise in water demand as a result of mining activities, intensification of agriculture production, increasing sedentarism and urbanization following socio-economic change and rapid economic expansion has been observed (Grit et al. 2015; Priess et al. 2015; Hartwig et al. 2016; Hofmann et al. 2016). In addition, higher temperatures resulting in rising evapotranspiration (ET) and slightly higher quantities of potential evapotranspiration (PET) and an overall increase in precipitation (P) variability are decreasing water availability (Batima et al. 2005; IPCC 2007; Menzel et al. 2011; Malsy et al. 2012; Grit et al. 2015; Hofmann et al. 2015; Priess et al. 2015; Hartwig et al. 2016; Hofmann et al. 2016). Traditionally, land use in Western Mongolia was dominated by a well-adapted animal husbandry system characterized by a high degree of mobility and flexibility, while field based agriculture played only a relatively minor role (Lkhagvadorj et al. 2013a; Lkhagvadorj et al. 2013b; Jordan et al. 2016). However, recent national policies target the intensification of agricultural land use with the aim of achieving food self-sufficiency and enhancing hay and fodder production to lower livestock mortality during harsh winters (Regdel et al. 2012; Pederson et al. 2013). Irrigated crop and fodder production is already a major consumer of surface water (alongside the watering of animals) in the Altay Mountains (Rockstrom et al. 2007; Pederson et al. 2013). Against this background, water distribution among water consumers in the watershed will be of increasing importance and the more efficient use of available water is a promising option to reduce potential conflicts.

Beside the short growing season, the harsh continental climate and limited economic access to agro-chemicals, fertilizer, quality seeds, irrigation equipment and agricultural machinery, the cropping sector in the study region is particularly restricted by temporarily limited water availability and high PET (defined as the amount of water that could be evaporated and transpired if soil water was unlimited, Priess et al. 2011; Hofmann et al. 2016). Evapotranspiration (including canopy interception, crop transpiration and soil evaporation) is a key component of the hydrological cycle and of the effective use of agricultural water, it is therefore closely linked to (agro)ecosystem productivity (Liu et al. 2013; Liu et al. 2015). In semi-arid regions, more than 70% of rainfall evaporates from land surfaces into the atmosphere, while the remaining proportion recharges groundwater and rivers (Wimmer et al. 2009; Menzel et al. 2011; Priess et al. 2011; Hülsmann et al. 2015). Consequently, to efficiently manage scarce water resources in water-limited environments, adequate estimates of ET are of major importance (Rockstrom et al. 2007; Lal and Stewart 2012). The 'Soil and Water Assessment Tool' (SWAT) model is a physically-based semi-distributed model which has been widely used in numerous watersheds around the globe to describe the use of water resources (Arnold and Fohrer 2005; Schuol et al. 2008; Hülsmann et al. 2015). Its particular strength is the integration of plant growth and agricultural management and it predicts reasonable ET values under a wide range of agro-climatic conditions (Earls and Dixon 2008; Liu et al. 2015).

The above mentioned situation in the Bulgan River catchment calls for a detailed understanding of local hydrological processes and water use in the catchment, which is of particular interest as the Bulgan River is a cross-border water resource shared between Mongolia and China (Xia et al. 2016). Therefore, the objectives of this study were (i) to describe land cover changes between 1972 and 2013, (ii) to characterize the current prevailing livelihood strategies and farming practices (such as management, irrigation systems and water use) in the river oasis Bulgan *sum*, Western Mongolia and (iii) to simulate water-use efficiency (WUE: aboveground biomass divided by ET) for different land cover classes with the SWAT in the Bulgan River watershed. The overall aim of this study was to evaluate the current farming practices with a special focus on irrigation management with the goal of supporting decision makers in developing more resilient and productive farming systems under changing socio-economic and climatic conditions in this arid/semi-arid watershed.

4.2 Materials and Methods

4.2.1 Study region

The field of research was the watershed of Bulgan River up to the outlet at Bulgan *sum* center, the administrative capital of the Bulgan district in the Khovd province, located in the foothills of the Western Mongolian Altay Mountains and the Dzungarian Desert (45-47°N, 89-91°E, Figure 1).

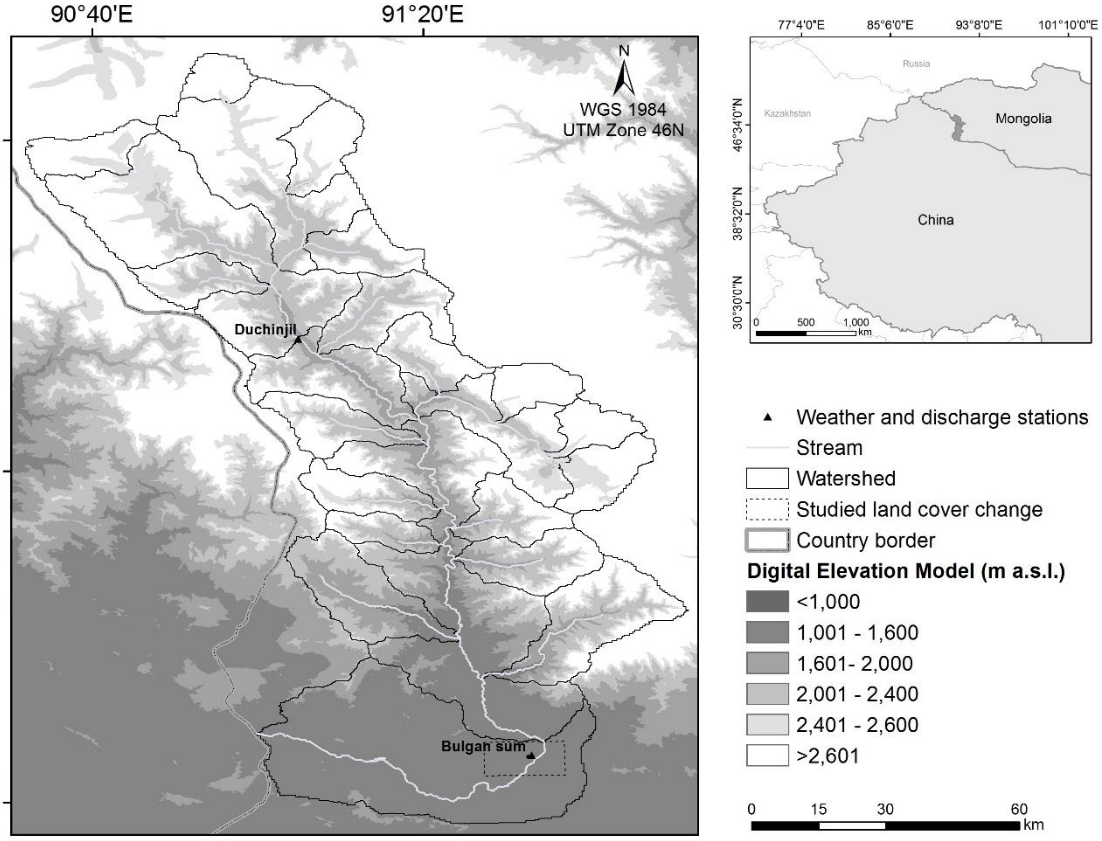

Figure 1. Study area within Mongolia (right) and the Bulgan River watershed outline, sub-basins and digital elevation model (left).

The Bulgan district covers a total land area of 8 105 km^2 and in 2012 had a human population of 9 018 and 154 058 domestic animals (2012, National Statistical Office of Khovd). For Bulgan *sum* (WMO code 44265, 1963-2014, 1186 m a.s.l.) and Duchinjill (WMO code 44263, 1977-2011, 1951 m a.s.l.), minimum average monthly air temperatures of -21 and -35°C, respectively, were recorded in January, while maximum temperatures of 21 and 24°C were reached in July, accompanied by an average annual P of 75 and 128 mm (coefficient of variation of 45/26%), respectively. The Bulgan River originates on the southern slopes of the Mongolian Altay and flows southwards entering the river oasis of Bulgan *sum* center crossing the Chinese border. It finally discharges into the Ulungur Lake in China (Zukosky 2008). Since rangeland covers a large part of the watershed, Kastonozems and Umbrisols predominate, whereas the soils in the floodplain are classified as Fluvisols and Cryosol (Karthe et al. 2016). Given the harsh continental climate, livelihoods depend largely on water drawn from the Bulgan River and groundwater wells allowing small-scale cultivation of crops, hay and fruits. The animal husbandry systems in the region can be described as classical mountain transhumance systems with seasonally migrating herds (mainly consisting of goats, sheep, cattle, in addition to horses and camels) or by settled herders who mainly own cattle, sheep and goats (namely fat-tail sheep, cashmere goats and Turano-Mongolian cattle, Jordan et al. 2016; Tsevegmed 2016).

4.2.2 Land cover change

Representative validation sites (n= 329) were recorded by means of a GPS device (Trimble Juno SB Handheld, Trimble Navigation Ltd., Sunnyvale, CA, USA) during field surveys from May to September 2013. The areas of irrigated plots were mapped in their entirety, owing to their small physical size but potentially large socio-economic importance. Subsequently, changes in land cover between 1972 and 2013 were analysed on the basis of two land cover maps derived from high-resolution satellite images taken by Corona (30-04-1972) and Pléiades (pansharpended Pléiades satellite images, 50 cm resolution, date: 12-08-2013, Astrium, Toulouse Cedex, France). The panchromatic Corona (KH-4B) satellite image was obtained from the U.S. Geological Survey's Earth Resources Observation and Science and had a maximum resolution of 1.8 m at nadir (Dashora et al. 2007). The image was georeferenced using readily recognizable features as ground control points, which were verified based on georeferenced satellite images. Land cover maps were generated on the basis of an independent supervised classification using the 'Sequential Maximum A Posteriori Classifier' in Quantum GIS (QGIS version 2.12.0, Quantum GIS Development Team, 2010; Geographic Information System, Open Source Geospatial Foundation Project) with the GRASS plugin (Version 6.4.4; GRASS Development Team, 2010). Similar reflectance resulted in misclassification of mountainous areas and urban areas which had to be reclassified by visual identification and mapped manually (Lillesand et al. 2014). The small size of irrigated fields hampered their automatic detection. Additionally, irrigated fields, areas where hay was grown, rangelands receiving water from the river and natural meadows showed similar spectral characteristics and were therefore combined as 'river water receiving sites'. In addition, the following classes were identified: 'urban area' (single houses, settlements, and industrial facilities), 'water' (bodies of open water such as rivers, streams and irrigation canals), 'rangeland' (grassland, bushes, areas with low vegetation cover, mainly dominated by *Krascheninnikovia ceratoides*, *Ephedra przewalskii*. *Stipa caucasica* and *Plantago major* communities), 'shrubland and woodland' (mainly *Salix turanica, Caragana leucophloea,* *Populus laurifolia* and *Hippophae rhamnoides* stands), 'sandy soil' (non-vegetated areas such as bare soil, sand dunes and river banks) and 'mountains' (rock outcrops within and outside the oasis). Based on this preliminary work, a detailed land cover and land use map was processed for 2013, including supplementary classes of 'irrigated crop land' (cereal, potato, melon and various vegetables), 'hay' (irrigated fenced rangeland) and 'fruit trees' (apple and plum) and 'sea buckthorn' (*H. rhamnoides*). The land cover maps produced were validated by ground truth observations with 100 accuracy points for each map, selected by the equalized stratified randomized selection method of ArcGIS® (Version 10.4.1, Environmental System Research Institute, Redlands, CA). Subsequently, a confusion matrix was computed including the overall classification accuracy, user and producer accuracies and kappa statistics.

4.2.3 Household survey

Within the inhabited river oases of Bulgan *sum*, a total of 98 agro-pastoral households (HHs) were sampled by a GIS-based, non-stratified randomized point selection procedure. If one of the randomized points was not located in the area of an agricultural field, the nearest HH within a radius of 30 m was selected. From July to August 2012, HH heads were interviewed by means of a semi-structured standardized questionnaire regarding HH characteristics (ethnicity, sex and age of family members, educational level), key traditional HH assets (car, motorcycle, tractor, bicycle, television, solar panel, snuff bottle, hunting gun, sewing machine, grass mower, plough), areas on which crops, vegetables and hay were cultivated, agricultural management (application of fertilizers, pesticides, and/or irrigation and use of agricultural produce), livestock characteristics (herd size, livestock species) and animal husbandry system (transhumance pattern, animal fodder and use of livestock products). Following the 'Categorical Principal Components Analysis' approach, a subset of relevant HH characteristics was summarized by removing variables with component loadings higher than 0.5 in either of the two principal dimensions (Appendix 1 and 2). The cluster goodness was evaluated following the methods described by Dossa et al. (2011). HHs selling any cultivated produce were considered to be market-oriented while subsistence-oriented HHs were those that sold no portion of the harvest.

4.2.4 Irrigation management

Irrigation events per season (n), flood irrigation duration (min), flow cross section (m^2), velocity ($m\ s^{-1}$), discharge ($m^3\ s^{-1}$) and the conditions of the irrigation canal network were recorded by the above mentioned semi-structured questionnaires, participatory farmer meetings and field surveys (n= 83). Additionally, the irrigation canal network was mapped by means of a Trimble GPS device (Trimble Juno SB Handheld, Trimble Navigation Ltd., Sunnyvale, CA, USA). Subsequently, the irrigation network data were transferred into a GIS and the missing main canal sections were supplemented based on the geo-referenced Pléiades image. Additionally, the general condition of the irrigation canals were classified according to the following classes good, medium and poor. Velocity measurements were taken over a period of 40 seconds using a FlowTracker® Handheld with a 2D side-looking acoustic doppler velocimetry probe (SonTek, YSI Environmental Company Smart QC, San Diego, CA, USA) at 63 points in the canal network. The mid-section discharge equation method (ISO standards 748 1997 and 9196 1992) was used with the velocity settings 0.6 for irrigation canals with a depth lower than 0.3 m and a setting of 0.2/0.8 for canals deeper than 0.3 m. Based on this data, the application rate (m^3 ha^{-1} $year^{-1}$) and productivity (m^3 kg^{-1} fresh matter, FM yield) of irrigation water was calculated. For the latter, the following yield data obtained from field measurements, governmental data and HH surveys were used: cereals 1.15 t FM ha^{-1}, potato 7.04 t FM ha^{-1}, vegetable 8.37 t FM ha^{-1}, sea buckthorn (*H. rhamnoides*) 3.40 t FM ha^{-1}, fruits 14.03 t FM ha^{-1}, products of fruit trees 2.27 t FM ha^{-1} and hay 4.12 t FM ha^{-1}.

