Spatiotemporal studies of evapotranspiration in Inner Mongolian grasslands

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父債子還

The son must pay his father's debts.

- Chinese proverb -

Contents

Abstract

Inner Mongolian grasslands are part of the vast Eurasian steppe belt and were used for nomadic pastoralism for thousands of years. As a result of political and economic changes in China in the last century, this mobile grazing management has been replaced by a sedentary and intensified livestock production. Stocking rates have increased substantially, overshooting the carrying capacity of the grasslands. These land use changes have induced severe grassland degradation. The impact and causes of grassland degradation have been investigated by the Sino-German joint research group MAGIM (Matter fluxes in grasslands of Inner Mongolia as influenced by stocking rate) in the Xilin River catchment of Inner Mongolia since 2004. This work is part of subproject P6, which amongst others pursues the goal of quantifying water balance exchange by micrometeorology and remote sensing.

The dominating process of water balance losses in Inner Mongolian grasslands is evapotranspiration (ET), whereby water vapour is released into the lower atmosphere. ET is highly variable in both time and space in this semi-arid environment, as it is coupled with the typically fluctuating amount of precipitation (P). However, despite ET being the key output process of the hydrological cycle of Inner Mongolian grasslands and despite its important role as an indicator for ecosystem functioning, little is known about its spatiotemporal distribution and variability in this remote area. Recent studies on ET have demonstrated variations due to phenology, soil moisture and land use, but these studies have been limited to short periods and have been conducted on a few field sites in close proximity with debatable representativeness for the 2600 km² of grasslands in the Xilin River catchment. The development of a number of remote sensing methods in the last decades has introduced various approaches to determining spatial ET from space, but the application of remotely sensed ET in regional long-term studies is still problematic. Nevertheless, a variety of surface parameters are provided by the sensor MODIS (moderate resolution imaging spectroradiometer) at a resolution of approx. 1km.

The aim of this work was (1) to close the gap between the limitations of available local ET measurements and the need for long-term studies on spatial ET in Inner Mongolian grasslands and (2) to analyse the spatiotemporal variability of ET and its implications on livestock management in this area. Therefore, micrometeorological data, remote sensing products and hydrological modelling with BROOK90 were integrated to model spatial ET for the grasslands of the Xilin River catchment over 10 years. The hydrological model BROOK90 calculates ET based on a modified Penman-Monteith approach including the separation of energy into transpiration and soil evaporation. The spatial application of the model was based on a land use classification restricted to the land use unit typical steppe. BROOK90 was parameterised from eddy covariance measurements, soil characteristics and MODIS leaf area index (LAI). Location and canopy parameters were provided individually, as well as the essential daily model input, including P and air temperatures for each pixel. Minimum and maximum air temperatures were calculated based on a relationship between measured air temperatures and MODIS surface temperatures ($R^2=0.92$ and $R^2=0.87$, n=81). Spatial P was estimated from a relationship found between the measured cumulative P of six rain gauges within the grasslands and the increase of MODIS LAI around these measurements ($R^2=0.80$, n=270).

Modelled ET is plausible and fits in the range of published results. ET was demonstrated to be highly variable in both time and space: the high spatiotemporal variability of eight-day ET is reflected by the coefficients of variation, which varied between 25% and 40% for the whole study area and were up to 75% for individual pixels. Soil evaporation reacts considerably more sensitively to precipitation pulses than transpiration. Modelled annual ET sums approached or exceeded precipitation sums in general; however, P exceeded ET in 2003, when exceptionally high precipitation occurred. The strong dynamics and the high spatiotemporal variability of ET clearly demonstrate that the current static livestock management is not adapted to the conditions of Inner Mongolian grasslands. New concepts for a sustainable livestock management could be developed in consideration of the intrinsic long-term patterns of spatial ET distribution and spatiotemporal variability identified in this work. Moreover, as this method for modelling spatial ET is not restricted to the grasslands of the Xilin River catchment, livestock management in other semi-arid grasslands could benefit from it as well.

Kurzfassung

Die Grasländer der Inneren Mongolei sind Teil des riesigen eurasischen Steppengürtels und wurden seit Tausenden von Jahren für die nomadische Weidewirtschaft genutzt. Als Folge der politischen und wirtschaftlichen Veränderungen in China im letzten Jahrhundert ist diese mobile Weidewirtschaft durch eine ortsgebundene und intensivierte Tierhaltung ersetzt worden. Besatzdichten wurden erheblich erhöht und die Tragfähigkeit der Grasländer wurde deutlich überschritten. Diese Landnutzungsänderungen haben schwerwiegende Degradationserscheinungen der Grasländer induziert. Die Ursachen und Auswirkungen der Degradation sind von der Deutsch-Chinesischen-Forschungsgruppe MAGIM (Matter fluxes in grasslands of Inner Mongolia as influenced by stocking rate) im Einzugsgebiet des Xilin-Flusses in der Inneren Mongolei seit 2004 untersucht worden. Diese Arbeit wurde im Rahmen des Teilprojektes P6 erstellt, welches unter anderem das Ziel verfolgt, Wasserhaushaltsprozesse mit Mikrometeorologie und Fernerkundung zu quantifizieren.

Der dominierende Prozess der Wasserbilanz-Verluste in den Grasländern der Inneren Mongolei ist die Verdunstung (ET), wobei Wasserdampf in die untere Atmosphäre freigesetzt wird. ET ist in diesem semi-ariden Ökosystem in Zeit und Raum sehr variabel, da an die in der Regel schwankenden Niederschläge (P) gekoppelt. Trotz der Schlüsselrolle, die ET im Wasserkreislauf der Inneren Mongolei einnimmt, und der wichtigen Rolle als Indikator für die Funktionsweise des Ökosystems, ist wenig über die raum-zeitliche Verteilung und Variabilität von ET in dieser abgelegenen Region bekannt. Neuere Studien haben ET-Schwankungen aufgrund von Phänologie, Bodenfeuchte und Bodennutzung dargestellt, aber diese Studien sind auf kurze Zeiträume beschränkt und wurden auf nur wenigen Standorten, die sich in

unmittelbarer Nähe befinden, durchgeführt. Dies stellt ihre Repräsentativität für die 2600 km² an Grasland im Xilin-Einzugsgebiet in Frage. Die Entwicklung von Fernerkundungsmethoden in den letzten Jahrzehnten hat verschiedene Ansätze zur Bestimmung der räumlichen ET hervorgebracht, jedoch ist die Anwendung von ET aus Fernerkundungsdaten in regionalen Langzeitstudien immer noch problematisch. Dennoch werden eine Vielzahl von Oberflächenparametern durch den Sensor MODIS (Moderate Resolution Imaging Spectroradiometer) bei einer Auflösung von ca. 1km zur Verfügung gestellt.

Das Ziel dieser Arbeit war (1) die Lücke zwischen den verfügbaren lokalen ET-Messungen und dem Bedarf an langfristigen Untersuchungen zu räumlicher ET im Grasland der Inneren Mongolei zu schließen und (2) die räumlich-zeitliche Variabilität von ET vor dem Hintergrund des Beweidungsmanagements zu analysieren. Daher wurden mikrometeorologische Daten, Fernerkundungsprodukte und hydrologische Modellierungen mit BROOK90 integriert, um die räumliche ET für die Grasländer des Xilin-Einzugsgebietes über 10 Jahre zu modellieren. Das hydrologische Modell BROOK90 berechnet ET auf Basis eines modifizierten Penman-Monteith-Ansatzes einschließlich der Aufteilung in Transpiration und Bodenverdunstung. Die räumliche Anwendung des Standortmodells basiert auf einer Landnutzungsklassifikation und wurde für die Landnutzungsklasse *typical steppe* durchgeführt. Eddy-Kovarianz-Messungen, Bodeneigenschaften und MODIS-Blattflächenindex (LAI) wurden zur Parametrisierung von BROOK90 verwendet. Sowohl Lage- und Pflanzenparameter, als auch die notwendigen Modelleingangsdaten (Tageswerte von P und Lufttemperaturen), wurden für jeden Pixel individuell zur Verfügung gestellt. Minimum- und Maximum-Lufttemperaturen wurden mittels einer Beziehung zwischen gemessenen Lufttemperaturen und MODIS-Oberflächentemperaturen berechnet (R^2=0.92 und R^2=0.87, n=81). Räumliche P wurden aus einem Zusammenhang zwischen gemessenen kumulierten P von sechs Niederschlagsmessern im Untersuchungsgebiet und der Erhöhung des MODIS-LAI im Bereich dieser Messungen abgeleitet (R^2=0.80, n=270).

Die modellierte räumliche ET ist plausibel und liegt im Wertebereich der publizierten Ergebnisse. Es wurde gezeigt, das ET sehr variabel in Raum und Zeit ist: die raum-zeitlichen Schwankungen der achttägigen ET wurden durch den Variationskoeffizienten dargestellt, welcher zwischen 25% und 40% für das gesamte Untersuchungsgebiet variiert und für einzelne Pixel bis auf 75% ansteigt. Die Bodenverdunstung reagiert wesentlich empfindlicher auf Niederschlagsereignisse als die Transpiration. Modellierte Jahres-ET-Summen erreichen oder überschritten die Niederschlagssummen in der Regel, jedoch übertraf P die ET im Jahre 2003, als außergewöhnlich hohe Niederschläge aufgetreten sind. Die starke Dynamik und die hohe raum-zeitliche Variabilität der ET zeigen deutlich, dass die aktuelle statische Tierhaltung nicht an die Bedingungen in den Innermongolischen Grasländern angepasst ist. Neue Konzepte für eine nachhaltige Viehwirtschaft könnten unter Berücksichtigung der inhärenten langfristigen Muster der räumlichen Verteilung von ET und ihrer raum-zeitlichen Variabilität, die in dieser Arbeit identifiziert wurden, entwickelt werden. Außerdem ist die Anwendung der entwickelten Methode für die Modellierung räumlicher ET nicht auf die Grasländer des Xilin-Einzugsgebietes beschränkt; die Weidewirtschaft in anderen semi-ariden Grasländern könnte ebenfalls davon profitieren.

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Erklärung

Hiermit versichere ich, dass ich die vorliegende Arbeit ohne unzulässige Hilfe Dritter und ohne Benutzung anderer als der angegebenen Hilfsmittel angefertigt habe; die aus fremden Quellen direkt oder indirekt übernommenen Gedanken sind als diese kenntlich gemacht worden. Bei der Auswahl und Auswertung des Materials sowie bei der Herstellung des Manuskriptes habe ich Unterstützungsleistungen von folgenden Personen erhalten:

- Prof. Dr. Christian Bernhofer (TU Dresden, Professur für Meteorologie)
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- Dipl. Hydrol. Sylvia Vetter (ehem. TU Dresden, Professur für Meteorologie)

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David Schaffrath, Tharandt, 31.01.2014

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Abbrevations

CNERN	Chinese National Ecosystem Research Network
CV	Coefficient of variation
EC	Eddy covariance
E	Soil evaporation
ET	Evapotranspiration
GPCP	Global Precipitation Climatology Project
IMGERS	Inner Mongolia Grassland Ecosystem Research Station
LAI	Leaf area index
MAGIM	Matter Fluxes in Grassland Ecosystems of Inner Mongolia
MODIS	Moderate Resolution Imaging Spectroradiometer
PET	Potential evapotranspiration
P	Precipitation
PDF	Probability density function
P-M	Penman-Monteith
RMSE	Root mean square error
T	Transpiration
Ts	Surface temperature

1. Introduction

This doctoral thesis was imbedded in the multidisciplinary Sino-German joint research project MAGIM (Matter Fluxes in Grassland Ecosystems of Inner Mongolia), which was funded by the German Science Foundation (Deutsche Forschungsgemeinschaft, DFG, Research Group 536). The principal objective of MAGIM was to analyse the effects of different grazing management systems on grassland productivity, on plant species diversity and on both nutrient and water cycles including biosphere-atmosphere exchange processes on the local and regional scales in the grasslands of the Xilin River catchment of Inner Mongolia, China (Butterbach-Bahl et al. 2011).