4.2.5 Soil and Water Assessment Tool (SWAT)

The continuous, physically based, semi-distributed hydrologic SWAT model developed by the USDA Agricultural Research Service was used in this study *(*Arnold and Fohrer 2005). All data entering the SWAT were compiled with ArcGIS® (Version 10.3) and ArcSWAT (Version 2012.10_3.18, Stone Environmental, Inc. Montpelier, VT, USA). Topographic data were obtained from a Digital Elevation Model (hole-filled seamless SRTM data V3, International Centre for Tropical Agriculture, Jarvis et al. 2008). A detailed land cover map for the study region was created on the basis of satellite image classification and ground truth observations (Oyundari et al. 2016). This land cover map was reclassified and adjusted to the SWAT land cover classification format. The following land cover classes were defined: rangeland (brush), rangeland (grasses), summer pasture, open forest, wetland (mixed), agricultural land generic, hay, orchards and rural residential (low density). Soil data (bulk density, electrical conductivity, pH, contents of calcium carbonate, organic carbon, clay, silt, sand, and rock fragments, and water holding capacity) of the study region were entered into the model according to the land cover class (n= 393, Goenster-Jordan et al. 2016; Jordan et al. 2015; Oyundari et al. 2016). Data on the soil hydrologic group, the available water capacity and the saturated hydraulic conductivity were not available and were therefore calculated using the Soil Plant Atmosphere Water Field and Pond Hydrology Model (Frevert and Singh 2005). Daily meteorological records of P, maximum and minimum temperatures, relative humidity and mean wind velocity for the period from 1977 to 2011 were obtained from two official meteorological stations: Baitag (Bulgan *sum* center) and Duchinjil (alpine belt). A statistical tool (Excel macro WGNmaker4.xlsm, Neitsch et al. 2005) was used to fill meteorological data gaps. Long-term solar radiation records were obtained from the SWAT website (http://swat.tamu.edu/). The ET (including canopy interception, crop transpiration and soil evaporation) and PET was calculated following the Penman-Monteith method (Allen et al. 1989). The SWAT model estimates ET on the basis of PET. PET is defined as the amount of water that could be evaporated and transpired if soil water was unlimited (potential soil water evaporation is simulated as a function of PET and leaf area index). The soil evaporation is predicted using exponential functions of soil depth and water content. Plant transpiration is estimated as a linear function of PET, leaf area index and root depth and can be limited by soil water content (Arnold and Fohrer 2005; Neitsch et al. 2005). Model input data on farmers' management (such as planting dates, fertilization, irrigation and harvest) and herders' management (such as yearly grazing duration of livestock, biomass consumed per day, manure deposits) were obtained from Jordan et al. (2016) and Tsevegmed (2016). Based on land cover types, soil characteristics and slope classes (0-10%, >10-20%, >20%), the watershed was manually subdivided into 23 sub-basins. Subsequently, thresholds of 20%/10%/20% (land cover/soil/slope) were set to divide the sub-basins into 317 Hydrological Response Units (HRUs, 'smallest unit of computation' treated as uniform in terms of hydrological processes) for which hydrological processes were computed. The simulated above-ground biomass at the peak of biomass production (July, kg dry matter ha^{-1}) was divided by the growing seasonal ET (April to July, mm) to quantify the WUE (kg ha^{-1} mm^{-1}) for each HRU. For this purpose, the period 2001-2009 (including three years of model warm-up) was chosen.

Two gauging stations of the Bulgan River (Bulgan: 46.09°N, 91.55°E, 1186 m a.s.l.; Baitag: 46.93°N, 91.08°E, 1951 m a.s.l.) with daily long term discharge records (1983-2013) were used for model calibration and validation. Model efficiency was evaluated using the Nash-Sutcliffe Efficiency (NSE), the Percent Bias (PBIAS) and the coefficient of determination (Pearson correlation, r^2). The most sensitive model parameters (SCS runoff curve number: CN2, soil evaporation compensation factor: ESCO, saturated hydraulic conductivity: SOL_K, biomass-energy ratio: BIO_E) were chosen for model calibration. Due to the lack of detailed watershed-scale measured data, a combination of measured and estimated values of average multi-year biomass data assessed in the study region (t ha^{-1}) were used for calibration and validation as suggested by Ávila-Carrasco et al. (2012).

Furthermore, the SWAT model was used to model (i) auto-irrigation (auto-irrigation was triggered by a water stress threshold of 0.9; whenever plant growth drops below this threshold, the model will automatically apply water until field capacity is reached) and (ii) auto-irrigation and fertilization (auto-irrigation and the application of goat manure if the model determines nitrogen stress, the model automatically apply goat manure; Arnold and Fohrer 2005; Neitsch et al. 2005).

4.3 Results

4.3.1 Land cover change

The comparison of the two analyzed satellite images of the Bulgan *sum* river oasis showed an apparent change from natural rangeland to mostly built-up areas and river water receiving sites over the 40-year period from 1972 to 2013. In 1972 the dominant land cover class was rangeland (62% of the total area), which decreased to 33% in 2013 (Figure 2). In addition, shrub and woodland decreased by 53% during this period and covered a total area of 4.23 km^2 in 2013. Although the area identified as sandy soil is small, its four-fold increase from 1972 to 2013 was remarkable (Figure 2). Urban areas also expanded four-fold during the study period, from 0.72 km^2 in 1972 to 2.79 km^2 in 2013, while river water receiving sites increased by a factor of six, resulting in a total area of 28.86 km^2 in 2013. The Kappa values of the classified images were 0.81 for 1972 and 0.80 for 2013. For both images, the user's and producer's accuracies of individual classes ranged between 0.75 and 0.94 (1972) and 0.79 and 1 (2013). During field surveys (2013), an irrigated area of 7.69 km^2 was identified, dominated by hay, fruit trees and sea buckthorn, accounting for about 27% of the densely vegetated area

(Table 2, Figure 2, 2013b). Cereals, vegetable and melons were cultivated on total area of 0.09 km^2 (Table 2).

4.3.2 Household survey

The respondents of the HH survey in Bulgan *sum* center were mainly male (88%) with an age ranging from 24 to 84 years. Most of the interviewed HHs belonged to the ethnicity of Torghud (81%) and Kazakh (15%). Most respondents had attended high school (41%) and only 1% was illiterate. The average family size of the 98 HHs was five individuals (SD: 1.68) including 2.13 (SD: 1.22) children, on average.

In the river oasis, 80% of HHs had settled permanently, while 19% were transhumant pastoralists. The majority of HHs combined crop cultivation and hay making with livestock husbandry (70%), whereas only 8% cropped fields exclusively. Almost all HHs owned livestock (91%), comprising 77 small ruminants (goats and sheep, with goats dominating: 69%), 14 cattle and 5 status animals (horse and camel) on average (Figure 3). The livestock (mainly small ruminants) was predominately (79% of all HHs) entrusted for herding to transhumance herders against payment of a fee. For herding these HHs paid 0.37 (SD: 0.15) and 0.47 (SD: 0.26) Euro animal^{-1} month^{-1} during summer and winter, respectively. However, during summer 28% of the HHs paid the fee in form of non-monetary goods (hay and food) while during winter, the fee was predominantly paid in cash. On average, 0.29 ha (SD: 0.49) crop and fruit tree land and 3.96 ha (SD: 6.56) hay land was cultivated per HH. 72% of the cultivated was in the immediate vicinity of the homestead and additional fenced areas were irrigated for hay production. Parts of the unfenced rangeland around the settlement were also used for hay production. Most crop producing HHs (52%) were market-oriented (products were sold at the local market in the village center). The cropping area of subsistence-oriented HHs was significantly smaller than that of market-oriented HHs (0.16 and 0.84 ha, respectively). On average 4.49 (SD: 2.22) crop species were grown; mainly potato, carrot and cabbage (supplemented by wheat and rye, melons and turnips), whereas all but one HHs produced hay. Only 20% of the HHs cultivated sea buckthorn, while 20% cultivated fruit trees. Crop production was characterized as low input farming system as only 52% of the interviewed HHs used fertilizers (mainly goat manure) and only 13% used pesticides. Nevertheless, about 42% of the respondents claimed to have fertile soils and only 20% of the HHs mentioned occurrence of salinization.

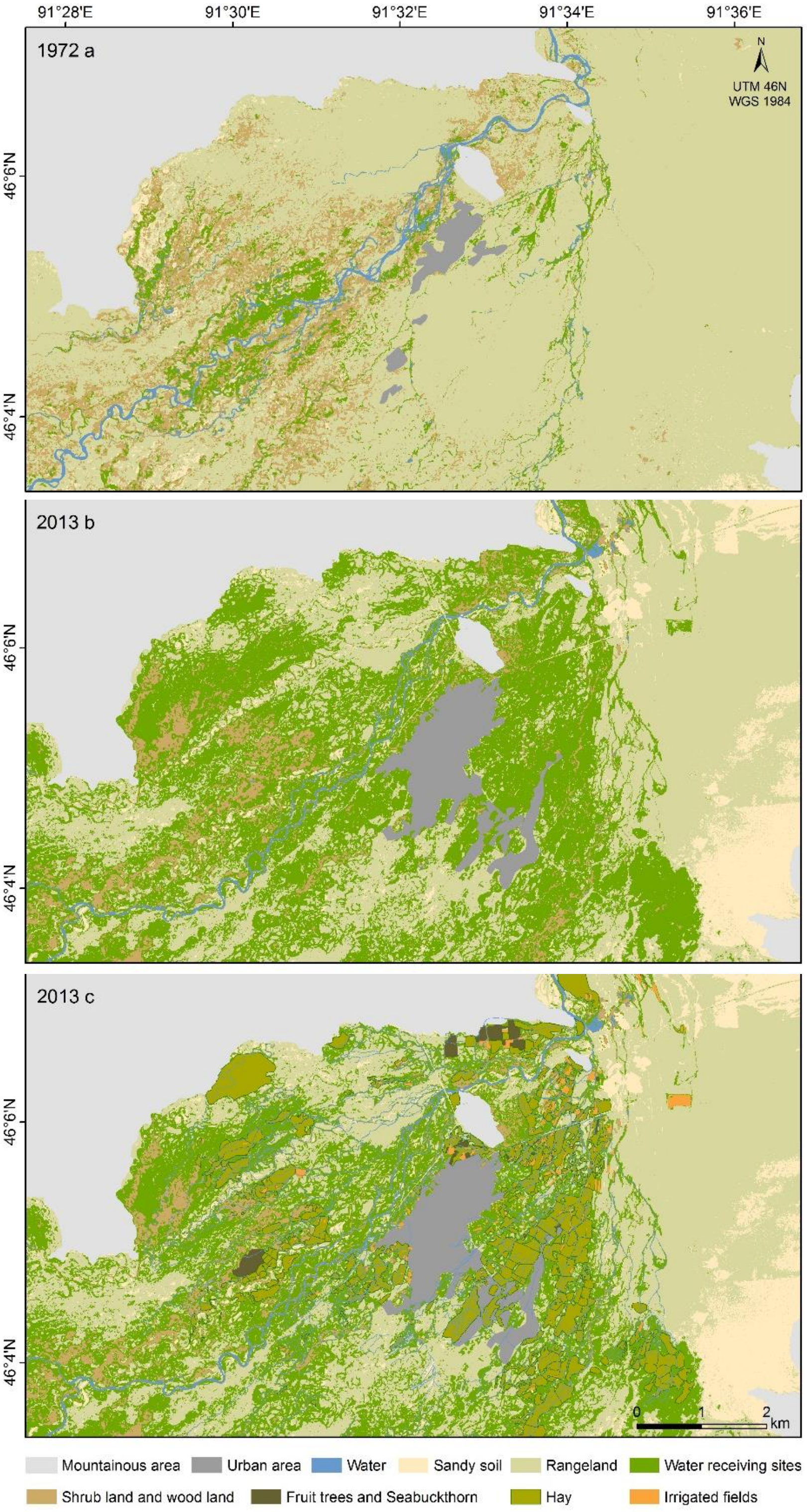

Figure 2. Land cover according to the satellite image classification from 1972 (a) and 2013 (b) and a detailed land cover and land use classification (2013 c) for the river oasis Bulgan *sum*, Mongolia.

None of the cropping HHs had contact with governmental or non-governmental agricultural extension services. The farm gate price margin per kg FM varied between 0.43 (SD: 0.20) for cabbage and 2.48 (SD: 0.00) Euro for fruit tree products. Average revenue was 0.43 (SD: 0.69) Euro per kg FM ranging from 0.04 for cabbage to 1.19 Euro kg^{-1} FM for fruit tree products (Appendix 3).

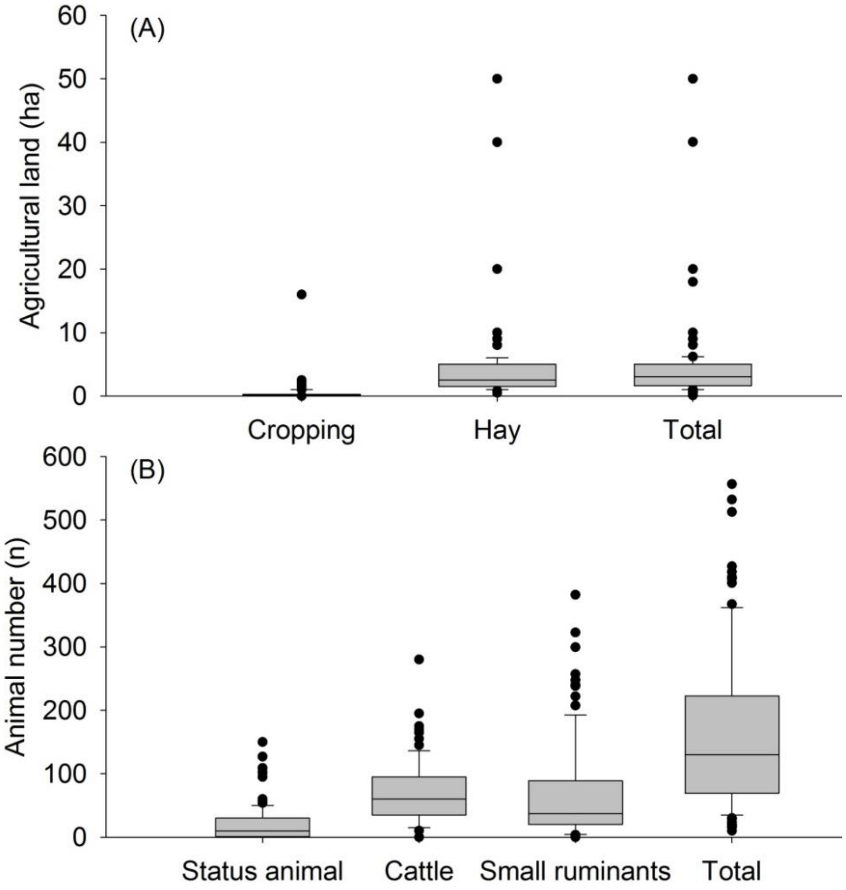

Figure 3. Cropping, hay and total agricultural land (A) and status animal (include horses and camels), cattle, small ruminants and total animal number (B) in Bulgan *sum* center, Mongolia, 2012. Medians (black lines inside the boxes), interquartile ranges (width of the boxes representing the middle 50% of data), total data ranges (whiskers), and outliers (black dots) are shown.

Three different livelihood clusters were identified: (i) sedentary HHs practicing field cropping and keeping livestock, both for subsistence needs (subsistence field cropping and livestock keeping: sCL, 46%), (ii) HHs keeping livestock for subsistence needs and practicing semi-commercial field cropping (subsistence livestock keeping and semi-commercial field cropping: LscC, 41%) and (iii) HHs keeping livestock for commercial needs and hiring labour for semi-commercial hay production (commercial livestock keeping and semi-commercial hay production cLscH, 13%, Table 1).

The sCL cluster was mainly dedicated to crop production (84%). Its HHs owned the lowest number of total livestock (n= 54.0, SD: 39.2) among all clusters and had the lowest number of assets per head (Table 1). This cluster was dominated by settled (91%) HHs and Kahzak (22%).

Table 1. Frequency distribution of agro-pastoral household characteristics for three distinguished livelihood clusters; (sCL: subsistence field cropping and livestock keeping, LscC: subsistence livestock keeping and semi-commercial field cropping, cLscH: commercial livestock keeping and semi-commercial hay production) Bulgan *sum* center, Mongolia, 2012 (values represents mean and percentages).

Livelihood clusters	sCL (n=45)	LscC (n=40)	cLscH (n=13)
Ethnicity (%)			
Torghut	73	87	92
Kazakh	22	8	8
Khalkha	2	3	-
Zakhchin	2	3	-
Accommodation (%)			
Ger and house	42	44	44
Ger	35	41	56
House	23	15	-
Way of living (%)			
Settled	91	75	54
Transhumance	9	25	38
Asset value (Euro)*			
Average asset per head	240	340	1041
Average asset per head including livestock	1296	1820	5331
Farm orientation (%)			
Only crop	11	8	-
Only livestock	16	28	23
Crop and livestock	73	64	77
Total livestock holding (n)			
Goat	35	57	185
Sheep	15	17	71
Cattle	12	13	25
Horse and camel	6	7	20
Agricultural land (ha)			
Crop area	0.3	1.0	0.1
Hay area	3.3	4.5	4.3

* Assets include the value of car, motorcycle, tractor, bicycle, television, solar panel, snuff bottle, hunting gun, sewing machine, mower and plough.

All monetary information was converted from the national currency (Mongolian Tugrik) into Euro, based on the average exchange rate from July to August 2012; 1 Euro = 1616 Mongolian Tugrik.

Their relatively intensive crop production was reflected by the fact that this cluster contained the highest number of HHs using fertilizers (64%) and the lowest percentage of HHs hiring external labor (55%).

The second cluster (LscC) practiced a combination of crop farming (mainly for self-consumption) and transhumance livestock husbandry. The HH head did most of the farm work, while about 25% of HHs hired helpers mainly for ploughing and haymaking. The average cropping area per HH was the largest in this cluster (Table 1) mainly due to a high proportion of fruit trees and/or sea buckthorn areas. The total mean of livestock per HH was in the middle range of all HHs (n= 76.5, SD: 56.4).

The third livelihood cluster (cLscH) with the lowest number of HHs was dominated by the Torghut ethnicity. There HHs still followed a transhumance way of life while crop production was exclusively performed by hired helpers who were employed mainly for ploughing, haymaking and crop harvest. Furthermore, this cluster had the smallest total cropping area (0.1 ha, SD: 0.1), however a relatively large share of hay land (Table 1). The highest value of assets per person was also found in cluster cLscH due to the highest total livestock number per HH (n: 298.0, SD: 85.9, Table 1).

4.3.3 Irrigation management

Apart from well water mainly water from the Bulgan River (91%) was used to irrigate agricultural areas in the river oasis. Three main earthen intakes directed river water to numerous inter-farm conveyances and distribution systems and finally into earthen field canals. Soil barriers constructed manually with shovels were used to divert water from the conveyance and distribution systems into farmers' fields. None of the irrigation canals were covered and only a fraction of canal bottoms and walls were compacted. Each family was solely responsible for flooding their plots while the maintenance of conveyance and distribution canals was the responsibility of all farmers. Each conveyance and distribution canal was shared by an average of 12.2 (SD: 13.1) families. The total irrigation canal network within the study area had a length of 330 km of which 21% were established before 1990 (Figure 2, 2013 c). The general condition of the irrigation canals was poor; 72% of the canals needed maintenance (canals classified as medium and poor condition) mainly due to dilapidated canal junctions, leakage of canal walls and high occurrence of sedimentation and vegetation within the canal. The average flow cross section and discharge varied between 0.08 m^2 (SD: 0.02) and 0.03 m^3 s^{-1} (SD: 0.02) for irrigation canals classified as poor to 0.22 m^2 (SD: 0.17) and 0.09 m^3 s^{-1} (SD: 0.11) for canals classified as good. The flow cross section of the irrigation canals was largest for hay, fruit tree and sea buckthorn (Table 2). The growing season length averaged 3.5 months (SD: 0.9) with plots being irrigated on average 15.2 (SD: 8.1) times during that period (Table 2). Melon and sea buckthorn were irrigated most frequently per season, whereas hay fields were irrigated least frequently (Table 2). The duration of each flood irrigation event (min m^{-2}) was lowest for cereals and highest for fruit tree fields (Table 2). The average water velocity was 0.4 m s^{-1} (SD: 0.2).

Most of the farmers (96%) reported that they observed a decreasing trend of available irrigation water, with the most cited reasons being an increasing level of desertification (51%), inefficient irrigation systems (35%), decreasing amount of river water (15%) and increasing mining activities (4%). The poor condition of the irrigation canal infrastructure, lack of machinery to maintain and construct canals and limited coordination of water distribution among farmers were cited as being responsible for the inefficient management of irrigation water.

Table 2. Irrigation systems characteristics including total irrigated area, plot size, length of growing season, flow cross section, duration of flood irrigation and irrigation events per season of the river oases Bulgan *sum* center, Mongolia, 2012 (standard deviations: SD).

Cultivars	Hay		Seabuckthorn		Fruit trees		Potato		Melon		Vegetables		Cereals	
Total irrigated area (ha)	716.97		25.00		17.88		3.20		2.24		1.96		1.78	
N	18		20		10		68		25		148		15	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Plot size (ha)	1.78	± 3.24	0.95	± 3.55	0.27	± 0.46	0.11	± 0.28	0.04	± 0.08	0.03	± 0.07	0.20	± 0.32
Length of growing season (month)	2.90	± 0.31	3.62	± 0.36	3.28	± 0.49	3.73	± 0.73	3.24	± 0.84	3.48	± 0.93	3.61	± 0.79
Flow cross section (m^2)	0.18	± 0.05	0.18	± 0.18	0.20	± 0.23	0.13	± 0.06	0.12	± 0.05	0.11	± 0.05	0.12	± 0.05
Duration of flood irrigation (min/m^2)	0.56	± 0.34	1.00	± 1.82	2.10	± 5.61	1.40	± 2.79	0.75	± 0.98	0.95	± 1.82	0.63	± 0.90
Irrigation events per season (n)	8.40	± 4.34	16.81	± 7.71	14.54	± 7.27	12.53	± 5.40	17.00	± 7.09	16.73	± 9.61	12.07	± 5.36

Overall, an area of 769 ha received irrigation water drawn from the Bulgan River with hay areas accounting for more than 90%. The average plot size varied between relatively small plots of 300 to 400 m^2 for vegetable and melon production and relatively large plots, up to 17 800 m^2, for hay and sea buckthorn production (Table 2). A total withdrawal of 555,460 m^3 irrigation water was estimated for the vegetation period, 86% of which was applied to hay fields. The application of irrigation water ranged from 657 (hay) to 2762 (vegetable) m^3 ha^{-1} $year^{-1}$, leading to an irrigation water productivity ranging from 1.64 (cereals) to 0.18 (melons) m^3 kg^{-1} FM yield (Figure 4). Taking the effective rainfall amount of the cropping season (60% of the total rainfall amount) into account (183 m^3 ha^{-1}, SD: 2.97) the water productivity decreased by 10% on average, ranging from 1.79 (cereals) to 0.20 (melons) m^3 kg^{-1} FM yield, but particularly for hay (28%) and sea buckthorn (25%). The potential income per unit of applied water varied from 0.58 (cereals) to 8.42 (sea buckthorn berries) € per m^3 (Figure 4).

4.3.4 Hydrological characteristics and SWAT modelling

The discharge of the Bulgan River was determined by three components: the base flow, melting water and P events, with a long-term annual average discharge of 9.53 m^3 s^{-1}. The discharge of the Bulgan River was characterized by a high intra- and inter-annual variability (Appendix 4). Two major runoff periods triggered by snow and ice melt in May and P events in June and July were identified. Peaks in September were connected to first seasonal snowfall events, which melted during the day. During the rest of the year, river discharge depends strongly on the base flow. The downstream discharge measurements at Bulgan *sum* showed higher values than upstream ones, which can be explained by the extended watershed which features higher drainage and surface runoff and a greater number of tributaries such as the Bain and Turgen River. Redirection of water for irrigation purposes (in average 25% ranging from 15% in July to 44% in September, based on discharge measurements in 2014, n=3) may soften the discharge peak at Bulgan *sum*.

The model evaluation statistics of the Bulgan discharge showed unsatisfactory results. The Nash-Sutcliffe efficiency (NSE value < 0 indicates that the observed mean is a better predictor than the model) as a performance rating of the calibrated discharge (2004-2009) was -2.00 and -1.21 for Bulgan *sum* and Duchinjil, respectively. The respective PBIAS values (85.08 and 94.02) indicated a clear underestimation of the simulated discharge values at both gauging stations, which could not be solved through the calibration procedure. The respective coefficient of determination (r^2= 0.50 and 0.45) indicated a moderate correlation of observed and simulated discharge. Also the simulated discharge reproduced the discharge peaks as a response to snowmelt and P. The main limitation of the model was that the base flow was not displayed (Appendix 5). However, the performance ratings of the different HRUs biomass data indicated a good fit (NSE= 0.58, PBIAS= 7.98 and r^2= 0.58).

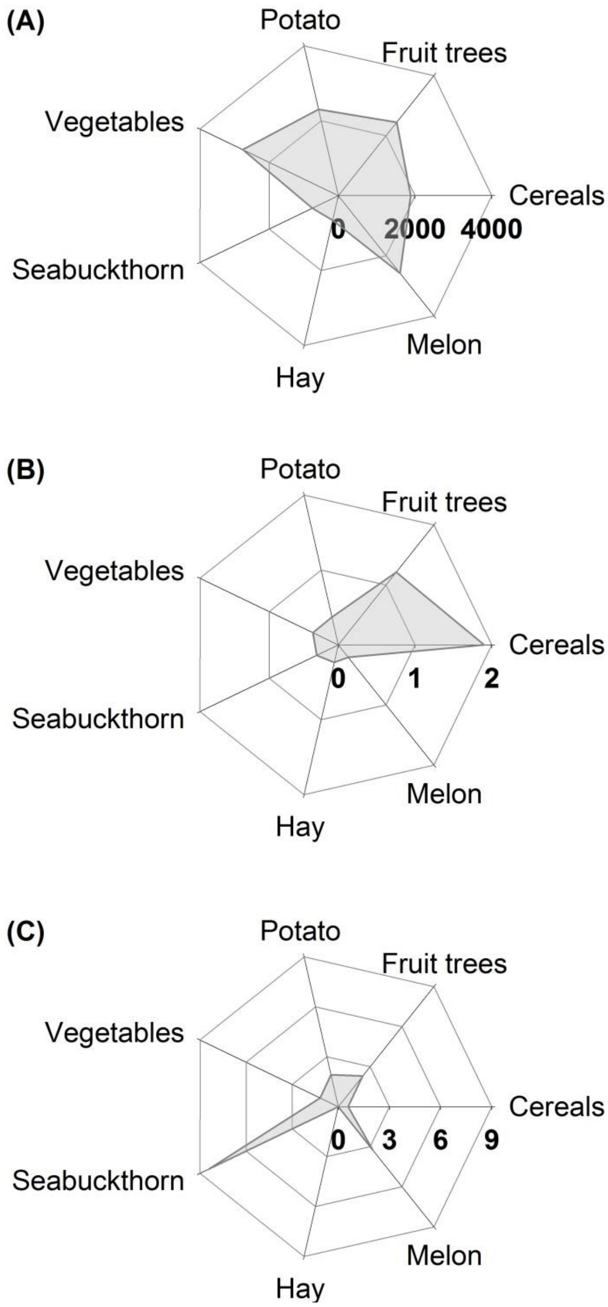

Figure 4. (A) Irrigation water application (m^3 ha^{-1} $year^{-1}$), (B) irrigation water productivity (m^3 kg^{-1} fresh matter yield) and (C) potential income (€) per unit of applied irrigation water (per m^3) of different crops, hay and fruits in the river oasis Bulgan *sum* center, Mongolia, 2013 (values represents means).

Based on the simulation period (2004 to 2009), the water balance components were quantified as follows: the watershed received 96 mm rain and 20 mm snow per year on average.

The growing season coincides with the period of major rainfall (May-September) in which the study area received an average of 81 mm (accounting for 70% of the average annual P, Figure 5). During the simulation period, the cumulative ET averaged 100 mm per year, representing 86% of the average annual P. The ET during the growing season ranged from 34.31 mm (SD: 1.72) for non-irrigated HRUs to 70.49 mm (SD: 12.10) for irrigated HRUs.

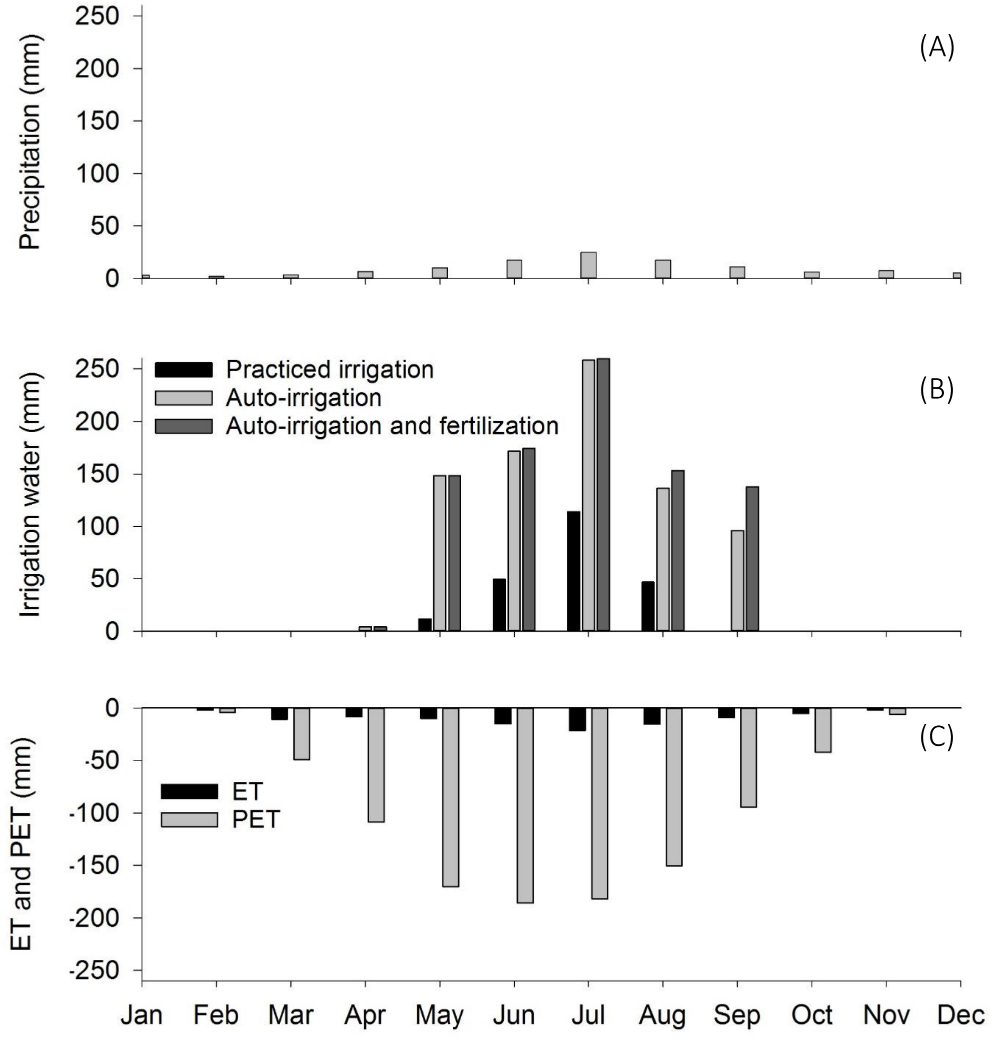

Figure 5. (A) Average monthly amount of precipitation (mm), (B) irrigation water application amounts for three different scenarios (practiced irrigation, auto-irrigation and auto-irrigation and fertilization), (C) evapotranspiration (ET) and potential evaporation (PET) based on the SWAT (Soil and Water Assessment Tool) simulation for the period 2004-2009, for the Bulgan watershed.

The cumulative PET per year reached an average of 993 mm. The average ET/PET ratio was 0.10, indicating prolonged periods of evaporative stress during the year. In total, 129 crop water stress days were estimated for the entire watershed (water stress was simulated in SWAT by a comparison of ET and PET).