The grasslands of Inner Mongolia are considered representative for the vast area of the Eurasian steppe (Bai et al. 2004) stretching from south-eastern Europe to northern China. Grasslands are one of the most widespread terrestrial ecosystems worldwide, and they cover approximately one-fifth of terrestrial land surface (Allard et al. 2007). Inner Mongolian grasslands are of great ecological, economic and cultural importance (according to Jiang et al. 2006, Kang et al. 2007), and they are referred to as the pastures of highest quality in China (Chen et al. 2008) and thus are almost entirely used for livestock grazing (Wiesmeier et al. 2011). Livestock husbandry mainly by grazing sheep has been the most important source of income for the local population for thousands of years.

Traditionally and until the middle of the twentieth century, Inner Mongolian grasslands were used for nomadic pastoralism, a socio-ecological way of culture which was adjusted to the carrying capacity of the environment (Scholz 1995) and thus proved to be sustainable. The extensive and mobile grazing management of nomadism has been substituted by a more intensive and sedentary livestock management in the 1950s and 1960s. As a result of political decisions and population pressure in China, Han Chinese farmers were settled into small villages or at individual farms in the grasslands and the former local people were forced to give up their nomadic way of life (Sneath 1998). Thus, grazing pressure increased around the settlements, and the total livestock numbers increased considerably. The area for one sheep decreased from 6.8 ha in the 1950s to 1.6 ha in the 1980s (Yiruhan et al. 2001). Kawamura et al. (2005) reported a further decrease and an average grazing intensity increase of 0.67 sheep units per hectare in the grasslands of the Xilin River in 2001.

Severe phenomena of degradation and desertification were introduced as a consequence of the current livestock management in Inner

Mongolian grasslands (Brogaard and Zhao 2002, Jiang et al. 2006, Han et al. 2009). The degradation is reflected in severe losses of soil organic matter, depletion of nutrients (Steffens et al. 2008) and in decrease of biomass, height and cover as well as species composition shifts (White et al. 2000, Zhao et al. 2005) reducing primary productivity and slowly converting the typical steppe grasslands into a less productive desert steppe (Tong et al. 2004). The increasing vulnerability to erosion eventually allows for frequent dust storms in Inner Mongolian grasslands, which originally were a sink area for dust and thus are considered a carbon pool of global significance (Breuer et al. 2004). However, the decrease of vegetation due to heavy grazing prevents dust deposition and promotes wind erosion (Hoffmann et al. 2008, Reiche et al. 2012).

Altogether, the degradation constitutes a central environmental problem, and its impact affects the livelihood of millions of local inhabitants in the grasslands and in the contiguous Chinese mainland. The reduced amount of available food resources for the livestock and the impaired living conditions for the population are contrary to an increased demand for food and space of the growing population in China.

As a consequence of the intrinsic value of Inner Mongolian grasslands and their drastic environmental changes, these grasslands have been a focus of research for more than 30 years. The Inner Mongolia Grassland Ecosystem Research Station (IMGERS) was set up in the grasslands of the Xilin River catchment in 1979 and became one of the key stations of the Chinese National Ecosystem Research Network (CNERN) in 1992. IMGERS was established to study the structure and mechanisms of the typical steppe grassland, for long-term monitoring of biotic and abiotic ecosystem drivers and to develop practical techniques for a sustainable resource utilisation and grassland restoration (CNERN 2006). The ecological research conducted in these grasslands in the fields of soil science, plant ecology, animal production, micrometeorology and remote sensing and their published results contribute to a better understanding of ecosystem functioning and to the protection and restoration of these grasslands as a reaction on the increasing public awareness of their degradation (Butterbach-Bahl et al. 2011).

Recent studies of the MAGIM project were collected in a special issue of the journal *Plant and Soil* (vol. 340, 1-2). In this issue, the ecological and economic conditions in the Xilin River catchment are integrated with the results of the MAGIM project by Butterbach-Bahl et al. (2011). They suggested considering the extreme sensitivity of the grasslands to stocking rates for the further development of the livestock management.

Other studies conducted on Inner Mongolian grasslands also have made clear that adjusting the currently poorly adapted land management practices is essential for the restoration and protection of the fragile ecosystems (Chen et al. 2003, Tong et al. 2004, Jiang et al. 2006, Han et al. 2009, Schönbach et al. 2009). However, although a few approaches may help toward adjusting the grazing management, e.g., by periodic grazing cessation (Liu et al. 2011) or biennial rotation of grazing and hay-making (Schönbach et al. 2011), a final clarification of potential solutions has not been achieved yet. On one hand, this is impeded due to the short-term economic benefits of high stocking rates proving the practical implementation to be difficult. On the other hand, the significant influence of the interannual and seasonal distribution of precipitation (P), temperature and soil moisture on vegetation dynamics and thus, available food resources for the livestock, are critical. The high interannual variability of P in this area is demonstrated by meteorological data of IMGERS showing P varying from 170 mm to 500 mm between 1982 and 2005 and, e.g., by the study of Xiao et al.

(1995) who demonstrated the importance of seasonal patterns of P to be as important as annual P in influencing primary production. The results of a controlled grazing experiment which was conducted over a six-year period within MAGIM, revealed the complex interactions of climate, vegetation and grazing (Ren et al. 2012, Auerswald et al. 2012).

Consequently, after investigating P as the major input to the water cycle, this study concentrates on evapotranspiration as its major output as well as on modelling the processes that link both within the hydrological cycle. Evapotranspiration (ET) is the combination of two fundamental processes of the hydrological cycle whereby water is converted to water vapour from the soil surface by evaporation and from the crop by transpiration (Allen et al. 1998). ET is site-specific as it depends on available water and energy (Li et al. 2007). In semi-arid environments such as Inner Mongolian grasslands ET is mainly controlled by the phenology of vegetation and soil water content (Zhao et al. 2007, Ketzer et al. 2008). ET almost entirely dominates water balance losses into the lower atmosphere in this region integrating other environmental factors, e.g., the abundance of P and its interactions with soils and vegetation. Despite the important role of ET, very little is known about the spatial distribution and variability of ET in the grasslands of the Xilin River catchment.

Regarding the variability of available water in the semi-arid Inner Mongolian grasslands and ET indicating ecosystem functioning, a spatiotemporal study of ET could enhance the understanding of inherent dynamics and variations. Knowledge of the spatial and temporal ET variability thus could be beneficial for the restoration and sustainable use of grasslands, and thus be a useful tool for the development of grassland management techniques.

Recently, a number of studies on ET in the grasslands of the Xilin River were published, e.g., Hao et al. (2007), Miao et al. (2009), Huang et al. (2010) and Wang et al. (2012). In these studies ET was measured in-situ at selected points by micrometeorology using the eddy-covariance (EC) method. The EC method is a widespread technique which is applied to measure the exchange of water vapour, carbon and energy between the surface and atmosphere (Baldocchi 2003, Grünwald and Bernhofer 2007). The results of ET studies in Inner Mongolian grasslands displayed ET varied in response to the phenology of vegetation and soil moisture (Hao et al. 2007) which is coupled to P (Miao et al. 2009). Hao et al. (2007) and Huang et al. (2010) reported ET to be close to zero in winter and peak ET to be 4 mm d^{-1} in summer whereas Wang et al. (2012) recorded a slightly higher maximum of almost 4.85 mm d^{-1}. All four studies indicated ET consuming P almost completely. In addition, ET was much smaller than the potential evapotranspiration (PET) indicating water stress, which could last over the whole growing season as in 2005 (Huang et al. 2010, Wang et al. 2012). The studies of Wang et al. (2012) and Miao et al. (2009) also revealed grazing to reduce ET as it significantly affects surface characteristics: surface temperatures and albedo are increased and soil water content may be reduced by grazing due to grazing effects on energy partitioning (Wang et al. 2012).

It is obvious that the ET studies conducted in Inner Mongolian grasslands provide valuable results for a better understanding of the local conditions and processes. However, although the study of Wang et al. (2012) was conducted over different land use regimes (ungrazed, continuously grazed and heavily grazed) it was performed in the same area and therefore refers to ET of a small section of the grasslands of the Xilin River catchment only with a most likely limited spatial variability in P. ET data of Hao et al. (2007), Miao et al. (2009) and Huang et al. (2010) was also measured in close vicinity to the study area of Wang et al. (2012), which, in consequence, condenses these studies to a small sample point within the 2600 km² grassland area of the Xilin River catchment. The published ET studies in these grasslands also cover relatively short periods of mostly two growing seasons each. Hao et al. (2007) observed ET in 2003 and 2004; Wang et al. (2012) reported 2005 and 2006 data; Miao et al. (2009) published results of 2006 and 2007 measurements. Huang et al. (2010) used EC data of four consecutive years (2003-2006) in their study. However, little is still known about the temporal and spatial distribution and variability of ET in the grasslands of the Xilin River, particularly over a longer period which is characterised by a high variability of precipitation (P) and green vegetation and thus ET.

The use of periodical remote sensing data is a potential tool for the spatial estimation of ET in the long-term because the installation and maintenance of the necessarily large number of micrometeorological towers or lysimeters is not practically feasible. The current actual limited number of stations already require plenty of time and effort, particularly in sparsely populated rural areas such as Inner Mongolian grasslands.

Quite a few approaches for the estimation of regional and global ET from remote sensing were developed over the last decades but the estimation of periodical spatial ET is still a challenge. Many approaches were recently reviewed and summarised by Kalma et al. (2008) and by Li et al. (2009). The authors noticed ET is often provided only during the time the satellite passes by on clear sky days. In general, the accuracy of the results varies greatly. Kalma et al. (2009) displayed the relative errors of some 30 published validations to be 15-30% or an average root mean square error (RMSE) of 50 W m^{-2}. Li et al. (2008) also conclude the more advanced physically based energy-balance models rely on ground-based measurements to a certain degree to derive turbulent heat flux on a regional scale. Kalma et al. (2009) discussed the problems of temporal scaling to extrapolate instantaneous ET to daily and longer periods and spatial scaling as well as multi-sensor data fusion techniques to manage intermittent sensor observations.

However, Cleugh et al. (2007) tested a Penman-Monteith (P-M) based approach in combination with MODIS (Moderate resolution imaging spectroradiometer) data for temperate forest and grazed savannah in Australia at 1-km resolution. Their work displayed good results (RMSE = 27 W m^{-2}) and was applied to model a three-year climatology of monthly ET for the Australian continent at 0.05° resolution. Thus, they displayed the possibility of using remote sensing data as spatial input for solving the well-known P-M equation.