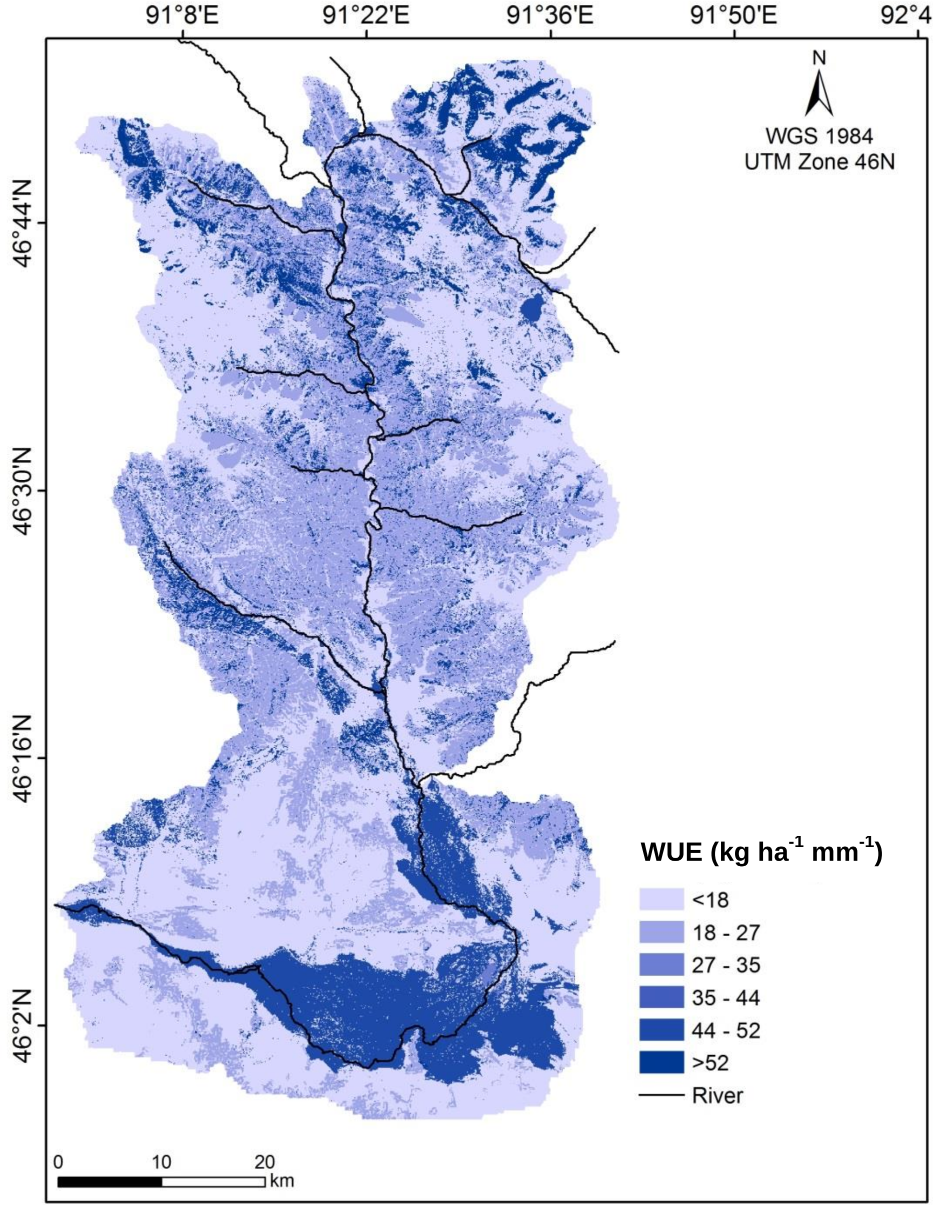

Figure 6. Water use efficiency (WUE, kg ha^{-1} mm^{-1}) for different hydrological response units in Bulgan *sum*, Mongolia. The WUE was simulated by SWAT (Soil and Water Assessment Tool) based on data of the growing seasons (April to July) from 2004 to 2009.

The average ET/P ratio during the growing season was 1.41 (SD: 0.56), while for non-irrigated HRUs it was 1.01 mm (SD: 1.05). The WUE$_{\text{Biomass}}$ ranged from 11 to 52 kg FM ha^{-1} mm^{-1} for rangeland and wetland. The WUE$_{\text{Biomass}}$ was higher in the mountainous areas compared with the lowlands in the floodplain (except the wetland area, Figure 6). Across the different rangeland types, an annual $\mathrm{WUE}_{\mathrm{Biomass}}$ of 14 kg FM ha^{-1} mm^{-1} was calculated (ranging from to 11 to 17 kg FM ha^{-1} mm^{-1}). For irrigated land, the SWAT model calculated average values of 15, 14 and 31 kg FM ha^{-1} mm^{-1} during the growing season for practiced irrigation management (based on questionnaire data and field surveys), the modelled auto-irrigation (auto-irrigation was triggered by a water stress threshold of 0.9) and auto-irrigation and fertilization (application of goat manure if the SWAT model determines plants are undergoing nitrogen stress), respectively. The modelled auto-irrigation and the combination of auto-irrigation and fertilization management increased the yield by about 46 and 77%, respectively, while the irrigation amount simultaneously increased from 222 to 814 and 892 mm (Figure 5).

4.4 Discussion

Mongolian agriculture is dominated by pastoral activities which is reflected in the fact that 73% of available land is used as pasture and only a minimal part is used as arable land (0.3%, Central Intelligence Agency 2013). However, recent national land use policies aim to expand and (re)intensify agriculture and enhance hay and fodder production to lower livestock mortality during harsh winters (Karthe et al. 2015; Pederson et al. 2013; Priess et al. 2015). Consequently, the number of farmers is rising. This transformation is further driven by changes in lifestyle, increasing frequencies of extreme weather events (such as *dzud* which is a Mongolian term for a severe winter in which large numbers of livestock die) and sedentarization of pastoralists (Addison et al. 2012; Liu et al. 2013; Hilker et al. 2014; Miao et al. 2016). Against this background, land cover and livelihood strategies in Mongolia have changed remarkably (Hülsmann et al. 2015; Priess et al. 2015; Hofmann et al. 2016). In the river oasis Bulgan *sum*, continued increases in livestock and human population and the transformation of traditional transhumance systems to increasingly sedentary ones are major drivers of land cover changes. Rangeland in the Bulgan district was subjected to increase in localized grazing pressure due to the rising numbers of livestock of 9% between 1972 and 2013, and a much stronger increase of 314% between 1972 and 2008 (before the *dzud* winter in 2009/2010, Appendix 6). Especially, the number of cashmere goats increased from 1972 to 2013 by 52% and from 1972 to 2008 by 258% (data source: Livestock Account, National Statistical Office of Mongolia, Appendix 6).

Grazing activities in the fragile rangeland areas further away from the Bulgan River are likely to cause negative effects on primary production, vegetation cover and seed production (Chen et al. 2007; Bruegger et al. 2014; Hilker et al. 2014; Chen et al. 2015). Additionally, extreme weather events such as droughts, harsh winters and dust storms could have fostered an expansion of sandy areas in the peripheral area (Liu et al. 2013; Lkhagvadorj et al. 2013a; Tao et al. 2015; Lamchin et al. 2016). Due to the prevailing westerly winds, aeolian coarse-grained sediments (sand, silt) were mainly deposited on the east facing lower slopes surrounding the floodplain (Lamchin et al. 2016). In contrast, the grazing activities in close proximity to the Bulgan River might entail beneficial effects on pasture productivity as a result of nutrient and organic matter return via excrements, improved water efficiency due to reduction of leaf area index and a potential improved light absorption due to reduced shading (Dangal et al. 2016; Lamchin et al. 2016). This aspect might represent a significant contribution to the expansion of high productive areas (river water receiving sites) in close proximity to the Bulgan River. The decrease of shrub and woodland were most likely the result of intensive grazing/browsing in combination with the use of wood for fuel and construction by agro-pastoral farmers, regulation and narrowing of the stream and fires (Wiehle et al. 2016). In contrast, urban expansion of the Bulgan *sum* center could be clearly shown over the four decades. The population number in the Bulgan district increased by 25% between 1980 and 2012 (data source: National Statistical Office of Khovd). Our results indicate that this trend was probably reinforced by changes in lifestyle and extreme weather events, which resulted in reduced mobility and sedentarization of pastoralists around settlements and the opening of the Sino-Mongolian border (since 1990), offering new marketing opportunities. Which is a trend also observed by Addison et al. (2012), Liu et al. (2013), Hilker et al. (2014) and Miao et al. (2016) in similar regions. There are two explanations for the expansion of river water receiving sites: firstly, the expansion of irrigated crop and hay land (likely connected with the population growth). According to local administrative data, 530 ha of crop land (including potato, cereals and vegetables) were cultivated on average between 1983 and 2014 (285 ha before 1990) in the Bulgan district (Appendix 7). The cropped area peaked in 2001 (1238 ha) directly after a *dzud* year. Following this maximum, about 90% of the cropland was abandoned, resulting in a cropped area of 122 ha in 2013 (data source: National Statistical Office of Khovd, Appendix 7). Secondly, the expansion of river water receiving sites could be explained by an indirect effect of the substantial enlargement of the irrigation canal network in the river oasis. Especially the area along the irrigation canals contained high productive vegetation and was potentially supported by groundwater from canal loss and irrigation water. In addition, reports from our interviews suggest that poor irrigation management led to unintended flooding of natural rangeland. These circumstances could partly explain the substantial increase of the highly vegetated area as water is the main limiting factor in this agroecosystem (Tang et al. 2007; Dangal et al. 2016; Lamchin et al. 2016).

As stated previously, there is strong evidence that these land cover changes are linked to the shift of livelihood strategies. Due to the spatial and temporal variability of water resources, transhumant pastoralism coupled with small-scale agriculture production has been a common land use and risk-minimizing strategy in Mongolia since the end of the 1950s (Pederson et al. 2013; Hofmann et al. 2016). In addition, agro-pastoral farming systems are known to supplement natural feed for livestock with cultivated fodder, improve crop production by stubble grazing and provide an additional source of income (Kakawanabe et al. 2001). Crop cultivation in this area is challenging in view of the low P amounts and high ET losses and is only practicable along river valleys offering access to sufficient irrigation water. Additionally, agricultural production is strongly limited by a short growing season, wind erosion and inadequate production technologies (Hofmann et al. 2016). In general, two types of irrigated cropping systems are dominant in Mongolia: (i) herder HHs cultivate hay and some cereals for fodder production and (ii) large scale production of cereals, practiced mainly in the 'breadbasket' of Mongolia (Selenge, Tuv, Bulgan and Darkhan-Uul aimags accounting for approximately 67% of cultivated area; Karthe et al. 2015; Hofmann et al. 2016). Though irrigated agriculture is significant in Mongolia, to our knowledge no detailed studies exist on irrigation water use (Hülsmann et al. 2015). As a result of our research we can clearly support that irrigated agriculture is of particular importance: 99 and 68% of studied HHs depended on the Bulgan River as a source of irrigation water applied to hay and crop fields, respectively. In addition, 100% of HHs relied on the river for drinking water for animals and domestic purposes. We found that agro-pastoral HHs along the valley of the Bulgan River predominantly practiced semi-commercial livestock keeping plus subsistence field cropping and commercial livestock keeping which supports the findings of Tsevegmed (2016) and Jordan et al. (2016). The livelihood diversification of the studied HHs was mainly an involuntary response to crisis (such as *dzud*) and should be considered a struggle for survival rather than an opportunity for improvement (Liao et al. 2015; Tsevegmed 2016). Results of a baseline survey conducted in the study region revealed that commercial field cropping HHs were characterized by the lowest income and low total value of asset (Tsevegmed 2016). Our data back these findings since we found lowest asset value per person in subsistence field cropping HHs. As stated by Tsevegmed (2016) the average yearly cash income of 1645 USD per HH and the total average HH animal number of 157 are not sufficient to ensure the livelihood of farmer HHs in the study region (Johnson et al. 2006; Gonchigsumlaa 2016; Tsevegmed 2016). Livelihood diversification in the study region could be considered a risk reduction strategy, however not as a means of stabilizing income and consumption, as concluded by Liao et al. (2015). The lack of farming experiences (on average, crop cultivation was practiced for 4 years, data source: National Statistical Office of Khovd), small field sizes (on average 0.3 ha), no or low fertilizer inputs, labour-competing pastoral activities, high investments in terms of labour/hired labour and capital, seasonal water scarcity (in the beginning and end of the growing season), a dilapidated irrigation system and limited access to markets decrease farm productivity and therefore reduce income potential. Considering the economic productivity, the highest value per water unit was gained with sea buckthorn berries (around 9 Euro per m^3). Therefore the cultivation of sea buckthorn is beneficial to improve the farmers' income in the study region especially in the light of future potentially more serve water scarcity as also observed by Gonchigsumlaa (2016). Nevertheless, the remoteness of Bulgan *sum* engendered inadequate marketing and processing opportunities. The economic productivity of vegetables and cereals was comparatively low. Prices of imported vegetable and cereals from China are more competitive and put pressure on local prices. However, the same development was not observed for hay because nearly all HHs harvested hay themselves in the Bulgan county (Gonchigsumlaa 2016). Selling of hay can be an additional income source for farmers in Bulgan *sum*, especially with regard to an improved management practice, which can increase hay production and can ease the workload of fulltime herder HHs.

Against this background, the water resources in the watershed Bulgan *sum* are likely to be stressed by increasing water demand, not only for agriculture, but also for drinking water and mining along the tributaries of the Bulgan river, and may even be reinforced due to socio-economical and climatic changes (Angerer et al. 2008; Batsukh et al. 2008; Lkhagvadorj et al.

2013a; Karthe et al. 2015). Besides the availability of water in form of river discharge, the estimation of ET is of major importance to optimize crop water management in water-limited environments such as the river oasis in the Bulgan *sum* watershed. The SWAT model was not able to satisfactorily simulate the discharge of the Bulgan River as the base flow was too low, and P and especially melt water peaks were underestimated. Failing of discharge simulation was also observed with the 'Community Land Model' used in the Mongolian Altay (Frerkes 2013). As melting snow and ice mainly contribute to the discharge of rivers originating in the Altay Mountains (50-70%, Davaa et al. 2007), the inclusion of glaciers, permafrost soils, snow cover, aufeis and river icing into the model is likely to increase the base flow during the course of the year (Wimmer et al. 2009; Menzel et al. 2011; Hülsmann et al. 2015; Karthe et al. 2015). Despite the above described deficiencies and uncertainties of our model simulations, our analyses provide useful insights about ET in the Bulgan watershed. However, the presented values must be treated with caution due to the uncertainties regarding the discharge simulation. The simulated ET rates were in the lower range compared to grassland ecosystems in (Inner) Mongolia (Chen et al. 2009; Miao et al. 2009; Nandintsetseg and Shinoda 2011; Lu et al. 2011; Liu et al. 2013; Karthe et al. 2016). As observed in similar geographic regions, the lower ET rates can be either explained by lower P amounts in association with a low leaf area index or by potential underestimation of total ET as a result of snow sublimation and evaporation from wet canopy surface (Liu et al. 2013). The annual ratio of ET to P (86%) was comparable to values of (Inner) Mongolian grassland ecosystems ranging from 66 to 94% (Miyazaki et al. 2004; Zhang et al. 2005; Li et al. 2007; Nandintsetseg and Shinoda 2011; Liu et al. 2013; Miao et al. 2016) and indicated that most of the P was returned to the atmosphere (Lu et al. 2011). The low ET/PET ratio (0.10) was in accordance with Ma et al. (2003) who reported values of 0.12 for the drier Selenge basin; as a consequence, the Bulgan *sum* watershed was under water stress most of the year. The ET of irrigated land during the growing season was 49% higher compared with natural rangeland. Considering the expansion of irrigated areas in the study region, the increasing demand for water needs to be filled by irrigation water. In addition, as higher temperatures are predicted for the study region in the near future (mean temperature increased by 0.70°C during the period 1977-2011), increases of snow sublimation, ET and PET are likely to occur (Wimmer et al. 2009; Byambaa et al. 2014).