In this work, the intend is to use the physically-based hydrological model BROOK90 (Federer et al. 2003, Federer 2013) to model ET for Inner Mongolian grasslands, as it provides detailed simulations of ET based on a daily time-step, requires little input data after parameterisation and is based on a P-M approach. The spatial application of BROOK90 is intended whereas the spatial information will be provided by MODIS data of the polar-orbiting TERRA satellite, which has a daily overpass before noon and before midnight. For more than 10 years, the MODIS science team regularly provides variables, e.g., leaf area index (LAI) and surface temperature (Ts) as eight-day composites at 1-km resolution in a processed form to users globally and free of charge.

According to the stated background and problems, the research questions posed in this doctoral thesis are as follows:

- Is it possible to derive spatial ET for the grasslands of the Xilin River catchment although ET was measured at just a few field sites in the vicinity of IMGERS, whereas P and green vegetation are characterised by a high spatial and temporal variability?

- Is the combination of remote sensing data, hydrological modelling and field data for model parameterisation suited to close the gap between local ET measurements and the high spatiotemporal variability of water budget components?

These general questions lead to more detailed specific questions such as

- Can the effect of interannual and spatial rainfall variability on green vegetation be detected by the MODIS leaf area index (LAI) in the Xilin catchment?

- How can the hydrological model BROOK90 be applied and parameterised for spatial modelling of ET?

- How can spatial P, as a precondition for the modelling of ET, be estimated? Is it possible to derive it from MODIS data?

- Can the long-term variability of ET be quantified in the grasslands of the Xilin river with this method?

- How do the ET results compare to published data and available data sets?

- What are the implications of spatial ET results on grazing management?

These questions are addressed in two main objectives:

(1) Development of a method for the periodical identification of spatial evapotranspiration in the grasslands of the Xilin River catchment, Inner Mongolia,

(2) Determination of the spatial and temporal dynamics and variability as well as the annual and long-term spatial patterns of ET in this area over a period of 10 consecutive growing seasons.

An aim-oriented step-by-step approach was applied to address the stated objectives:

(i) In a first step, an analysis of the state, temporal and spatial variability of vegetation and of precipitation (P) data of the Xilin River catchment was conducted. LAI, based on satellite measurements from MODIS, GPCP (Global Precipitation Climatology Project) data and in-situ P data of six stations was utilised to study the spatiotemporal distribution and dynamics of both variables as well as their interaction in the Xilin River catchment.

(ii) The second step was intended for demonstrating the feasibility of combining remote sensing (MODIS) and EC data-based parameters with the hydrological model BROOK90 to simulate spatial ET of a 4x4 pixel test site in the vicinity of the well-known and documented field sites. During this step, BROOK90 was parameterised and its robustness was tested by stepwise reduction of meteorological input data. A simple relationship between mean LAI and P, which was found within (i), was used to generate different P input data for each grid cell.

(iii) Then, the approach of (ii) was modified to extend the applicability from test site level to the entire grassland area of the Xilin River catchment (2600 km²). The method was modified to derive ET from MODIS data and the BROOK90 model without the necessity for additional ground-based information once the model is parameterised. The main challenge of this step was the estimation of P for each individual pixel as the high spatial variability of P neither allows for the application of the algorithm used in (ii) nor for spatial interpolation of observed P from the few stations.

(iv) Finally, based on the development in the second and third step, the method was applied over a period of 10 years. Model results were analysed to identify the spatial and temporal variability as well as the spatial patterns of ET from 2002 to 2011.

The results of each of these four steps have been published as a single peer-reviewed publication each in international peer-reviewed journals, which are presented in the following chapters. A list containing these publications and their Digital Object Identifier is provided at the end of this document.

2. Spatiotemporal variability of grassland vegetation cover in a catchment in Inner Mongolia, China, derived from MODIS data products

Schaffrath D, Barthold FK, Bernhofer C (2011) Spatiotemporal variability of grassland vegetation cover in a catchment in Inner Mongolia, China, derived from MODIS data products, Plant Soil 340, 181-198.

Full article is available under

→ http://dx.doi.org/10.1007/s11104-010-0465-4

3. Spatial simulation of evapotranspiration of semi-arid Inner Mongolian grassland based on MODIS and eddy covariance data

Vetter SH, Schaffrath D, Bernhofer C (2012) Spatial simulation of evapotranspiration of semi-arid Inner Mongolian grassland based on MODIS and eddy covariance data, Environ. Earth Sci. 65 (5), 1567-1574.

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Variability and distribution of spatial evapotranspiration in semi arid Inner Mongolian grasslands from 2002 to 2011

David Schaffrath[1,2*] and Christian Bernhofer[1]

Abstract

Grasslands in Inner Mongolia are important for livestock farming while ecosystem functioning and water consumption are dominated by evapotranspiration (ET). In this paper we studied the spatiotemporal distribution and variability of ET and its components in Inner Mongolian grasslands over a period of 10 years, from 2002 to 2011. ET was modelled pixel-wise for more than 3000 1 km^2 pixels with the physically-based hydrological model BROOK90. The model was parameterised from eddy-covariance measurements and daily input was generated from MODIS leaf area index and surface temperatures. Modelled ET was also compared with the ET provided by the MODIS MOD16 ET data.

The study showed ET to be highly variable in both time and space in Inner Mongolian grasslands. The mean coefficient of variation of 8-day ET in the study area varied between 25% and 40% and was up to 75% for individual pixels indicating a high innerannual variability of ET. Generally, ET equals or exceeds P during the vegetation period, but high precipitation in 2003 clearly exceeded ET in this year indicating a recharge of soil moisture and groundwater. Despite the high interannual and innerannual variations of spatial ET, the study also showed the existence of an intrinsic long-term spatial pattern of ET distribution, which can be explained partly by altitude and longitude ($R^2 = 0.49$). In conclusion, the results of this research suggest the development of dynamic and productive rangeland management systems according to the inherent variability of rainfall, productivity and ET in order to restore and protect Inner Mongolian grasslands.

Keywords: BROOK90; MODIS; MAGIM; LAI; Steppe; Xilin; Grazing; Precipitation; Long-term

Introduction

Evapotranspiration (ET) indicates ecosystem functioning in the semi-arid grasslands of Inner Mongolia, since it is controlled by the phenology of vegetation and soil moisture (Zhao et al. 2007, Ketzer et al. 2008) and dominates water balance losses into the lower atmosphere almost entirely in this region (Vetter et al. 2012). Although several field studies on ET exist in the Xilin river catchment of Inner Mongolia, China (Hao et al. 2007, 2008, Huang et al. 2010, Miao et al. 2009 and Wang et al. 2012), these studies are restricted by a short period up to a few years and refer to point measurements of a few field sites in this area only. Thus, only little is known about ET of a longer period and about its spatial distribution and variability in this area, where precipitation (P), green vegetation and consequently the components of ET, soil evaporation (E), transpiration (T) and evaporation from intercepted rain (E_i) are highly variable in both time and space. According to the common variability of these parameters, the grasslands were used by nomads as pastures for centuries. The current livestock management, which is static and exceeds the carrying capacity of the grassland ecosystem, introduced severe problems of degradation and desertification in this area and in Inner Asia in general (Han et al., 2009; Jiang et al., 2006, Brogaard and Zhao 2002, Sneath 1998, Reiche et al. 2009). Tong et al. (2004) reported these grasslands are affected by a decrease of vegetation biomass, height and cover as well as species composition shifts, which slowly

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convert the typical steppe into a less productive desert steppe. The negative impacts of the ongoing processes of degradation are, e.g., the reduction of the available food resources for the livestock and reduced living conditions for the people due to the increasing vulnerability to erosion. The enormous area of Chinese grasslands (approx. 4 Mio. km^2) have been a sink area for dust over centuries, but the recent decrease of vegetation, which is mainly caused by overgrazing and unadapted livestock management, prevents dust deposition and promotes wind erosion (Hoffmann et al. 2008, Reiche et al. 2012a). Grassland degradation and its accompanying problems, e.g., dust storms, constitute a central environmental problem for the livelihood of the local population in grasslands and the surrounding Chinese mainland. The results of the intense ecological research activities in these grasslands approve the necessity of the development and adjustment of the land management practices to restore and protect the fragile ecosystems of the Xilin river catchment as suggested by a number of recent publications, e.g., Jiang et al. (2006), Han et al. (2009), Schönbach et al. (2009) and Butterbach-Bahl et al. (2011). The six years of a controlled grazing experiment showed the importance of the seasonal distribution of P, temperature and soil moisture on vegetation dynamics and indicated the complex interaction of grazing, vegetation and climate (Auerswald et al. 2012, Ren et al. 2012). However, these studies and the majority of the ecological grassland studies in Inner Mongolia were conducted in the vicinity of the Inner Mongolia Grassland Ecosystem Research Station (IMGERS) and on the point or plot scale. Regarding the recognised sensitivity of the grassland conditions to the spatial and temporal variability of available water and the dominating role of ET on ecosystem functioning of semi arid regions, the spatiotemporal investigation of ET for a larger area and over a longer period can enhance the understanding of the inherent variability and dynamics of the Inner Mongolian grasslands to support the development of better adapted and sustainable livestock management systems. Hence, the objective of this study is the identification of the spatial and temporal variability of ET and T in the grasslands of the Xilin river catchment over a longer period and the spatial pattern of long-term ET. Therefore, we applied the approach of Schaffrath et al. (2013), which allows for the spatial application of the hydrological model BROOK90 (Federer 2002) and thus, the calculation of ET and its components (E, T and E_i) during the vast bulk of the rainy season and vegetation period. The approach of Schaffrath et al. (2013) clearly showed the capability of detecting the spatial and temporal distribution of P and ET in this area in 1 km and 8-day resolution with only a few additional ground-based data, mainly needed for model calibration. These data were derived from eddy-covariance (EC) based measurements. The necessary daily meteorological model input and the phenological course of vegetation were derived from 1 km MODIS (Moderate resolution imaging spectroradiometer) leaf area index (LAI) and surface temperature (Ts) data products. The available data enabled to model ET for ten consecutive growing seasons (from 2002 to 2011). Local P was estimated for more than 3000 grid cells in this remote area based on the linear relationship between MODIS LAI gain and measured P around six gauging stations ($R^2 = 0.76$, $n = 90$) (cp. Schaffrath et al. 2013). In this paper we tested the robustness of this approach with a larger dataset (270 observations). In addition, pixel-wise relief information was integrated into the model. Therefore, we derived altitude, slope and aspect (1 km resolution) from the SRTM (Shuttle Radar Topography Mission) data product.

Material and methods

Description of the study area

The study area is the typical steppe land use unit (approximately 2600 km^2) of the Xilin river catchment in the Inner Mongolia autonomous region of China. It is situated in the east of the Mongolian plateau between 44.13° N to 43.41° N and 116.12° E to 117.24° E. The elevation ranges between 1000 and 1500 m above sea level. The relief is characterized by relatively even plains, gentle hills, mountains and high plateaus. Figure 1 shows the location and a hillshade representation of the study area.

The typical steppe covers 72% or 2600 km^2 of the catchment and is considered representative of semi-arid temperate grasslands which are stretched over large parts (more than 40%) of China (Akiyama and Kawamura 2007, Fan et al. 2007, Kawamura et al. 2003). The Institute of Botany of the Chinese Academy of Science maintains the Inner Mongolia Grassland Ecosystem Research Station (IMGERS) in this area. IMGERS was established in 1979 to study the drivers and the functioning of the grassland ecosystem and focuses on the development of sustainable ecosystem management as well (Kang et al. 2007). These grasslands are comparably extensively researched, including the studies of the interdisciplinary Sino-German Research Group MAGIM (Matter fluxes in Grassland Ecosystems of Inner Mongolia), which were also conducted at IMGERS and its experimental field sites since 2004 (cp. Butterbach-Bahl et al. 2011).