Rangeland productivity in semi-arid climates is mainly affected by annual P, air temperature, soil characteristics, crop species and grazing intensity (Lu et al. 2011) and is known to develop various adaptations to avoid or tolerate water deficits (such as seasonal control of leaf stomata, resistance to cavitation, deep rooting to exploit groundwater, reduction in leaf area, and different photosynthetic pathways; Begg and Turner 1976, Fischer and Turner 1978). The balance between P and ET on the rangeland sites may reflect the native vegetation's success in adapting to the limited water availability (Nandintsetseg and Shinoda 2011). However, it also indicates that nomadic herders rely on sufficient rainfall to maintain livestock health and productivity. P, snow melt, soil moisture content before July and the length of growing season are major drivers of rangeland productivity and thereby the WUE in Mongolia (Suzuki et al. 2003; Miyazaki et al. 2004; Jordan et al. 2016). Furthermore, studies on irrigation and fertilization effects on rangelands and steppe indicate that the productivity is substantially constrained by nutrient availability even under ambient P levels (Yuling and Lein 2010; Ronnenberg and Wesche 2011). However, an improvement in productivity due to increasing water availability mainly depends on its distribution and intensity (Munkhtsetseg et al. 2007; Ronnenberg and Wesche 2011). As indicated in this study, rangeland surrounding the Buglan River had the highest WUE (as it was groundwater influenced), followed by high altitude pastures which were characterized by snow melt water and relatively high soil organic matter content. The rangeland productivity in the Dzungarian Desert and the river valley was low, most probably due to low P amounts, steep slopes, low organic matter content of soil and low infiltration rates.

The irrigation water productivity and WUE in this study could be overestimated as the irrigation application efficiency was not considered. Studies of smallholder farmers in semi-arid climates indicate a major loss of irrigation water before reaching farmers' fields (Kahlown and Kemper 2004; Ahmad and Choudhry 2005; Reddy et al. 2013) mainly caused by deteriorated canal junctions, overtopping of banks, dead storage in over excavated sections of the canals and leakage through highly permeable upper portions of the canal banks, sedimentation and growth of vegetation in the canal (Kahlown and Kemper 2004; Bobojonov and Aw-Hassan 2014). As earthen irrigation canals were common in the study area, it can be assumed that a considerable amount of water was lost through the beds and the sites resulted in low conveyance efficiency (Bobojonov and Aw-Hassan 2014). These circumstances may also explain the relatively low flow velocity and discharge in the irrigation canals of Bulgan *sum* (Ahmad and Choudhry 2005). Improvements of the canal system (such as compacting, regular cleaning of vegetation within the irrigation canal) are known to reduce water losses from canals carrying water to farmers' field and enhance the conveyance as well as the irrigation efficiency (Hickmann 2006; Bobojonov et al. 2016).

The timing of irrigation events and amounts of water applied were not well adapted to crop water requirements, either due to lack of knowledge, water limitation - especially during start and end of growing season, competing pastoral activities and/or limited access to advanced machinery (Schweitzer 2012; Drechsel et al. 2015; Hofmann et al. 2016). The seasonal irrigation amounts and irrigation water productivity were substantially lower compared with the results of studies conducted in Central Asia (Rockstrom et al. 2007; Yuling and Lein 2010; Frenken 2013; Reddy et al. 2013; Deng and Zhao 2015; Li et al. 2015; Rumbaur et al. 2015; Bobojonov et al. 2016). The short growing season and water scarcity in spring prevented plants from reaching full maturity. Livestock returning to the floodplain from the summer pastures was grazing on fields which had not been fully harvested. Additionally, low/no application of fertilizer in the study region reduced the irrigation water productivity as well as the WUE to a great extent. The manure which grazing livestock deposited on crop and hay fields could be considered a major nutrient source (Hofmann et al. 2016). As indicated by the baseline survey, nutrient deficits were likely as nutrient exports, primarily through crop harvest, could be assumed, and these nutrients were not replaced by organic and/or chemical fertilizers (Hofmann et al. 2016). Simulations of the SWAT model indicated that on-farm management improvements such as an adopted irrigation management adjusted to the crop growing state and the seasonal water availability (auto-irrigation) was likely to increase crop and hay yields up to 77% (Molden et al. 2010; Myagmarsuren and Tuul 2012; Hofmann et al. 2016). An increase in WUE was even more pronounced in the SWAT simulation involving auto-irrigation and auto-fertilization. Fertilizers could effectively improve both soil fertility and crop yield and might be beneficial in potential water savings (Hofmann et al. 2016).

To summarize, the extensive farming systems in the river oasis of Bulgan *sum* were characterized by agro-pastoral livelihood strategies that relied to a great extent on the support of hired labour. The watershed was characterized by low P amounts and high ET losses that are likely to limit productivity. The expansion of river water receiving sites increased the ET and might threaten the watershed's water resources. The cropping systems were characterized by low irrigation water productivity due to low/no application of fertilizer, and poor maintenance of the irrigation canal network.

4.5 Conclusions

The major expansion of sites receiving water from the Bulgan River, increased farming activities of pastoral HHs, high ET/P ratios and PET values and a potential rise of ET, especially due to land cover changes (from extensive to more intensive land use management) as well as changing climate potentially enhance water scarcity in the Bulgan *sum* watershed. To increase biomass productivity per unit water evaporated and transpired, improved irrigation technologies (reduced losses through drainage, seepage, percolation and evaporative outflows) and management practices (such as the introduction of compost) are needed. The introduction of small-scale greenhouses (used as nurseries to prolong the short growing season), snow irrigation in spring (to increase water availability) and the introduction of legumes (such as alfalfa) for fodder production could increase the economic and ecological productivity and so the WUE in the river oasis of Bulgan *sum*. However, most importantly, knowledge gaps of famers need to be addressed. Further in-depth studies are needed to verify if the SWAT simulated increase of WUE by improved irrigation and fertilizing methods are realizable.

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4.7 Appendix

Appendix 1. Description of used variables for the categorical component analysis (CATPCA) on 98 farmer households in Bulgan *sum* city, Mongolia (2012).

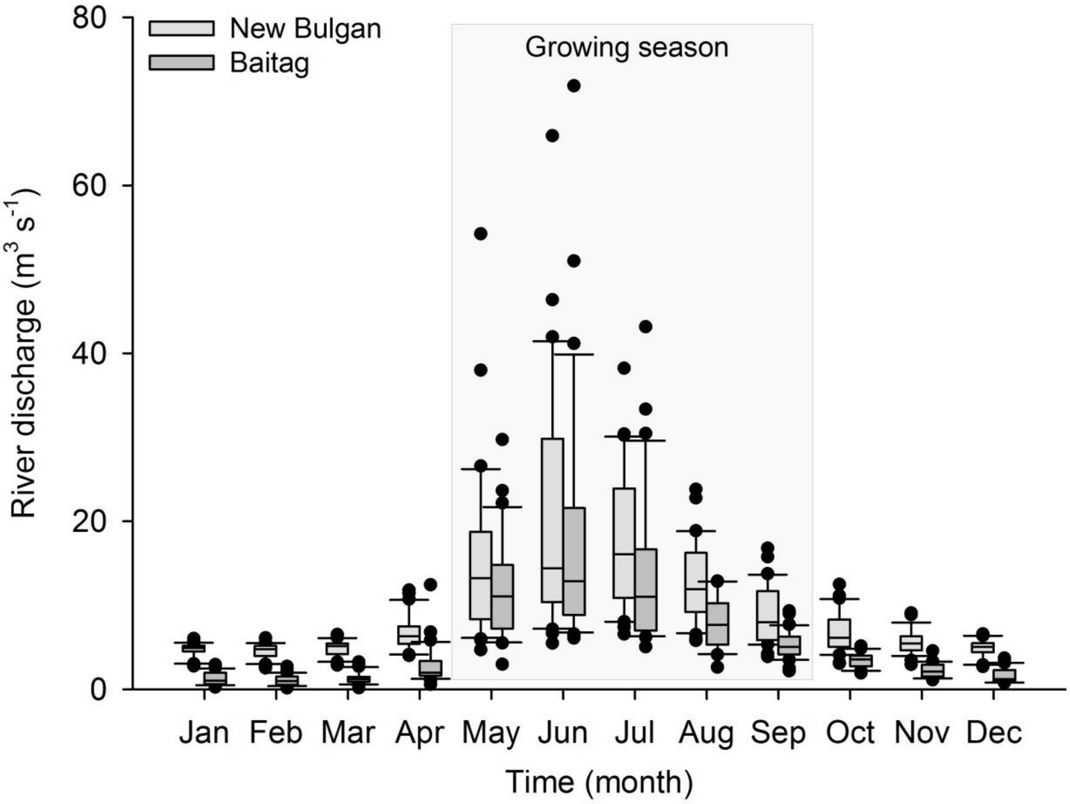
Variable name	Description of variable and coding
Ethnicity	Ethnic group (1=Kazakh, 2=Zakhchin,3=Khalkh, 4=Torguud)
Farm_type	Livestock farmer household, Household with livestock, other?
No_family	Number of family members permanently living in the household (n)
Children	Number of childrens in the household (n)
Live_permanent	Way of living (1=transhumance, 2=settled, 3=other)
Livingplace	House type (1=tent/yurt/ger, 2=house, 3=both, 4=other)
Clothes_total_person	Cumulative yearly expenses per person (Euro)
Asset_person_Euro_livestock	Cumulative value of property per person including livestock (Euro)
Perce_sell	Percentage of sold production (1=0%, 2= <25%, 3=25-50%, 4=50-75%, 5= >75%, 6=100%)
Type_of_plot	Type of plot for agricultural production (1=irrigated fields, 2=homegarden, 3=greenhose, 4=other)
Hire_people_farm	Hired people for agricultural activities (1=yes, 2=no)
Production_sell	Percentage of sold production (%)
Animal_fodder	Cultivation of animal fodder (1=yes, 2=no)
Crop_area_ha	Size of cultivated crop land by the household (ha)
Hay_area_ha	Size of cultivated hay land by the household (ha)
Quality_soil	The quality of the soil (1=fertile soil, 2=medium fertile soil, 3=less-fertile soil, 4=degraded soil)
Org_type	Usage of fertilizer (1=anorganic, 2=anorganic and manure, 3=anorganic and ashes, 4=no fertilizer)
Mainusage_harvest	Main usage of harvest (1=own consumption, 2=animal fodder, 3=own consumption and selling, 4=own consumption and animal fodder, 5=other)
Area_channel	The size of irrigation channel discharge area (cm^2)
Water_origin	Irrigation water origin (1=well, 2=spring, 3=river)
Irr_event_season	Cumulative irrigation events per season (n)
N_plant_species	Number of cultivated plant species (n)
Hay_sell	Selling of hay (1=yes, 2=no)
Past_cond_all	Pasture conditions (1=excellent, 2=good, 3=fair, 4=poor)
Transhumance	Distance traveled during the course of the year (km)
No_all_to	Total number of owned livestock (n)
Status_animal	Total number of owned status animals (horses and camels; n)
Big_animal	Total number of owned large animals (cattle; n)
Small_animal	Total number of owned small ruminants (sheep, goats; n)

Appendix 2. Categorical component analysis model summary and component loadings of 98 farmer households in Bulgan *sum* center, Mongolia (2012).

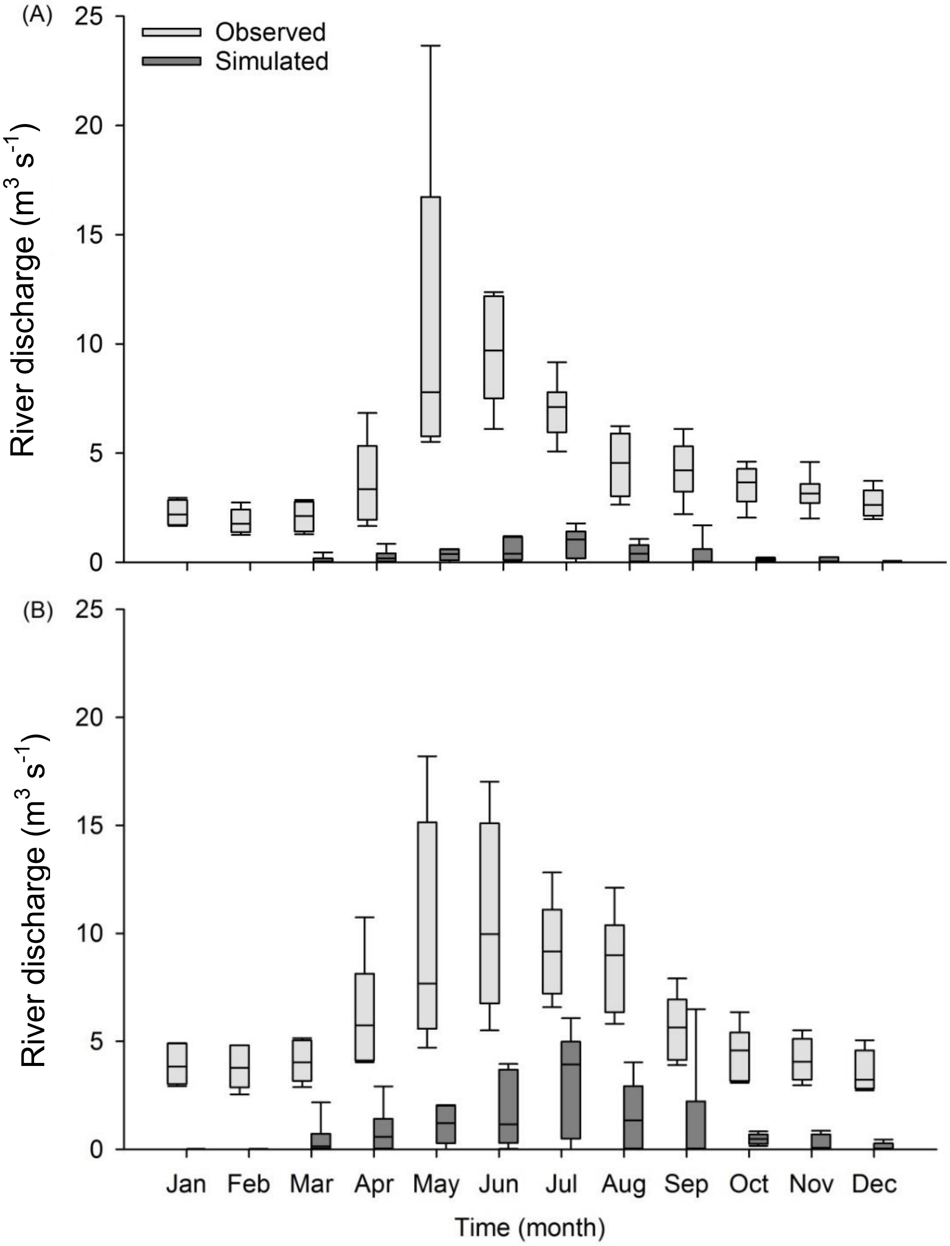
Overall model	Parameter estimate	
Total Cronbach's Alpha	0.94	
Total Eigenvalue	7.47	
Explaining x % of total variance	57.43	
Two-dimensional model	Dimension 1	Dimension 2
Cronbach's Alpha	0.86	0.67
Total Eigenvalues	4.84	2.62
Explaining x % of total variance	37.25	20.17
Component loadings		
Perce_sell	- 0.05	0.98
Production_sell	- 0.02	0.98
Hay_area_ha	0.47	- 0.13
Mainusage_harvest	0.08	0.63
Irr_event_season	0.23	- 0.41
N_plant_species	0.29	- 0.24
No_all_to	0.99	0.02
Status_animal	0.83	0.05
Big_Animal	0.73	0.04
Small_animal	0.94	- 0.02
Transhumance	- 0.51	- 0.21
Asset_person_Euro_livestock	0.93	0.11
Live_permanent	- 0.52	0.07

Appendix 3. Mean revenue (Euro kg^{-1} fresh matter: FM) of different agriculture commodities in Bulgan *sum* center, Mongolia (2012, standard deviations: SD).