In the study area, the climatic conditions are characterised by a strong contrast of long, cold and dry winters and short, warm and relatively wet summers. Spring and autumn are short transitional seasons (Domroes and Peng 1988). While the mean annual temperature is 1°C, the January mean temperature is −20°C and in July it is 21°C (Kawamura et al. 2005); the frost-free period generally lasts between 80 and 100 days. The amount and distribution of precipitation is highly variable and over 70% of the annual

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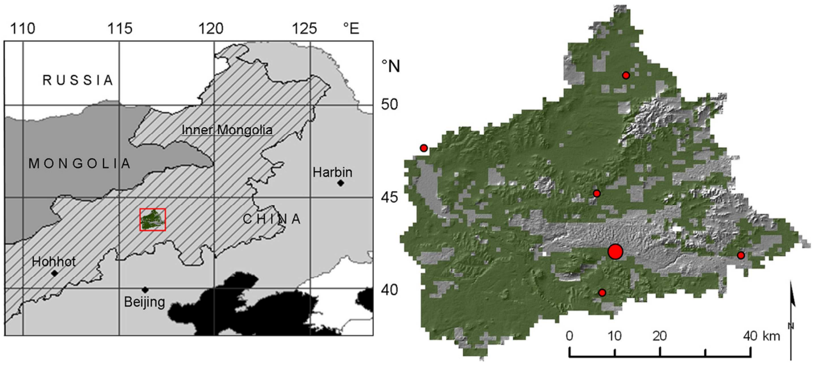

Figure 1 Location of the study area in Central Asia (left side) and hillshade map (right side) of the Xilin river catchment (grey). The study area is shown in 1 km resolution and in green colour (grassland or typical steppe), the location of precipitation measurements as red circles, the location of the Inner Mongolia Grassland Ecosystem Research Station (IMGERS) is depicted by the large red circle.

P falls between May and August (Chen et al. 2005), when moist air masses are transported from South-China and Japan towards this region. The long term annual mean P at IMGERS (1982–2005) is 330 mm, however annual P varies between 170 and 500 mm. Tong et al. (2004) and Schaffrath et al. (2011) reported the decline of P in northern directions in the Xilin river catchment.

According to the World Reference Base for Soil Resources (WRB), the most common soil groups of the study area are *Phaeozem*, *Chernozem* and *Kastanozem* which differ in colour, thickness and the amount and depth of secondary carbonates but they are also characterised by relatively small differences of soil texture, since sand is the dominant particle fraction (cp. Wiesmeier et al. 2011, Barthold et al. 2013). The vegetation of the study area is characterised by C3 grasses, mainly *Leymus chinensis* and *Stipa grandis*. However, degraded areas are characterised by a decrease of these species and an increased appearance of *Cleistogenes squarrosa* and *Artemisia frigida* (Tong et al. 2004). As these grasslands are the primary natural resources in this area and as they are referred to as the pastures of highest quality in China (Chen et al. 2008), they are almost entirely used for livestock grazing (Wiesmeier et al. 2011).

The hydrological model BROOK90

For this study, we used BROOK90 (Federer 2002, Federer et al. 2003), a sophisticated and process-oriented hydrological model that simulates the components of the total ET, transpiration (T), evaporation from intercepted rain (E_i) and soil evaporation (E), by a physically-based two-layer model (Shuttleworth and Wallace 1985), as well as vertical soil water movement and streamflow for a certain location at a daily time-step. BROOK90 has been applied for a variety of water balance related studies, e.g., Combalicer et al. (2010), Armbruster et al. (2004), Schwärzel et al. (2007, 2009), Vilhar et al. (2010) and Schaffrath et al. (2013). The model is parameter-rich: soil hydraulic parameters and root density are parameterised for several layers below ground, since matrix potential and hydraulic conductivity are essential for the simulation of soil water movement. Here, BROOK90 uses a modification of the Campbell (1974) expression with a near-saturation interpolation of the Clapp and Hornberger (1978) formulation. In BROOK90, canopy characteristics are described by year-round specification of LAI and vegetation height changes over the year. ET is modelled by a Shuttleworth and Wallace (1985) approach, which in turn is based on the Penman-Monteith equation (PM) here shown for latent heat flux (*L.ET*), Eq. (1):

$$L.ET = \frac{\Delta(R_n\text{-}G) + c_p\rho_a VPD/r_a}{\Delta + \gamma\left(1 + \frac{r_c}{r_a}\right)} \tag{1}$$

where *L.ET* is the latent heat flux from the canopy (W m^{-2}), Δ is the rate of change of saturation vapour pressure with temperature (Pa K^{-1}), R_n is the net radiation above the surface (W m^{-2}), G is the ground heat flux (W m^{-2}), c_p is the specific heat capacity of air at constant pressure (J kg^{-1} K^{-1}), ρ_a is the density of air (kg m^{-3}), VPD is the vapour pressure deficit in the air (Pa), γ is the psychrometric constant (Pa K^{-1}), r_c is the canopy resistance (s m^{-1}), and r_a is the aerodynamic resistance between the canopy and a reference height at which VPD is measured (s m^{-1}).

T and E are calculated separately by the Shuttleworth and Wallace (1985) modification of the PM equation where:

$$L.ET = L.T + L.E \tag{2}$$

and:

$$L.T = \frac{\Delta(A\text{-}A_s) + c_p\rho_a VPD/r_{ac}}{\Delta + \gamma + \gamma(r_{ss}/r_{ac})} \quad (3)$$

$$L.E = \frac{\Delta A_s + c_p\rho_a VPD_o/r_{as}}{\Delta + \gamma + \gamma(r_{ss}/r_{as})} \quad (4)$$

with VPD_0 the vapour pressure deficit at the effective source height (Pa), A is R_n - G or the available energy above the canopy (W m^{-2}), and A_s is R_{ns} - G or the available energy at the ground (W m^{-2}), R_{ns} is the net radiation above the soil surface (W m^{-2}). The different water vapour and sensible heat pathways and resistances from the soil and from the canopy are taken into account by the model, since resistances are defined separately as: canopy surface resistance (r_{sc}), resistance to restrict vapour movement from the leaf surfaces to the effective source height for water vapour in the canopy (r_{ac}), resistance to movement of water vapour from inside the soil to the soil surface (r_{ss}) and resistance to vapour movement from the soil surface to the source height (r_{as}).

In general, potential T is based on maximum leaf conductance and vapour pressure deficit (VPD). However, actual T is reduced below potential T when water supply to the plant is limited by plant resistance, rhizosphere resistance and minimum leaf water potential (Federer et al. 2003). The aerodynamic resistance varies according to leaf area index and canopy height; it is modified from Shuttleworth and Gurney (1990). E is calculated from soil water potential in the top soil layer; potential E_i is calculated indirectly from the existing soil surface wetness of the Shuttleworth and Wallace equation and the canopy height (Federer 1996). Further and more detailed information about BROOK90 are provided by Federer et al. (2003); a helpful and detailed tool is the online documentation of the model (Federer 2002).

Parameterisation of BROOK90

Micrometeorological data of the MAGIM project were used for the initial parameterisation of BROOK90 (Vetter et al. 2012): between 2004 to 2009 eddy covariance (EC) measurements were conducted at several grassland sites differing in livestock management (ungrazed, winter grazed, continually grazed, heavily grazed) to obtain representative data on the conditions of typical steppe in the Xilin river catchment (Ketzer et al. 2008, Wang et al. 2012). The EC towers were equipped with three-dimensional sonic anemometers *CSAT3* (Campell Scientific, USA) to detect the turbulent fluctuations of temperature and wind. *LI-7500* (LI-COR Inc., USA) infrared gas analysers were used for the measurement of H_2O and CO_2 concentrations. Ketzer et al. (2008) and Wang et al. (2012) describe the setup design of these towers in more detail. The measured and calculated values of ET, radiation flux density, soil heat flux density, air temperature, humidity, and precipitation as well as information on LAI and soil parameters were used for the initial parameterisation of BROOK90, which concentrated on the period from May through September since there is little to no plant activity from October to April. Also, ET is very small during this period. Since the model does not allow for year-round specifications of albedo, it was set to 0.2 as suggested for temperate grasslands by Federer et al. (2003). This value is also in good agreement to our measurements and research (Fan et al. 2007, Ketzer et al. 2008). Canopy conductance (g_c), which determines transpiration and thus, largely influences the simulated output, was estimated from daily ET (converted to latent heat flux *L.ET*) of the EC measurements using a re-arranged PM equation (Eq. 5):

$$r_c = \frac{1}{g_c} = \left(\frac{\Delta}{\gamma}\beta - 1\right)\cdot r_a + \left(\frac{\rho_a c_p}{\gamma}\frac{VPD}{L.ET}\right) \quad (5)$$

where: r_c is the canopy resistance (s m^{-1}), β is the Bowen ratio (H L.ET^{-1}), r_a is the aerodynamic resistance (s m^{-1}) which was estimated according to Thom and Oliver (1977), ρ_a is the density of the air (kg m^{-3}), c_p is the specific heat capacity of air at constant pressure (J kg^{-1} K^{-1}), γ is the psychrometric constant (Pa K^{-1}) *VPD* is the saturation vapour pressure deficit (Pa), and *L.ET* is the latent heat flux (W m^{-2}).

According to the analysis, g_c showed a clear dependency on VPD and soil moisture and the typical maximum $g_{c,\ max}$ (95% quantile) was 6 mm s^{-1}. The model uses maximum $g_{c,\ max}$ according to Jarvis (1976); depending on the effects of temperature, VPD, soil moisture and incoming short-wave radiation on stomatal opening, g_c is set to a fraction of $g_{c,\ max}$.

A more detailed background on the initial parameterisation of BROOK90 for the grasslands of the study area, validation and simulated results at the experimental field sites of MAGIM are summarised by Vetter et al. (2012) and Schaffrath et al. (2013). This study is based on the initial parameterisation of the model with several modifications for the application in a much larger area. An overview of the organisation of parameters and daily input data are shown in Figure 2. The concept is based on the work of Schaffrath et al. (2013) who calculated ET separately for every 1 km^2 pixel of the study area. Individual parameters were used if available (e.g. LAI, latitude, slope and aspect), but some general assumptions were necessary due to limited field data: the same relative root distribution over depth has been used as described for temperate grasslands according to Jackson et al. (1996) and Federer et al. (2003) and one standard soil profile for all pixels was generated, although the analysis of soil texture of more than 30 soil profiles sampled within the study area by the MAGIM project (Wiesmeier et al. 2009, Wiesmeier et al.