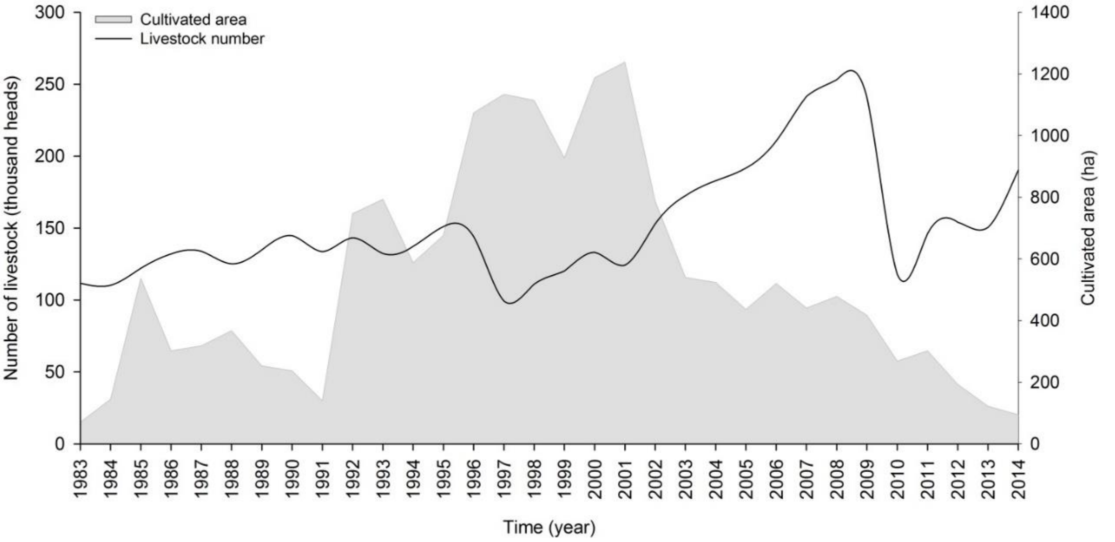
Agriculture commodities	Mean revenue (Euro kg^{-1} FM)	SD	n
Fruit trees	1.19	1.82	2
Cereals	0.79	0.21	4
Melon	0.56	0.16	5
Potato	0.54	0.91	25
Onion	0.43	0.35	4
Vegetable	0.35	0.22	7
Seabuckthorn	0.35	1.58	5
Carrot	0.34	0.31	18
Other	0.34	0.35	13
Cabbage	0.04	0.49	7



Appendix 4. Average monthly discharge ($m^3 s^{-1}$) of the Bulgan river at Bulgan *sum* (1186 m a.s.l.) and Duchinjil (1951 m a.s.l.), Mongolia (1983-2013).



Appendix 5. Observed and Soil and Water Assessment Tool (SWAT)-simulated river discharge (m^3 s^{-1}) of the Bulgan river at Duchinjil (A, 1951 m a.s.l.) and Bulgan (B, 1186 m a.s.l.) for the period 2004 to 2009.



Appendix 6. Number of total livestock and cultivated area (ha) in Bulgan county, Mongolia from 1983 to 2014 (data source: National Statistical Office of Khovd).

Appendix 7. Yield of potato, cereals and vegetable and cultivated area in Bulgan county, Mongolia from 1983-2014 (data source: National Statistical Office of Khovd).

5. Chapter

General discussion

5.1 Sustainable intensification of agricultural systems in Oman, China and Mongolia

Numerous environmental impacts and tradeoffs make 'classical' agricultural intensification a debatable strategy (Chapter 1; Figure 1) and call for alternative management practices that reduce impacts on natural resources, produce food and environmental assets and make better use of existing resources (such as land, water and biodiversity) and technologies (Tilman et al. 2011; Garnett et al. 2013; Pretty and Bharucha 2014; Rockstrom et al. 2016). Such so-called 'sustainable intensification' may be defined as a form of production characterized by agricultural outputs obtained with minimal environmental impact and avoiding the expansion of agricultural land while at the same time increasing the efficiency of natural, physical, financial and human resource investments (Baulcombe et al. 2009; Pretty and Bharucha 2014; Rockstrom et al. 2016). The sustainable intensification of agriculture will require crop varieties and livestock breeds with a high productivity whilst enhancing the utilization of agro-ecological processes, such as closed nutrient cycling and biological nitrogen (N) fixation, and minimizing the negative impact of system management on externalities, such as greenhouse gas emissions, loss of biodiversity and the dispersal of pests (Conway and Barbier 2009; Pretty and Bharucha 2014).

Mainly through substantial increases of fertilizer usage, intensification of agro-ecosystems has triggered a considerable rise in crop productivity (Janzen 2004; Smith et al. 2008; Rockstrom et al. 2016). However, between 1960 and 2000, the use efficiency of e.g. N in cereal production decreased globally from 80 to 30 percent (Erisman et al. 2008). The decline of the fertilizer use efficiency is the result of an inappropriate application of increased fertilizer amounts as most of applied fertilizer cannot be taken up by plants. Consequently, the surplus of soil nutrients likely to end up in water bodies and the atmosphere with potentially negative implications (Janzen 2004; Smith et al. 2008). For example, high rates of urea or NPK fertilizer cause high levels of reactive N (NH_4^+ and NO_3^-) in soils which are likely to contribute to N emission from agro-ecosystems in the form of nitrate (may lead to pollution of groundwater and eutrophication of surface water), dinitrogen oxide (may contribute to global warming) and ammonia (may lead to decline in air quality, Weil and Brady 2016). Under semi-arid climate conditions, such intensification processes (Figure 1c, 1d) and strongly positive C and nutrient balances, respectively, raise concerns about substantial element losses from agroecosystems, particularly through soil gaseous emissions (Buerkert et al. 2010; Predotova et al. 2010; Goenster et al. 2015).

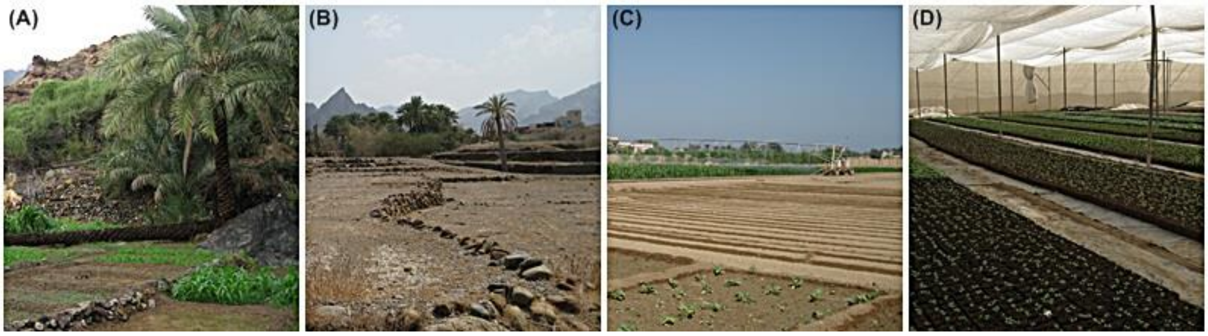


Figure 1. Agricultural intensification development of traditional mountain oasis (A) towards abandoned mountain oasis (B), large scale agricultural systems near the coast (C) and vegetable production in a greenhouse (D) in Oman.

Reduction of soil gaseous emissions can be achieved by adapted crop rotation and farming system design, maintenance of soil fertility, restoration of degraded land, and improved nutrient and manure management (Smith et al. 2008). Manure and compost application can help to maintain soil organic C and affect crop production positively by improving soil structure and availability of water and nutrient for plants while reducing water and nutrient losses (Varma et al. 2007; Buerkert et al. 2010; Weil and Brady 2016) whereby timing and management of applications are essential. However, in semi-arid environments, large amounts of C and N are emitted before plants' peak demand due to high mineralization rates (Buerkert et al. 2010; Predotova et al. 2010; Goenster et al. 2015). Slowing down the mineralization rate could reduce losses via leaching and gaseous emissions and thereby result in a long-term accumulation of soil C and N (Khan et al. 2008). Activated charcoal and tannin additives have the potential to reduce organic matter degradation, to retain nutrients and to lower rates of nutrient mineralization (Kraus et al. 2003; Lehmann and Joseph 2009; Ippolito et al. 2012). Ingold et al. (2015b) stated that the soil application of activated charcoal and tannin in combination with goat manure might slow down the turnover of goat manure, reduce nitrogen losses and consequently improve nitrogen cycling on irrigated sandy soils in Northern Oman. The organic matter decomposition and C and N release under sweet corn and radish were significantly affected by activated charcoal and tannin application (Ingold et al. 2015a; Ingold et al. 2015b). However, the application of tannin-enriched manure also resulted in a reduced dry matter yield of both crops (Ingold et al. 2015a; Ingold et al. 2015b). Considering the results of the study presented in Chapter 2 it can be stated that the application of tannin lowered gaseous emissions as peaks of gaseous C and N emission were reduced and temporally shifted in tannin amended compost and soil. In contrast to these results, emissions of all gases increased in compost amended with activated charcoal. Based on these results, particularly tannins appear to be a promising amendment to mitigate gaseous emissions, especially under semi-arid conditions. Apart from the environmental perspective, the improvement of the fertilizer use efficiency also has an economical aspect. A case study investigating effects of a reduction of nutrient losses at field-level and farm-level estimated that average annual N losses decreased by 23 to 45% and net farm income increased by $395 to $4,593 after farms adopted a nutrient management plan (van Dyke et al. 1999). The impact of the reduction in nutrient losses varies within and across farms according to particular farm characteristics, fertilizer management and climate.

In view of the above, the improvement of nutrient use efficiency by reducing leaching and gaseous emissions and the use of slow-release fertilizers are of major ecological and economic importance contributing to the livelihood of farmers under semi-arid environmental conditions. Despite the environmental, economic and agronomic benefits offered by slow release fertilizers, their practical use in agriculture is still very limited (Shaviv and Mikkelsen 1993; Snyder et al. 2009). The use of slow release fertilizers should be further studied to reduce production costs, develop optimal fertilizer compositions to induce synergy effects, better understand the mechanisms which control nutrient release, and predict release rates and patterns under laboratory and field conditions.

Grazing livestock of nomadic pastoralists is the most common and widespread type of land use in (semi-)arid environments such as Western China and Mongolia (Squires et al. 2010; Milner-Gulland et al. 2011). However, extensive nomadic herding systems are continuously shifting towards more intensive agro-pastoral production systems on susceptible grazing lands (Zhang et al. 2007; Squires et al. 2010). As a consequence livestock production will increasingly compete with natural resources for food production, particularly land and water (Thornton 2010; Eisler et al. 2014). Although Western China and Mongolia are moving towards more intensive livestock production, the observed increase in total production is mainly due to an increase in animal numbers and not to an increase in productivity (Eisler et al. 2014). Low fodder quality and quantity combined with low market prices often force livestock herders to accept minimum levels of productivity which need to be compensated by large numbers of animals as observed in the Chinese-Mongolian Altay (Herrero et al. 2010; McDermott et al. 2010).

The impact of intensified grazing activities on primary production, vegetation community structure and soil properties has been a controversial topic in rangeland ecology (Fernández-Giménez and Allen-Diaz 1999; Vetter 2004; Vetter 2005). In general, intensified grazing is thought to lower rangeland productivity, increase fragmentation of grass cover, reduce soil fertility, increase soil compaction and unpalatable grass species or a combination of all of them (Addison et al. 2012; Bruegger et al. 2014). Despite this, under certain conditions, grazing of herbivores can stimulate rangeland productivity and increase the occurrence of preferred species compared to ungrazed situations (Dangal et al. 2016; Lamchin et al. 2016). Moreover, the paradigms about equilibrium and non-equilibrium dynamics in semi-arid environments are highly debated among rangeland ecologists (Fernández-Giménez and Allen-Diaz 1999; Sullivan and Rohde 2002; Vetter 2005). The equilibrium theory assumes biotic feedbacks such as density-dependent regulation of livestock populations and livestock density as main drivers of vegetation composition, cover and productivity (O'Neill 2001). Conversely, the non-equilibrium theory proposes little impact of grazing livestock on forage resources due to decoupled resource-consumer (plant-herbivore) interactions and rather identifies stochastic abiotic factors (e.g. variable rainfall) as main drivers, which result in highly variable and unpredictable primary production (Fernández-Giménez and Allen-Diaz 1999; Sullivan and Rohde 2002; Vetter 2004). Instead of an ‘either-or’ assumption, some authors argue that rangeland dynamics in semi-arid environments encompass elements of the equilibrium as well as of the non-equilibrium theory at different scales (Briske et al. 2003; Vetter 2005). Following this assumption, the effect of grazing depends not only on grazing intensity but also on soil types/texture, plant species composition, rangeland management and the climate, in particular the precipitation pattern (Vetter 2004; Addison et al. 2012; Liu et al. 2013). The approach of the study presented in Chapter 3 followed this perspective and a mixture of abiotic and biotic factors were identified as the main drivers for herbage productivity and quality. It has been assumed that official regulations of herd and pasture management as well as higher spring rainfall contribute to higher herbage yields on Chinese pastures as compared with Mongolian ones. In contrast, lower livestock mobility within seasonal pastures, increased goat numbers and high seasonal stocking rates raise concern about biomass yields and herbage allowance in the Mongolian Altay.