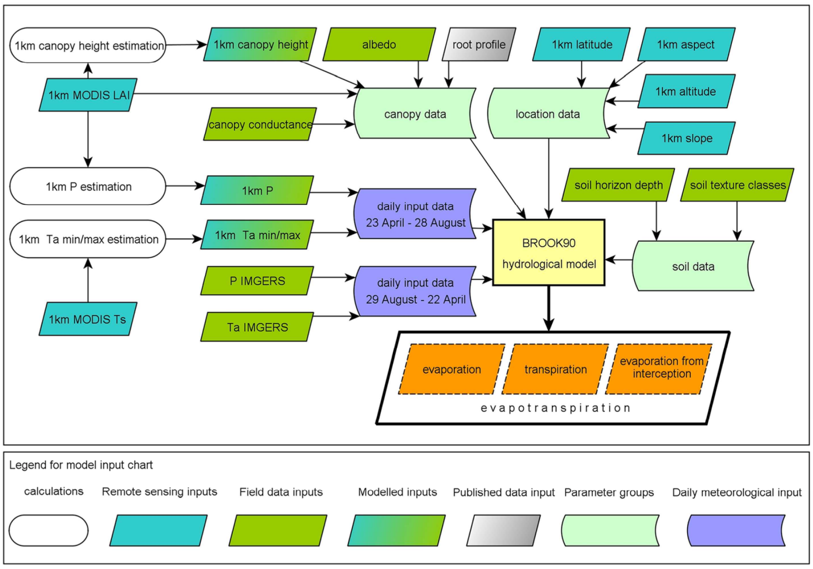

Figure 2 Flowchart of the sources and organisation of model input and parameters for the calculation of spatial ET.

2011, Steffens et al. 2011) showed some variations in the partitioning of the material. However, sand is the dominating particle fraction in the soils of the study area and the effect of the variations in texture on ET was found to be relatively small: the entire range of observed texture profiles was simulated to quantify the effect of the variations on ET in a small test area in Vetter et al. (2012). Then, three soil profiles that resulted in the minimum, mean and maximum ET were simulated for the whole study area in 2006 by Schaffrath et al. (2013). The results showed some effects on ET which deviated between −11% and +6% from ET simulated with the soil profile used in this study that is considered representative for the study area as it is resulting in average values of ET (Table 1). Also, since BROOK90 deduces soil water retention and movement from soil texture classes, minor differences are neglected by the model. Individual LAI was taken from the MODIS MOD15 data product (collection 5) and the dates and values of the most significant LAI changes were parameterised during the course of every year. MOD15 LAI is available every 8 days and contains the highest LAI at a pixel during an 8-day observation period. BROOK90 provides 10 supporting points for the annual LAI course. The LAI of DOY (Day of the year) 1 and DOY 366 were set to zero for all pixels. DOY 113 (23 April) and DOY 240 (28 August), which are the start and the end dates of the study period, were linked with the LAI at that time. The remaining six dates were filled with the DOY and LAI of the six most significant LAI-changes. Vegetation height (h, in cm) was roughly estimated (h = 35.5 LAI, $R^2 = 0.49$), based on a relationship between measured vegetation height and LAI data from MAGIM as well as from publications (Fan et al. 2009, Zhang and Zhao 2009). These data were implemented analogously to LAI. Information on latitude was taken from the MODIS coordinates. Individual 1 km values of altitude, aspect, and slope were calculated from the SRTM (Shuttle Radar Topography Mission) data product.

Calculation of daily model input

One important reason for using BROOK90 in this study is the ability of the model to derive necessary calculation

Table 1 Parameters of the soil profile used in this study

Soil horizon	Texture class	Thickness (cm)	S%	ψ_f kPa	θ_f m^3 m^{-3}	θ_s m^3 m^{-3}	K_f mm d^{-1}
A1	sandy clay loam	45	0	−6.3	0.317	0.420	4.2
A2	sandy loam	23	0	−7.9	0.266	0.435	5.5
C	loamy sand	50	0	−3.8	0.203	0.410	3.5

Soil hydraulic parameters and thickness were deduced from texture of available data (> 30 samples of soils in the typical steppe land use unit of the Xilin river catchment) after Clapp and Hornberger (1978), provided by Federer (2002), the most important soil parameter input for BROOK90 are stone fraction (S), matrix potential at field capacity (ψ_f), volumetric water content at field capacity (θ_f), porosity / water content at saturation (θ_s), hydraulic conductivity at field capacity (K_f).

input from a few daily meteorological input data once the model is parameterised. The minimum daily input data set consists of precipitation (P), minimum air temperature (Ta_min) and maximum air temperature (Ta_max) to determine daily ET. Additional information on solar radiation, wind speed and vapour pressure are desirable, but not essential, since they are also generated by BROOK90: solar radiation is estimated from known information of latitude, slope, aspect and DOY by multiplication with a constant (0.55) for typical atmospheric attenuation; wind speed at 10 m is set to constant 3 m s^{-1} and vapour pressure is estimated from saturation vapour pressure at Ta_min (Federer 2002). The use of the approximated values from 8-day Ta data results in the loss of effects in daily variation, but these effects are assumed to be small because comparison of the ET simulated with the full measured data set were compared with ET simulated with input data generated by BROOK90 by Vetter et al. (2012), who showed relevant effects to be well described and general trends in ET not to be affected. Also, the calculated ET results are presented with a temporal resolution of 8 days.

Estimation of spatial precipitation

P was modelled for every grid cell on the basis of a linear relationship between measured P sums and the LAI gain of the MODIS MOD15 LAI data product (collection 5) of a 3x3 pixel domain around the P measurements (Figure 1 and 3). The LAI gain is defined as the positive difference of two corresponding pixels in two consecutive MODIS LAI captures (8-day interval) in which the LAI observed at the later date is used as the minuend.

The empirical model was firstly described by Schaffrath et al. (2013). Here, we present an improved version with more observations (n = 270) during three years of measurements (2005, 2006 and 2008) resulting in a more robust relationship ($R^2 = 0.80$) compared to the old version with data of 2006 only ($R^2 = 0.76$, n = 90). In general, the model (cumulative LAI gain vs. P sums of all measurements) is translating into a mean of 11.3 mm of P for a LAI gain of 0.1 and vice versa. Among the six stations, site specific relationships exist, ranging from 9.5 mm to 14 mm. The old version of the model (Schaffrath et al. 2013) showed a larger uncertainty due to the wider range of site specific relationships (from 10 mm to 21 mm). However, P for each grid cell was calculated using the mean relationship for every 8-day interval, Eq. 6:

$$P_i = \sum_{i=1}^{n} 113.2(LAI_{i+1} - LAI_i) \qquad (6)$$

Eq. 6 was applied to the calculated LAI gain of a 3x3 averaging kernel for each pixel. This method was applied until the end of August (28 August, DOY 240) only; Schaffrath et al. (2013) revealed problems in detecting reliable P beyond this date, because LAI in general no longer increases due to reduced radiation and temperature triggering the begin of senescence.

The thus derived 8-day P values were scaled to daily values with a cascade model after Olsson (1998). This step was required because BROOK90 works with daily input of P. The scaling cascade model was trained with P time series from all available stations (60 years in total). In a next step, the disaggregated P was corrected

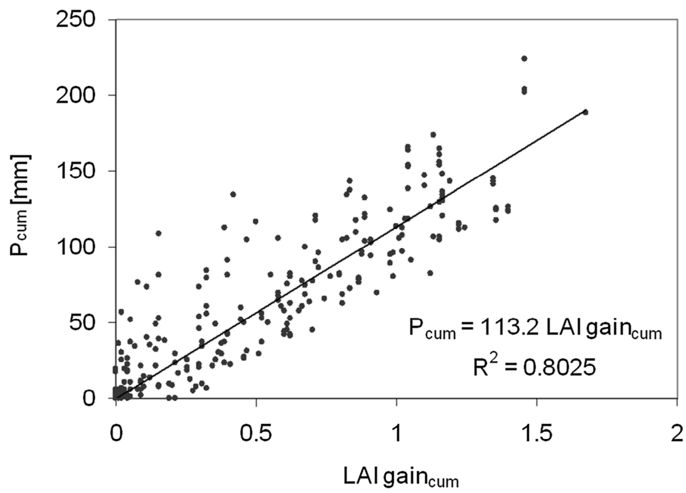

Figure 3 The relationship between the measured cumulative P from six stations and the corresponding mean cumulative gain of MODIS LAI (n = 270).

for losses due to wind, according to Richter (1995), Eq. 7:

$$P_{corr} = P + b \cdot P^{\varepsilon} \tag{7}$$

where b and ε are coefficients that describe station parameters and the type of P. According to Richter (1995) b was set to 0.345 and ε to 0.38 correcting P for a free-standing station in flat terrain measuring rain between April and September.

Estimation of spatial air temperatures

For the calculation of ET with BROOK90, daily input of minimum and maximum air temperatures are obligatory. They were generated from the MODIS 8-day Ts (surface temperature) product MOD11A2. The product provides day-time and night-time temperatures and Vetter et al. (2012) found a well-established relationship between the measured minimum air temperatures ($Ta\_\min_m$) at our stations and the Ts calculated by MODIS aboard the TERRA satellite at night (Ts_TN), which was used to derive pixel-wise minimum air temperatures ($Ta\_\min_{mo}$) for this study: over the period from 2005 to2008 (23 April to 30 September), the 8-day mean $Ta\_\min_m$ and Ts_TN showed a high correlation ($R^2 = 0.92$, $n = 80$) which allowed for the calculation of minimum air temperatures from the relationship shown in Eq. 9:

$$Ta\_\min_{mo} = 0.8314 Ts\_TN + 0.9592 \tag{8}$$

The Ts of the MOD11A2 data product was also used to model maximum air temperature ($Ta\_\max_{mo}$): Vetter et al. (2012) showed it correlates relatively well ($R^2 = 0.88$, $n = 80$) with the measured maximum air temperature ($Ta\_\max_m$) at the stations, when calculated after Eq. 9:

$$Ta\_\max_{mo} = 0.1985(Ts\_TD - Ts\_TN) + 8.7827 + Ta\_\min_{mo} \tag{9}$$

where Ts_TD is the TERRA MODIS Ts at daytime. Since $Ta\_\min_{mo}$ and $Ta\_\max_{mo}$ were derived from the MOD11A2 data product, that provides the average temperatures during 8-day intervals, $Ta - \min_{mo}$ and $Ta\_\max_{mo}$ were treated as daily values changing every 8 days in BROOK90.

Generation of daily model input from 29 August to 22 April

Model input outside the study period (from 29 August to 22 April) was not derived from MODIS data, because the method of estimating P from LAI cannot be applied during this time and the MODIS Ts product may shows an increased number of missing values due to snow cover in the region. Therefore, the daily input during this period was provided from other reliable sources: from 2001 (the 2001 model run was used to initiate the model) to 2009, meteorological data of IMGERS was used. Data gaps were filled with data of our micrometeorological measurements. Unfortunately, IMGERS data were not available to us in 2010 and 2011 and our stations only collected data until 2009. Thus, daily Ta was calculated from the mean Ta of IMGERS between 2001 and 2009; daily P was filled from P at IMGERS in 2002 (average P during this period). We are aware of the loss of the spatial variation in the daily model input, but we assume little influence on the modelled results, because air temperatures are generally below 0°C and P was very low (mean value = 53 mm during this period) as well.

Multi-year spatial application of BROOK90

BROOK90 version 4.4e software was used with an adaptation for batch processing. Every pixel in this study was calculated and treated separately. There is no interaction between adjacent pixels. The model simulated ET for every pixel with its individual location parameter set, canopy parameters (LAI and canopy height changes over the year) and daily input data set (P, minimum and maximum air temperature). The simulations started with an initial run (2001 data) to generate initial values of snow storage, groundwater storage and matrix potential of each soil layer for 2002. Analogously, the final values of every year were transferred to the start of the following year.