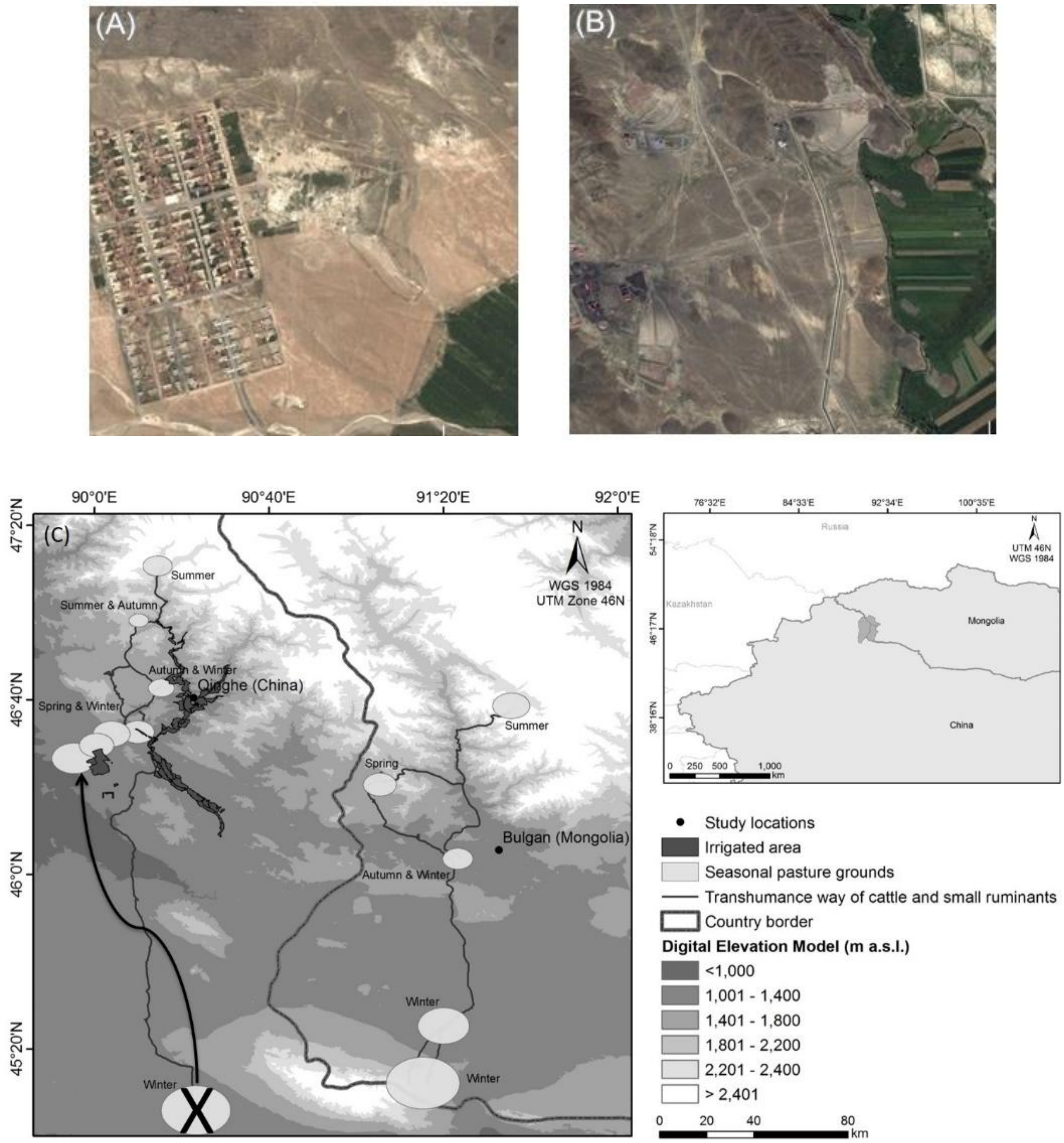


Figure 2. (A) State sponsored houses for settled herders, (B) exemplary rangeland fragmentation due to irrigated crop land, roads and mining activities in the Qinghe County, Western China (Source: Google Earth images) and (C) seasonal pastures and transhumance ways of small ruminants and cattle and expansion of irrigated land (Source: Hoffmann 2015 unpublished) in Western China and Mongolia.

Particularly the increased number of livestock (especially cashmere goats) is widely seen as a major cause of land degradation (Sternberg 2008; Hilker et al. 2014).

This problem might even be exacerbated by the expansion of irrigated crop land, settlements and political regulations (such as state-sponsored fencing programs, clearance of 'degraded' rangeland and/or forced resettlement of pastoralists, Figure 2a) in China and irrigated hay production at the autumn/winter pastures in Mongolia. During the last year of our study period, it was observed that Chinese small ruminant herds shifted their long-distance movements from the desert steppe to pastures sites in close vicinity to the settlement (located in the mountain steppe/flood plains; Figure 2a). This was mainly triggered by an expansion of irrigated agricultural land and mining activities in the desert areas (Figure 2b). Chinese livestock had to shift to less productive sites (outside the fertile floodplains) which might enhance the potential of degradation at the highly fragile desert areas. Another consequence of land use change is the expansion of irrigated hay land in China to maintain animal performance (Figure 2b and c). This land use intensification process (intensive grazing activities) could further decrease biomass production as well as promote negative vegetation composition changes. This likely leads to site-specific rangeland degradation on seasonal pasture sites on both sides of the border (Figure 3) and puts into question the long-term sustainability of the system under current use.

Figure 3. Indications of rangeland degradation: (A) salinization of irrigated rangeland site, (B) destruction of vegetation cover at highly frequented livestock pathways, (C) destruction of vegetation cover around the homestead and night corrals of livestock and (D and E) erosion gullies in the Chinese-Mongolian Altay (2012/2013).

In addition, the nutrient supply of cattle and small ruminants at the main seasonal pastures does not allow for high livestock performance (Tsevegmed 2016; Shabier 2016). The straightforward solution to reduce animal numbers is less favorable as herders have few opportunities to diversify their incomes even though this option could be a huge advantage for rangeland conditions and thus animal nutrition. Alternative measures towards a sustainable intensification are outlined in the following.

The predominant herd-release strategy and the absence of daily active herding practices resulted in localized degradation and hampered the full exploitation of the seasonal rangeland sites on both sides of the border. Main reasons for the non-application of active herding strategies were the lack of water sources and labor capacity, loss of traditional knowledge and absence of an effective coordinating authority. Active herding strategies have a large potential to optimize the exploitation of all pasture sites (unused high yield pasture sites were identified at higher elevations and further away from the camp sites) and can consequently improve animal nutrition and reduce localized grazing pressure on both sides of the border (exemplary illustrated for the Mongolian summer pasture, Figure 4).

Additionally, the preservation of herder's large-scale mobility is of major importance. The declining mobility pattern has been explained by institutional weaknesses rather than by environmental change (Undargaa and McCarthy 2016). Governmental support on the Chinese side of the border such as itinerant shops at the main seasonal pastures, regular bus connections to the district centers, hay transportation facilities and regular visits of traders for livestock, milk-products and wool might be a good measure to ensure the large-scale mobility on the Mongolian side also. In addition, fixed dates for transhumance movements (restricted access to the pastures until the end of the main flowering period) which are prescribed and controlled by the local government seem to be of major importance to maintain herbage yield and quality, especially in the summer pastures of the Chinese-Mongolian Altay.

To sum up, it can be said that mobility (at small and large scale) can be used to maintain/improve livestock productivity, herbage yields and quality. However, to move the livestock sector towards a sustainable intensification level, further improvements need to be made to increase revenues from livestock products.

As in many regions of Mongolia, the resource 'water' in the Bulgan river watershed is increasingly jeopardized by a rising demand and extensive changes in land use and cover (Rockstrom et al. 2007; Regdel et al. 2012; Priess et al. 2015; Tsevegmed 2016).

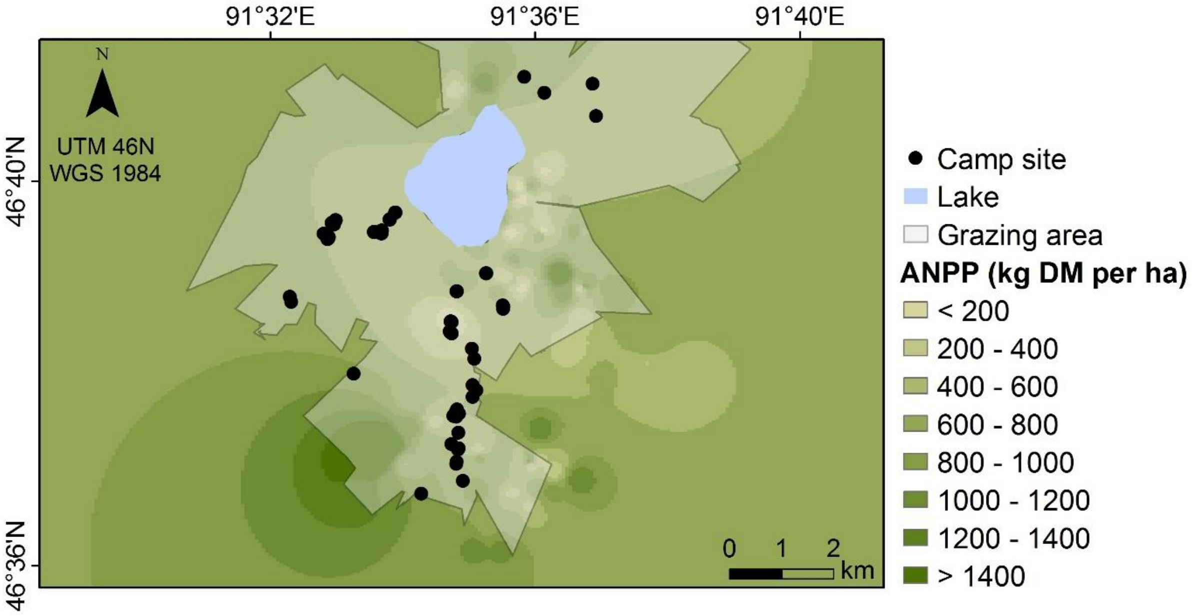


Figure 4. Spatial extent of grazing area and underutilized grazing sites at the *Tsunhal Nur* summer pasture, Mongolia in 2014 (ANPP: above ground net primary production of herbaceous vegetation, Source: modified map based on Altmann et al. 2016).

The river oasis of Bulgan *sum* was subjected to extensive changes from natural rangeland to mostly built-up areas and river water receiving sites while shrub and woodland were simultaneously reduced. In the long run, this conversion will likely lead to a reduction of water availability, as was observed elsewhere in Mongolia (Dombrowsky et al. 2014; Malsy et al. 2015). Besides certain pastoral activities, the farming systems of the river oasis were run by famers with often limited experience, lack of adequate nutrient inputs, a poor irrigation system and rising water consumption leading to low yields and low water-use efficiencies (Priess et al. 2011; Bobojonov and Aw-Hassan 2014; Bobojonov et al. 2016; Hofmann et al. 2016). The dilapidated irrigation canal system was characterized by high conveyance losses of earthen channels, on-farm distribution losses, lack of channel maintenance and improper drainage of fields (high losses through leaching and evaporation) and high losses during application and conveyance (Figure 5; Bobojonov et al. 2016). An adequate quantification of water use and determination of water losses in agricultural systems are of major importance (Molden 2013). Up to 90% of water used in the agriculture sector is lost by evapotranspiration (Rana and Katerji 2000) which is one of the major elements in the hydrological cycle that governs the water yield of the river watershed, reservoir capacity and ground water recharge (Rana and Katerji 2000; Lu et al. 2011; Liu et al. 2015).

Figure 5. Reasons for irrigation losses and necessity of canal maintenance: (A) practiced surface irrigation, (B) high occurrence of sedimentation and vegetation within the canal, (C) dilapidated canal junction and (D) leakage in canal walls in Bulgan *sum*, Mongolia, 2013.

Methods to measure or predict evapotranspiration are quite diverse and include hydrological approaches (soil water balance and lysimeter measurements), micro-meteorological approaches (such as aerodynamic methods), plant physiology approaches (such as sap flow methods) and statistical approaches (such as the Pennman-Monteith model, Allen et al. 1989; Rana and Katerji 2000). Direct measurements of evapotranspiration are difficult, costly and may not provide sufficient information in space and time, therefore several hydrological models were developed to estimate this parameter. Such models are based on comprehensive input data sets, which comprise information on soil, crop, management, climate, and socioeconomics. The application focus can reach from large management-based to more detailed process-oriented scales (Larsen et al. 2016). Results of these models can be very helpful to capture the complexity of farming systems and/or watersheds, to identify management options across space and time and to identify potential areas for which more detailed field studies can be conducted (Allen et al. 1989; Kang et al. 2008; Zhang et al. 2011; Antle et al. 2016). However, it is important to understand that all models are a simplification or approximation of reality (Burnham and Anderson 2002) and cannot substitute the classical agronomic field trial even though the latter is resource intensive in terms of work, time and costs. Therefore, the use of models is always a compromise between complexity and practicability (Larsen et al. 2016).

Given SWAT’s open access and detailed documentation, the model has been used successfully across a wide range of scales reaching from simulated plot size to continental watersheds over various periods (Francesconi et al. 2016).

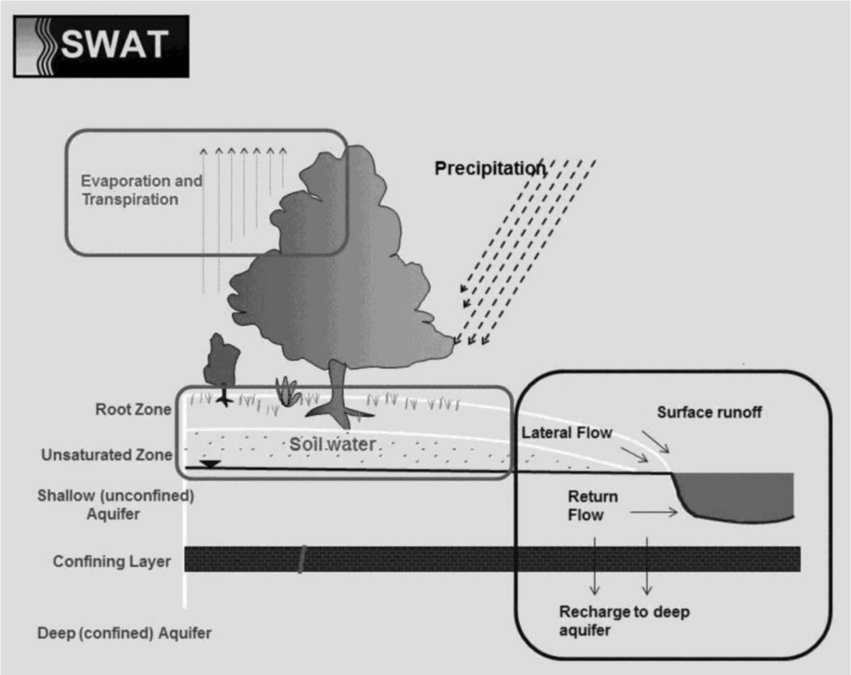


Figure 6. Schematic figure of the hydrological cycle simulated by the Soil and Water Assessment Tool (SWAT) model (Source: Texas AgriLife Research 2011).

Multiple input parameters and process-based biogeochemical sub-models improve the applicability to simulate and estimate water flow dynamics and several variables of water quality and plant growth which support the assessment of land and agricultural management options (Gassman et al. 2007; Douglas-Mankin et al. 2010). Additionally, SWAT model predictions allow conclusions on best management practices, irrigation management, climate change predictions and land use change (Krysanova and Srinivasan 2015). The simulated hydrological cycle of the SWAT model (Figure 6) is based on following water balance equation:

$$\mathrm{SW_t} = SW_0 + \sum_{i=1}^{t} \left(R_{day,i} - Q_{surf,i} - E_{a,i} - W_{seep,i} - Q_{gw,i} \right)$$

(Equation 1)

where SW_t is the final soil water content (mm H_2O), SW_0 is the initial soil water content at day *i* (mm H_2O), t is the time (days), R_{day} is the precipitation amount at day *i* (mm H_2O), Q_{surf} is the runoff amount at day *i* (mm H_2O), E_a is the evapotranspiration amount at day *i* (mm H_2O), W_{seep} is the water amount entering the vadose zone from a soil profile at day i (mm H_2O) and

Q_{gw} is the amount of return flow at day *i* (mm H_2O, Arnold and Fohrer 2005; Neitsch et al. 2005).

The use of the SWAT model of the Bulgan river watershed indicated that most of the precipitation was returned to the atmosphere. Additionally, a low evapotranspiration/potential evapotranspiration ratio showed that the Bulgan river watershed was under water stress for most of the year.

Furthermore, the huge expansion of river water receiving sites, increased farming activities of pastoral households, high (potential) evapotranspiration/precipitation ratios, potential rise of evapotranspiration due to land cover changes (Figure 7) and inadequate irrigation practices highlight the need for a careful use of the scarce water resource in the Bulgan *sum* watershed. To overcome these adverse circumstances, sustainable intensification methods are needed. The crucial importance of water for agricultural production was highlighted in the concept of increasing water productivity ('more crop per drop') introduced in the mid-1990s (Merrey 1996). Crop yield improvement in line with a high water use efficiency is a major target particularly in semi-arid environments (Blum 2009; Molden 2013). This calls for an improved water productivity which can be achieved by: (i) an increase of the marketable yield for each unit of water transpired, (ii) a reduction of all outflows (such as drainage, seepage and percolation), plus evaporative outflows except for crop stomatal transpiration and, (iii) an (improved) use of rainfall, stored water and water of marginal quality.

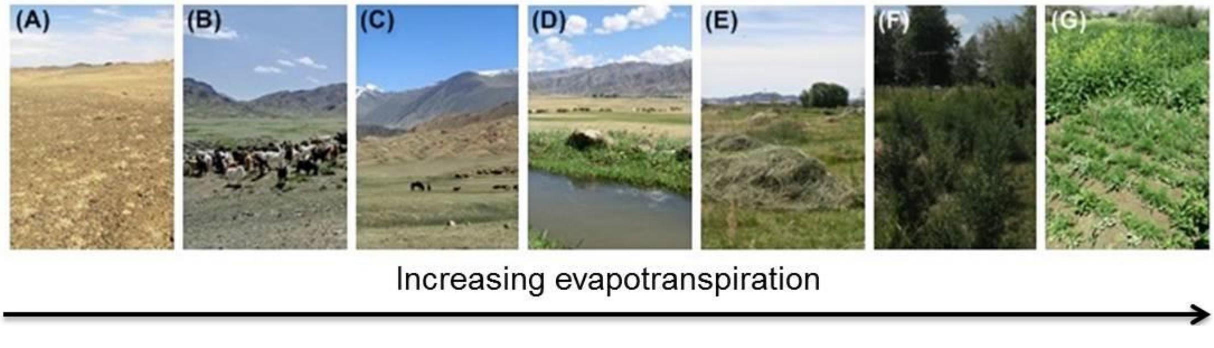


Figure 7. Increasing evapotranspiration losses from (A) rangeland in the desert steppe, (B) rangeland, (C) rangeland at the alpine belt, (E) meadows around the Bulgan river, (E) irrigated hay land, (F) irrigated sea buckthorn shrubs and fruit trees and (G) irrigated crop production in the Bulgan river watershed, Mongolia, 2013.

For the Bulgan river watershed, the SWAT model indicated that irrigation practices adapted to crop needs significantly increased yields, which could be further enhanced by the application of fertilizers (Chapter 4). The introduction and/or improvement of irrigation methods was the major driver for the improvement of agricultural productivity in many semi-arid regions (Bobojonov et al. 2016). However, the intensification of irrigation practices alone is often likely to result in land degradation (e.g. salinization, Lioubimtseva and Henebry 2009). Raised-bed planting could be a method to rationalize water use and enhance water productivity (He et al. 2015). Raised-bed planting is known as an affordable technology to reduce water application to the land while minimizing water loss from percolation (Figure 8). Additionally, this technique might allow the aeration of roots, an efficient use of fertilizer and easier control of weed. Furthermore, reducing soil evaporation to increase crop transpiration can positively affect evapotranspiration, water use efficiency and water productivity. Management practices that influence soil moisture include irrigation techniques, irrigation strategies and mulching practices. The application of irrigation water during the morning and evening could substantially reduce evapotranspiration. Covering the soil surface with mulch is an effective method to reduce evaporation (Figure 8). Several studies show the importance of mulching to decrease evaporation losses per unit yield (Ding et al. 2013; Wang et al. 2014). Apart from an additional fodder source, intercropping systems of e.g. alfalfa and rye could have beneficial effects on soil properties, nutrient supply and yield which may increase the water use efficiency and productivity (Figure 8, Zhang et al. 2015).

In summary, even under the current conditions of limited knowledge about crop production, labor shortage and limited financial resources, many promising and affordable options exist to improve the water productivity and water use efficiency aiming at a more sustainable intensification system in the Bulgan *sum* watershed.

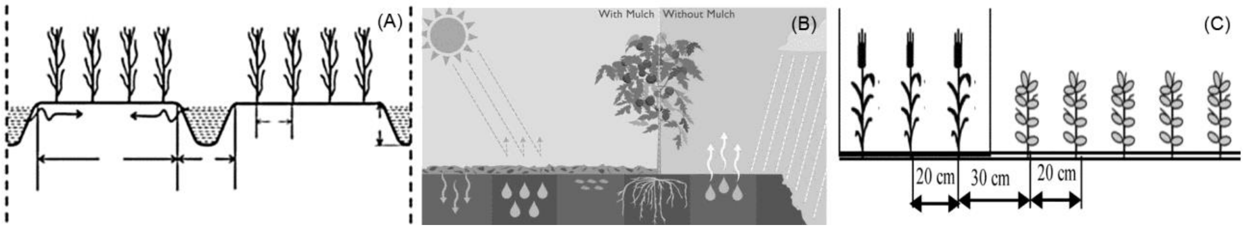


Figure 8. Schematic illustration of (A) raised-bed planting, (B) mulching methods and (C) intercropping of rye and alfalfa (Source: Zhang et al. 2015; FAO 2016; McLaughlin 2016).

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6. Chapter

Conclusions and recommendations

In the following, conclusions and recommendations are provided for each chapter in view of the respective hypothesis.

Chapter 2 titled 'Effects of activated charcoal and tannin added to compost and to soil on carbon dioxide, nitrous oxide and ammonia volatilization'.

Hypothesis:

> Amended compost or soil with tannins leads to a stabilization of organic matter and reduces the turnover.

Conclusions:

- Considerable carbon and nitrogen losses through gaseous emission were identified.
- Peaks of gaseous CO_2 and N_2O and NH_3 emission were reduced and temporally shifted in tannin amended compost and soil.
- Tannins applied directly to the soil reduced cumulative emissions of CO_2, N_2O and particularly NH_3 in comparison to the control.
- Tannins applied to compost reduced cumulative gaseous emission for carbon and for nitrogen emissions compared to unamended compost.
- Emissions of all gases increased in activated charcoal amended compost.
- In summary, it can be concluded that tannins appear to be a particularly promising amendment to composts and soil to mitigate gaseous emissions.

Recommendations:

- For a comprehensive evaluation of activated charcoal and tannin as additives for manure and/or compost, different sources of charcoal and tannin need to be screened for their effects on soils and plants.
- Neglected biomass of date palm branches, date kernels and immature, not marketable dates might be a potential resource which could be tested for charcoal/biomass production and/or as tannin-rich compost ingredients.
- As a potential important pathway of element losses, leaching of carbon and nitrogen should be additionally quantified allowing a more comprehensive picture of element flow.

Chapter 3 titled 'Spatio-temporal patterns of herbage availability and livestock movements: A cross-border analysis in the Chinese-Mongolian Altay'.

Hypothesis:

> Despite similar natural conditions, the differences in recent socio-political and socio-economic developments on the Chinese and Mongolian side of the border have a large impact on the local transhumance systems in the Altay-Dzungarian region and on rangeland utilization as indicated by herbage offer and quality.

Conclusions:

- The average cumulative annual lengths of cattle and small ruminant transhumance routes were similar within the countries.
- Throughout the year, the cattle herds spent more time on a specific pasture in Mongolia than in China, whereas the sojourn of small ruminants was comparable in both countries.
- The average size of utilized grazing areas within the seasonal pastures was twice as high in China as in Mongolia, whereby utilized grazing areas of small ruminants were comparable.
- Average herbage allowance at the onset of a grazing period was twice as high in China as in Mongolia, whereby only the Chinese spring pasture showed lower values than the Mongolian one.
- Across all seasonal pastures the hemicellulose concentration was 1.5 times higher in Mongolia; crude protein and phosphorous concentration were comparable in both countries.
- In summary, it can be concluded that official regulations on animal numbers, temporal and spatial allocation of pasture utilization combined with higher spring rainfall amounts seem to generate higher herbage yields on the Chinese site. In Mongolia, increasing number of goats, reduced livestock mobility and high seasonal stocking rates in combination with low precipitation until May affect biomass yield and herbage allowance. In contrast, no apparent differences were identified for the herbage quality.

Recommendations:

- Increasing intra-seasonal herd mobility and active daily herding practices may enhance rangeland productivity and reduce local grazing pressure, especially on spring and summer pastures in Mongolia and on autumn and winter pastures in China.
- The implementation of access dates and reducing the duration of herds' sojourn in particular areas (especially summer pastures) likely help to improve herbage offer and to sustain animal production.
- These restrictions must allow the flexible reaction of herders to the high inter- and intra-annual variation of precipitation and sudden adverse weather conditions.
- To maintain the large-scale mobility as a core feature of the transhumance system, amenities should be provided to herders even at remote pasture locations. As it can partly be observed in China, such measures could include mobile shops and medical services, public transport between the pastures, and regular visits of traders in livestock, dairy products and wool.
- To justify the increased work load and economic cost of active herding, the development of niche markets for clean, green and maybe even organic products in urban demand centers of China and Mongolia is of importance.
- For a comprehensive evaluation of the animal husbandry systems in the Chinese-Mongolian Altay the inter-specific grazing pressure of different herder households within the seasonal pastures need to be studied.

Chapter 4 titled 'Water use of agro-pastoral livelihood systems in the Bulgan river watershed of the Altay Mountains, Western Mongolia'.

Hypothesis:

Land cover changes and current farming practices lead to increasing stress on scarce water resources in the Bulgan River watershed.

Conclusions:

- The comparison of two land cover maps (1972 and 2013) of the Bulgan *sum* river oasis showed an apparent change from natural rangeland to mostly built-up areas and river water receiving sites.
- The prevailing livelihood strategies in the river oasis were (i) sedentary households (HHs) practicing field cropping and keeping livestock, both for subsistence needs, (ii)

HHs keeping livestock and practicing semi-commercial field cropping for subsistence needs and (iii) HHs keeping livestock for commercial needs and hiring labour for semi-commercial hay production.

- The application of irrigation water for vegetables was around four times higher compared to amounts for hay.
- The irrigation water productivity was highest for melons and lowest for cereals (0.18/1.64 m^3 kg^{-1} fresh matter yield).
- The average income per unit applied water was 2.94 Euro per m^3.
- The water-use efficiency (WUE) ranged from 11 to 52 kg fresh matter ha^{-1} mm^{-1} for rangeland and wetland.
- Auto-irrigation as well as auto-irrigation and fertilization management simulated by the SWAT model increased the yield of fruit trees, irrigated crop, vegetable and hay.
- In summary, it can be concluded that the large expansion of river water receiving sites, little experienced famers, lack of adequate inputs, poor condition of the irrigation system, increased farming activities of pastoral households, high potential evapotranspiration rates and a potential rise of evapotranspiration, in particular due to land cover changes (from extensive to more intensive land use management) and a changing climate, affect the water resources in the Bulgan *sum* watershed.

Recommendations:

- To increase biomass productivity per unit water evaporated and transpired, improved irrigation technologies (such as reduction of drainage, seepage, percolation and evaporative outflows) and fertilization practices (such as the introduction of compost) are needed.
- The introduction of small-scale greenhouses (used as nurseries to extend the short growing season), snow irrigation in spring (to increase water availability in spring) and the introduction of legumes (such as alfalfa) for fodder production could improve the economic and ecological productivity and, consequently, the WUE in the river oasis of Bulgan *sum*.
- The knowledge gap of famers needs to be addressed.

In-depth studies are needed to verify and to specify an increase of water-use efficiency through improved irrigation and fertilizing methods as shown by the SWAT simulations.

List of publications

Peer-reviewed articles

Jordan, G., Goenster, S., Munkhnasan, T., Shabier, A., Buerkert, A., Schlecht, E. (2016a): Spatio-temporal patterns of herbage availability and livestock movements: A cross-border analysis in the Chinese-Mongolian Altay. Pastoralism 6, 1-17.

Jordan, G., Shabier, A., Munkhnasan, T., Goenster, S., Buerkert, A., Schlecht, E. (2016b): Cross-border analysis of biomass vvailability and stocking densities on seasonal pastures in the Chinese-Mongolian Altay-Dzungarian Region. 10th International Rangeland Congress, Saskatoon, Canada.

Altmann, B., **Jordan, G.**, Schlecht, E. (2016): A community-based approach to identifying grazing pressure and land-use management structures among herders in the Altay Mountains, Mongolia. 10th International Rangeland Congress, Saskatoon, Canada.

Jordan, G., Predotova, M., Ingold, M., Goenster, S., Dietz, H., Joergensen, R. G., Buerkert, A. (2015): Effects of activated charcoal and tannin added to compost and to soil on carbon dioxide, nitrous oxide and ammonia volatilization. Journal of Plant Nutrition and Soil Science 178, 218–228.

Ingold, M., Al-Kindi, A., **Jordan, G.**, Dietz, H., Schlecht, E., Buerkert, A. (2015): Effects of activated charcoal and quebracho tannins added to feed or as soil conditioner on manure quality in organic agriculture. Organic Agriculture 5, 245–261.

Rosenstock, T. S., Diaz-Pines, E., Zuazo, P., **Jordan, G.**, Predotova, M., Mutuo, P., Abwanda, S., Thiong'o, M., Buerkert, A., Rufino, M. C., Kiese, R., Neufeldt, H., Butterbach-Bahl, K. (2013): Accuracy and precision of photoacoustic spectroscopy not guaranteed. Global Change Biology 19, 3565–3567.

Conference contributions

Jordan, G., Ulziisuren, B., Goenster-Jordan, S., Buerkert, A. (2016): Irrigated crop production in a floodplain river oasis of the Mongolian Altay Mountains. Tropentag Conference - Solidarity in a competing world - fair use of resources, Vienna, Austria. Poster Presentation.

Jordan, G., Buerkert, A., Schlecht, E. (2015): The role of environmental factors and grazing on rangeland productivity along an altitudinal gradient in the Chinese and Mongolian Altay. Tropentag Conference - Management of land use systems for enhanced food security – conflicts, controversies and resolutions, Berlin, Germany. Poster Presentation.

Jordan, G., Tsevegmed, M., Buerkert, A., Schlecht, E. (2014): Is traditional transhumance an adapted strategy or an overhauled way of rangeland management in the Chinese and Mongolian Altay? Tropentag Conference - Bridging the gap between increasing knowledge and decreasing resources, Praque, Czech Republic. Talk.

Jordan, G., Predotova, M., Ingold, M., Dietz, H., Buerkert, A. (2012): Effects of activated charcoal and tannin added to soil and compost on carbon and nitrogen emissions. Tropentag Conference - Resilience of agricultural systems against crises, Goettingen, Germany. Poster presentation.

Jordan, G., Ingold, M., Dietz, H., Buerkert, A. (2011): Agronomic effects of biochar and polyphenols as compost additives to irrigated Raphanus sativus in Oman. Tropentag Conference - Development on the margin, Bonn, Germany. Poster presentation.

Ingold, M., **Jordan, G.**, Schlecht, E., Buerkert, A. (2011): Effects of biochar application to goat manure on irrigated radish in Northern Oman. UK Biochar Conference, Edinburgh, Scotland. Poster Presentation.

Affidavit

Hiermit versichere ich, dass ich die vorliegende Dissertation selbständig, ohne unerlaubte Hilfe Dritter angefertigt und andere als die in der Dissertation angegebenen Hilfsmittel nicht benutzt habe. Alle Stellen, die wörtlich oder sinngemäß aus veröffentlichten oder unveröffentlichten Schriften entnommen sind, habe ich als solche kenntlich gemacht. Dritte waren an der inhaltlichen Erstellung der Dissertation nicht beteiligt; insbesondere habe ich nicht die Hilfe eines kommerziellen Promotionsberaters in Anspruch genommen. Kein Teil dieser Arbeit ist in einem anderen Promotions- oder Habilitationsverfahren durch mich verwendet worden.

Witzenhausen, 17.10.2016 ___________________________________

Greta Jordan