Comparison with MODIS evapotranspiration

A global 8-day 1 km spatial ET data product (MOD16) is generated by the MODIS science team. It is available online (http://www.ntsg.umt.edu/project/mod16, accessed 20 January 2013). The calculation is also based on the PM equation and the datasets are estimated using the ET algorithm by Mu et al. (2007 and 2011) that is based on the work of Cleugh et al. (2007), who estimated 16-day evapotranspiration for Australia using MODIS data and surface meteorology. A comparison of our results with the MODIS data product is highly useful, not for strict validation of either ET, but it is a possibility to check their plausibility and to identify similarities and differences in both data sets. Also, based on the low number of published works, we assume the scientific community seems to hesitate using the globally available MOD16 ET product despite the need of spatial information on ET for a broad range of applications. Although the MOD16 ET does not separate E and T, it is an exclusive opportunity to compare our ET results with spatial ET that is already available in the same spatial and temporal resolution and over the same period (2002–2011).

Results

Spatiotemporal variability of evapotranspiration

The characteristics of the annual courses of the mean ET in the study area are quite diverse (Figure 4), but ET is low (between 0.3 mm d^{-1} and 0.6 mm d^{-1}) at the end

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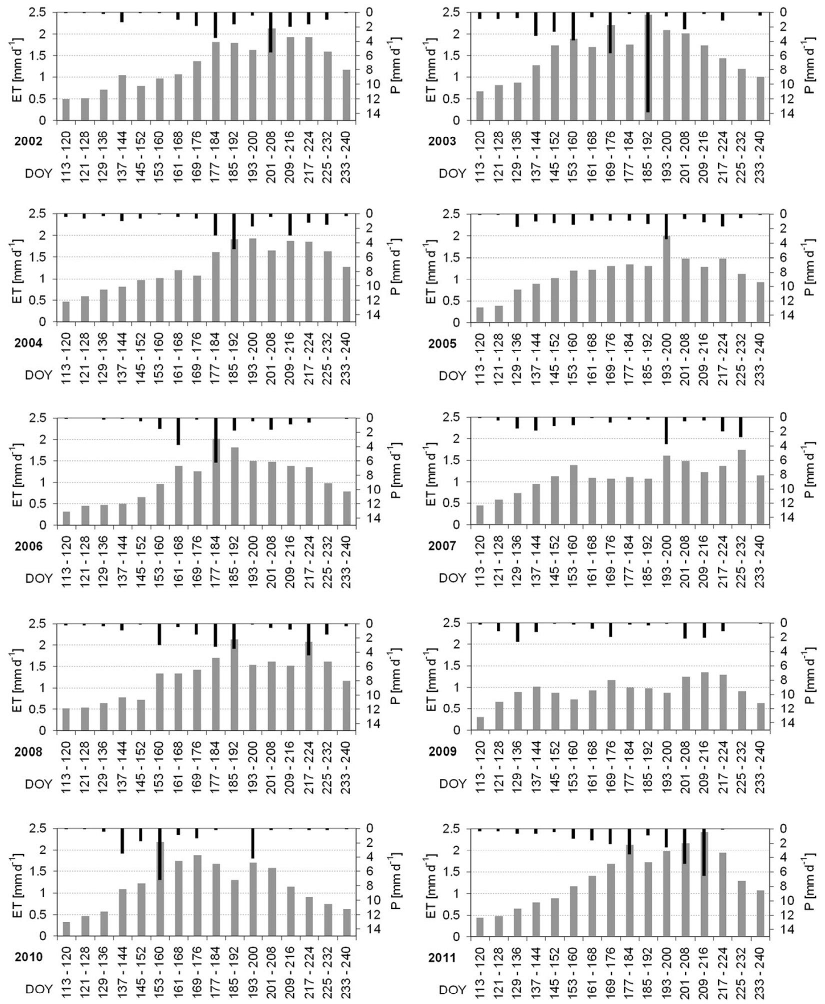

Figure 4 The annual courses (2002 to 2011) of the mean ET (grey bars) and P (black bars) in the study area from 23 April (DOY 113) to 28 August (DOY 240).

of April (DOY 113–120) in every year. A substantial increase of ET occurs in every year, but with significant differences in the date and in the magnitude of the increase: in some years, spring and early summer ET increased gradually (e.g., in 2004, 2007 and 2011). In 2006 and 2008 a considerable increase of ET occurred late, at the beginning of June (between DOY 153 and DOY 160). The mean maximum ET of 8-day intervals in the grasslands ranged from very low 1.4 mm d^{-1} in 2009 up to 2.4 mm d^{-1} (in 2003 and 2011). However, the highest ET of a single pixel was 5.2 mm d^{-1} during an 8-day period in July of 2003 (DOY 185–192). The date of peak-ET was highly variable too; it occurred very early in 2010 (at the beginning of June, DOY 153–160) and very late in 2007 (in the mid of August, DOY 225–232). Also, the temporal distribution of ET showed a unimodal distribution in 2005 and 2006, a bimodal distribution in 2008 and a multimodal distribution, e.g., in 2002 and 2004. In general, ET declines in August and is between 0.6 mm d^{-1} and 1.3 mm d^{-1} during the last 8-day interval of the study period (DOY 233–240).

The mean ET sum of the study area and annual study period (23 April to 28 August) was 158 mm from 2002 to 2011 with a standard deviation (SD) of 22. mm and a coefficient of variation (CV) of 14%. Lowest ET was modelled for 2009 (119 mm) and highest ET for 2003 (199 mm). In general, annual ET equals annual P (ET/P = 0.99), however in 2003 when P was much higher (301 mm) than the average annual P of our study period (165 mm), the linear relationship between annual P and

ET is not valid, since ET was significantly lower (199 mm) than P (Table 2). The analysis of the 2003 data revealed simulated vertical flow below the soil profile of 76% (77 mm) of the difference between P and ET. The remains (25 mm) were stored in the parameterised (1.2 m) soil profile; in all the other much dryer years the moisture stored in the soil decreased between 23 April and 28 August as Table 2 shows.

The band between minimum and maximum ET in Figure 5a shows the spectrum of the magnitude of ET in the study area from 2002 to 2011 and the CV indicates the mean interannual ET-variability in the study area in 8-day intervals. The 8-day CV of ET is generally high and variable and significantly higher than the CV of annual ET in the study area. Figure 5a) shows a substantial increase of the variability from minimum (25%) around mid of May (DOY 129–136) to maximum (40%) at the begin of June (DOY 145–160) indicating an increase of uncertainty of ET in the study area at that time.

The spatiotemporal CV of ET from 2002 to 2011 is shown in Figure 6. In contrast to the mean values for the whole area of Figure 5a, the individual pixels in Figure 6 show a wider spectrum of variability with a CV of up to 75%. Also, the spatial pattern and amount of the CV is highly variable over the course of the year. Despite high interannual and innerannual variations of spatial ET, the ten years of modelled ET indicate the existence of a long term spatial pattern of ET with areas of very low mean ET (0.77 mm d^{-1}) and areas with more than twofold ET (1.99 mm d^{-1}). In general, ET is higher in the eastern part of the study area (Figure 7) and the mean ET for the grasslands over the whole period is 1.24 mm d^{-1}

The partitioning of ET into E and T and their variability

The annual courses and the amount of E and T as well as their ratio are very variable, too. E and T are very low (below 0.5 mm d^{-1}) at the beginning of the study period (end of April). In general, E is slightly higher than T until the end of May. In some years, e.g., 2002 and 2004, a substantial increase of E or T does not occur until the beginning of June (DOY 153–160); in other years, e.g. 2003 and 2010, the increase of both E and T was earlier, in mid May. Although the amount and course of E and T are quite variable, E generally dominates over T in spring. T will increase and generally dominates over declining E in summer. However, in spring of 2006, T dominated over E and two distinctive peaks of E occurred around mid and end of June. Also, large differences of the amount of E or T are quite common between two consecutive 8-day intervals. At the end of each years study period (end of August), E was very low again (below 0.5 mm d^{-1}) and T varied between 0.5 mm d^{-1} (2009 and 2010) and 1 mm d^{-1} (2002 and 2004). The variability of 8-day T observed in the study area during the 10 years is shown in Figure 5b. Although the CV of T varies between 25% and 35% and thus, is lower than the CV of ET (cp. Figure 5a), it also increases in spring and early summer. However, in July the CV of T drops below 30% and is further decreasing. The widening band between the mean minimum and maximum T shows a broad spectrum of modelled T in the grasslands throughout the analysed vegetation periods.

The differentiated courses of E and T are shown as the probability density functions (PDF) and the courses of the components of ET (E, T and E_i) for a very wet (2003) and very dry year (2009) in Figure 8: here, the left side in the beanplots shows the PDF of all pixels for E (red colour) and the right side shows the PDF of T (green colour). While E and T as well as their spatial differences are small during the first three 8-day intervals (DOY 113–136) in both years, the stretched PDFs of E and T show a substantial increase and also the more pronounced spatial differences in 2003 afterwards. A slight increase of T occurs in 2009, but compared to the 2003 data, E and T stay on a very low level throughout the whole study period. E_i, which is visible from the difference between the + and the ▲ in the figure, is also very small in 2009. In 2003 there are several 8-day intervals (e.g., from DOY 169–176 and DOY 185–192) with

Table 2 Overview of the summed-up model results from 23 April to 28 August

	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	MEAN
P [mm]	168.2	300.8	160.9	141.7	136.3	141.4	162.1	116.4	150.5	174.6	165.29
ET [mm]	167.5	198.6	165.4	145.5	139.6	145.8	165.1	119.2	154.5	179.7	158.09
T [mm]	89.7	113.0	92.7	83.3	80.2	79.2	88.1	69.4	91.1	102.4	88.91
E [mm]	66.8	73.5	61.3	54.4	50.5	59.1	66.0	44.7	56.5	63.6	59.64
Ei [mm]	11.0	12.1	11.4	7.8	8.9	7.5	11.0	5.1	6.9	13.7	9.54
VRFL [mm]	13.7	77.3	10.9	3.8	4.2	3.5	8.8	1.5	14.1	18.6	15.64
P-ET-VRFL [mm]	−13.0	24.90	−15.40	−7.60	−7.50	−7.90	−11.80	−4.30	−18.10	−23.70	−8.44
ET/P	0.99	0.66	1.03	1.03	1.02	1.03	1.02	1.02	1.03	1.03	0.99
T/ET	0.54	0.57	0.56	0.57	0.57	0.54	0.53	0.58	0.59	0.57	0.56

Note VRFL is the vertical flow through the parameterised soil and P-ET-VRFL corresponds to the change in soil moisture during that time.

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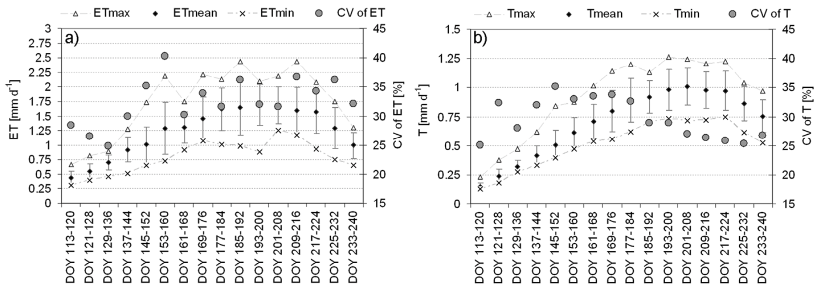

Figure 5 Temporal variability of a) ET and b) T in the study area from 2002 to 2011. The figure shows minimum, mean and maximum values of ET and T of the study area as well as their standard deviations and the mean coefficient of variation (CV) of spatial ET.

considerable amounts of E_i, up to 0.4 mm d^{-1} or approx. 15% of ET indicating high LAI and P. The spatiotemporal distribution of the variability of T is displayed in Figure 9. Here, the calculated CV of T is shown analogously to Figure 6 every 8 days, from 2002 to 2011. However, the spatial distribution of the CV of T is distinct from the spatial variability of ET in Figure 6. The spatial patterns of the CV in Figure 9 are different for each 8-day interval, but there are similarities, e.g., the CV is lower in the western and south-western part of the study area in spring and early summer (until approx. DOY 184) than the CV in the northern part. Afterwards, the difference between these areas is less pronounced, e.g., due to a decrease of the CV of T in the northern areas. Table 2 shows the T, E and E_i sums (23 April-28 August) as well as the T/ET ratios from 2002 to 2011. T was higher than E throughout the study period and the ratio between T and ET was relatively balanced (between 0.53 and 0.59) regardless of the amount of P. E_i accounts for 4% to 8% of ET.

Comparison of BROOK90 evapotranspiration with MOD16 evapotranspiration data

In general, the spatial mean values of ET of the MOD16 product are in the range of our modelled ET in the

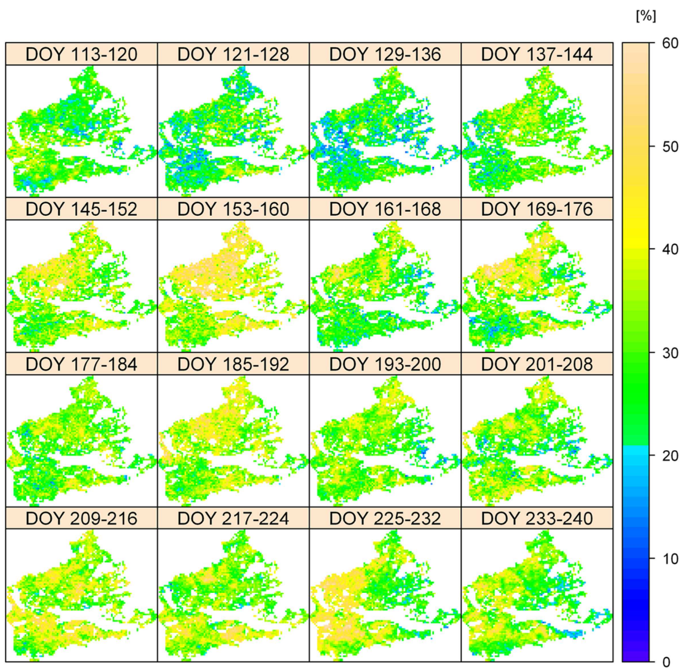

Figure 6 Illustration of the spatiotemporal variability of ET in 8-day intervals in the study area. The coefficient of variation (CV) was used to quantify the variability of ET from 2002 to 2011; the higher the CV, the higher the variability. For reasons of visibility, the figure does show the CV up to 60%, though the CV of a few pixels was higher (up to 75%).

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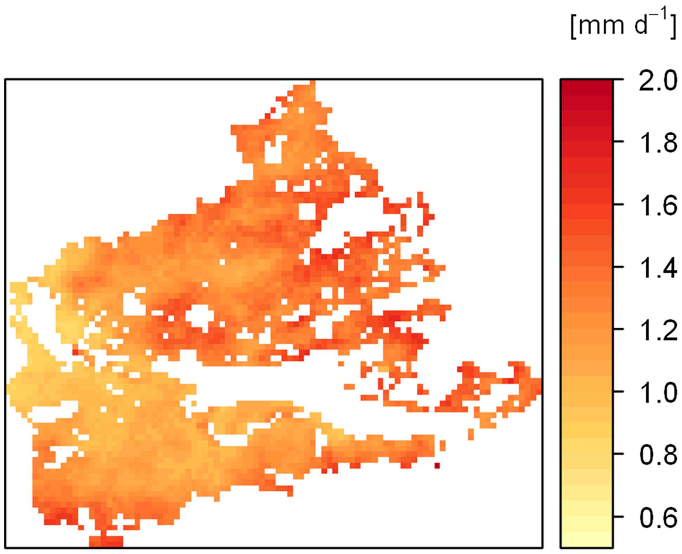

Figure 7 The spatial pattern of the long term (2002–2011) mean spatial distribution of ET in the grasslands of the Xilin river catchment.

study area. Both simulations of ET show similarities in the annual courses of ET, but ET of the MOD16 data product is always lower in spring and early summer than the ET modelled by BROOK90. Figure 10 shows the spatial mean values of ET in the study area of both data sets (8-day values). According to the regression, MOD16 ET accounts for about 80% of our modelled ET ($R^2 = 0.63$, n = 160), mainly due to the lower ET values in spring.

However, in summer, MODIS ET sometimes exceeds our modelled ET. The correlation of annual ET is slightly higher ($R^2 = 0.79$, n = 10) and on the annual basis MOD16 ET is also 80% of ET modelled by our method. Some differences exist between both data sets when comparing the spatial ET, but in most scenes the spatial pattern is similarly (Figure 11). However, the MOD16 ET in general has a higher contrast than our modelled results, which show a finer spatial differentiation of ET.

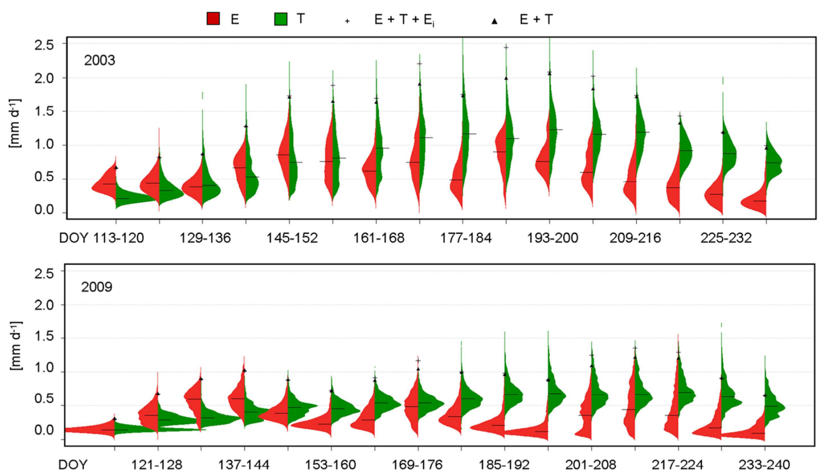

Figure 8 Probability density functions and median (black horizontal line) of the spatial distribution of the components of ET in two selected years (2003 and 2009). Evaporation is depicted on the left side in red and transpiration is shown on the right side in green. The + shows ET as the sum of its three components and the triangle shows ET without E from intercepted rain.

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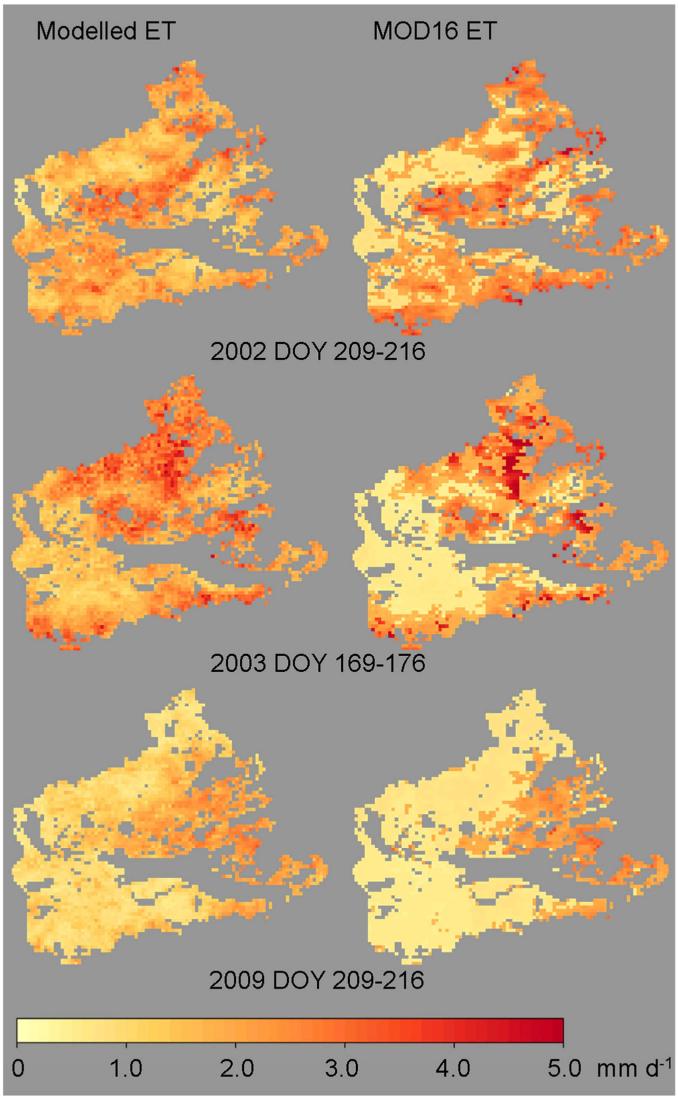

Figure 11 Examples of the spatial distribution of the comparison between modelled BROOK90 ET and MODIS MOD16 ET.

pattern of ET modelled with BROOK90 (mean value = 1.24 mm d^{-1}, range from 0.77 to 1.99 mm d^{-1}).

Discussion

Modelled results

For the first time, a long-term study of spatial ET was conducted for the grasslands of Inner Mongolia. This is of particular importance, as ET can not only be considered a key component of the water cycle in this region or regarded as water flux into the atmosphere, but ET also integrates other environmental factors, e.g. the abundance of P, and its interactions with soils and vegetation. The analysis of the model results revealed a pronounced spatial and temporal variability of innerannual and interannual ET, in which the variations of ET were mainly governed by the distribution of P. The temporal (8-day) distribution of P was quite diverse and the annual courses of ET and the high CV of ET reflect this variability very well. The date and amount of peak-ET of the whole study area were also very variable: in this study peak-ET was reached between the beginning of June and mid August and it varied between 1.4 mm d^{-1} and 2.4 mm d^{-1} (8-day interval, cp. Figure 4). In general, the spatial differences of ET in the grasslands of the Xilin river catchment were highest during periods of high mean ET, as from DOY 185–192 in 2003, when ET varied between 0.7 mm d^{-1} and 5.2 mm d^{-1}. However, for the most part of the data (90%), ET was between 1.5 and 3.5 mm d^{-1} at that time, indicating exceptional dry or wet local conditions or a misclassification of a few pixels led to these extreme differences.

Despite all the identified variations of ET, the results showed a primary spatial pattern of long-term ET (10 years). The pattern can be explained partly by the effects of longitude and altitude, since ET generally decreases in western directions ($R^2 = 0.35$) and in lower altitudes ($R^2 = 0.38$). The fundamental relationship of both factors and long-term ET, is even more pronounced when they are combined ($R^2 = 0.49$). On the contrary, the influence of latitude on ET is little and can be neglected ($R^2 = 0.07$).

In the study of Schaffrath et al. (2013) ET approximately balanced P in the study area in 2006 and this study confirms this in general in the long-term (ET/P = 0.99, Table 2). The ET-studies of Miao et al. (2009), Lu et al. (2011) and Wang et al. (2012) also report ET to approach or exceed P in this area. Excess ET over P during the vegetation period, which was also modelled in our study from 2004 on, is related to a decrease of soil water storage during this period. However, the linear character of the annual relationship between P and ET was not applicable in 2003, when P was clearly above average (301 mm) and ET was 199 mm only. Some of this moisture was stored in the soil (25 mm) but the bulk (77 mm) was modelled as vertical gravitational flow through the parameterised soil profile indicating a possible groundwater recharge in this exceptionally wet year. However, due to the diverse geology in the basin with deep layers of Quaternary deposits and volcanic rocks (Barthold et al. 2013) and the simplified parameterisation of a soil profile with 1.2 m depth only, the water flow pathways are a bit speculative. But the geological setting and the existence of groundwater-irrigated agricultural land in the basin indicate the existence of groundwater aquifers, which may be recharged during an exceptional wet year like in 2003. However, the enormous difference between P and ET in 2003 may not be regarded to be a common phenomenon in high P years, because a significant amount of P in 2003 occurred during a short period (Figure 4). A more balanced distribution of high annual P over a longer period and many smaller P-events will most likely increase ET, while the water flow into deeper layers is reduced. The study of Lu et al. (2011), which analysed ET-soil water relationships in the grasslands of Inner Mongolia, also showed the larger the rainfall events, the deeper the pulses in soil moisture change. Also, in their study, small events below 6 mm did not even cause any sustained changes of soil moisture in the upper soil layers.

A strength of this study and an advantage over the MOD16 ET data is the transfer of the matrix potential (ψ, every 10 cm) of every pixel and time-step and from 31 December to 1 January of the following year, because it allowed for the effects of inner- and interannual soil water storage variations. This could explain the finer increments of ET and the higher values of spring ET of our results. The variations of ψ (as simulated by BROOK90) were more pronounced in the upper soil layers: expressed as the mean value of the 3029 pixels of the study area, ψ of 31 December varied between −23 kPA in a very wet year like 2003 and −90 kPA in a dry year like 2009 at the 0.1 m level ($\sigma = 19$ kPA, n = 10), whereas ψ at a depth of 1.1 m just varied between −17 kPA in 2003 and −51 kPa in 2009 ($\sigma = 10$ kPA, n = 10).

The low spring ET values and high contrast between adjacent pixel of the spatial 8-day ET are limiting the MODIS MOD16 ET data for local ET studies in this area. Nevertheless, the good agreement of the spatial patterns , 8-day ET mean values ($R^2 = 0.63$) and the long-term (10 years) spatial pattern of ET between both data sets ($R^2 = 0.79$) indicate the reasonableness of our modelled ET and the potential of the MODIS MOD16 ET data for long-term grassland studies. The MOD16 ET data is available from 2000 to 2012, however, according to the project description, it will not be processed in near-real time (http://ntsg.umt.edu/project/mod16, accessed 19 June 2013).

Schaffrath et al. 2011 showed the spatial and temporal variability of LAI is controlled by the temporal and spatial distribution of P events during the growing season and this study showed the variability of ET to be dependent on P as well. The multidimensional view on ET in this study (temporally from 8-day, and yearly up to a ten-year period and spatially from 1 km^2 to the complete typical steppe land use unit of the Xilin river catchment) allowed for the quantification of the variability and the identification of individual ET (8-day, yearly) and a general (10 years) map of the long term ET over the last decade. Both, the high innerannual and the interannual variation of ET and its variable pattern stress the need for the adaptation of static land use regimes towards dynamic land use strategies and the remarkable position of traditional nomadic pastoralism in this area. Nomadism is regarded as a traditionally adapted socio-economic way of culture which is adjusted to the variable carrying capacity of the environment. This traditionally common lifestyle in drylands worldwide proved to be sustainable over at least two thousand years by grazing according to the environmental conditions (Scholz 1995). Apart from the important economical value and function of the grasslands today, they also provide a natural and ecological barrier against the vast deserts of Central Asia for Central China as grassland soils and surfaces show: particles deflated in deserts are accumulated in these grasslands under natural conditions (Reiche et al. 2012b). The recent and ongoing land use change showed the current livestock management to be poorly adapted resulting in the degradation of these fragile ecosystems (Zhu and Wang 1993, Zhou et al. 2002, Chen et al. 2003, Tong et al. 2004, Jiang et al. 2006, Han et al. 2009). We consider this spatial study to be a highly useful motivation for the restoration of the grasslands through development of a sustainable rangeland management, which by adjusting numbers and distribution of livestock according to the conditions takes into account the inherent variations of P, LAI and ET in this area.

Uncertainties and potential sources of error

The accuracy of our ET estimations is highly dependent on the quality and accuracy of the used input data. One important potential error source is P. Several issues exist: P may be under estimated occasionally, because it is not always followed by a gain in LAI and thus can not be detected (Schaffrath et al. 2013). Another inherent issue of estimating P from LAI gain is the gap between a possible P event and the gain of grassland LAI. The 8-day intervals of MODIS LAI and our estimated P will smooth this effect but can also lead to an inconstant temporal bias in P estimations of individual periods. We are also aware of the possible uncertainty of the statistically scaled 1-day P on 1-day ET model results and thus provide the results from the 8-day resolution on. Another potential error source of P is introduced by using the mean relationship between P and LAI from data of all of the six stations, because they vary site specifically. However, the extended model used for this study strengthens the robustness of the relationship between MODIS LAI gain and measured P ($R^2 = 0.80$, n = 270 instead of $R^2 = 0.76$, n = 0.76). This is in agreement with the mean percentage error of modelled P, which was 21% only when compared to the measured P at the six stations.

Some other generalisations of input data may influence the results as well: minimum and maximum air temperatures are mean values of eight-day periods and thus day-to-day variations are neglected. This is certainly a higher uncertainty than the error introduced by the calculation of Ta_min and Ta_max from MODIS Ts. Also, input data between 29 August and 22 April does not result from remote sensing data because our method for P estimation does not work without vegetation growth and uncertainties and data gaps of MODIS Ts due to snow cover may not allow for the estimation of Ta during this period. Thus, micrometeorological data of IMGERS and EC-stations of the MAGIM project were used for all of the 3029 pixels and spatial characteristics could not be taken into account. This is a simplification but the impact of this generalisation on modelled ET is relatively small because most of the P (70%) occurs between May and August (Chen et al. 2005), ET is low in winter and the spatial variability of ET is still low in spring.

There are also several issues regarding the use of MODIS LAI: MODIS LAI tends to be higher than the actual LAI in this area. This could result in the overestimation of modelled ET under wet conditions. However, our modelled ET shows reasonable values, which are in the range of published field data in this area, e.g., Hao et al. (2007, 2008) and Wang et al. (2012). We also observed an increase of MODIS LAI after the shift from collection 4 to collection 5 of the data product. The actual course of LAI over the year is implemented in BROOK90 by 10 possibilities to adjust LAI changes and date, which is a slight limitation in the study area because some smaller changes in LAI are neglected. Canopy height is represented as a function of LAI, which is a rough estimation, too. There are also only ten dates available to set canopy height in BROOK90.

Modelled ET is also based on one representative soil profile only, which is a generalisation of the distribution of soils in the study area. However, the analysis of available soil data throughout the area showed some variation in horizon depths and texture, but always sand to be the dominating particle fraction. We examined the impact of 18 different soil profiles on modelled ET of a 4x4 pixels area (cp. Vetter et al. 2012) and modelled ET for the whole study area with the three soil profiles which resulted in the lowest, mean and maximum ET (Schaffrath et al. 2013). The influence of soil texture on ET was found to be highest in spring (±25%) and significantly lower (±10%) in summer when ET is dominated by T. In general, the results of modelled ET varied between −11% and +6% from ET modelled with the soil profile used in this study. The application of a soil map as modelled by Barthold et al. (2013) may reduces the uncertainty; however, the map does provide the mean soil texture for the Ah horizon of soil groups according to the WRB (IUSS Working GROUP WRB 2007) only, without detailed information of deeper soil layers. The use of model generated solar radiation and a constant wind speed does not affect the general trends of ET; however, small additional systematic effects of their daily variations on ET may be undetected (Vetter et al. 2012). Some features of the model BROOK90 could impact the accuracy of modelled ET as well: there is no provision for dew, rime and variations of albedo; also, the model does not include non-green leaves which may intercept solar radiation but do not transpire.

All the uncertainties from the daily input data and the generalisation of parameters could introduce errors or biases in modelled ET, which are difficult to detect and quantify.

Conclusions

The study clearly shows the spatial variability and temporal dynamics of ET in this water-limited region over a ten-year period. The study also emphasises the importance of long-term investigations in semi-arid grassland ecosystems, where atmosphere-plant and soil interactions are highly variable, since a wide spectrum of variations of natural conditions in both, time and space, may not be detected in a short study period of a few months or years. This paper also revealed the importance of spatial ET results, which are superior to point scale measurements, by, e.g., the EC-technique, and highly useful to enhance the understanding of ecosystem functioning particularly in sparsely populated and semi-arid regions. Despite some limitations due to the 8-day temporal and 1 km spatial resolution of the method applied, we found a long-term spatial pattern of ET, which is partly based on longitude and altitude and a high spatial, innerannual and interannual variability of ET, which is triggered by the distribution of larger P-events. The high variability of ET indicates the advantage of dynamic land management practices over static land use regimes in Inner Mongolian grasslands.

Therefore, based on these findings and in order to protect and restore the grassland ecosystems of Inner Mongolia, the need for the adaptation of static land use regimes towards intelligent and dynamic land use strategies, which control grazing and stocking rates according to the variable environmental conditions and the remarkable position of the sustainable practice of nomadic pastoralism in this area are stressed.

Abbreviations

CV: Coefficient of variation; DOY: Day of the year; E: Soil evaporation; E_i: Evaporation from intercepted rain; EC: Eddy-covariance; ET: Evapotranspiration; g_c: Canopy conductance; IMGERS: Inner Mongolia grassland ecosystem research station; LAI: Leaf area index; MAGIM: Matter fluxes in grassland ecosystems of Inner Mongolia; MODIS: Moderate resolution imaging sprectrradiometer; PM: Penman-Monteith; P: Precipitation; PDF: Probability density function; SD: Standard deviation; SRTM: Shuttle radar topography mission; T: Transpiration; Ta_min: Minimum air temperature; Ta_max: Maximum air temperature; Ts: Surface temperature; VPD: Vapour pressure deficit; WRB: World reference base for soil resources.

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

CB and DS proposed the topic, conceived and designed the study. DS carried out the experimental study (data preparation and modelling) and the analysis of the results. CB supervised the study and helped out solving specific problems. DS wrote the manuscript and prepared the figures. Both authors read and approved the final manuscript.

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6. Summary of results

In this section major findings are presented in response to the research questions posed in chapter 1, whereas the results of each peer-reviewed research article are shown in the results section of chapters 2 to 5 in detail (Schaffrath et al. 2011, Vetter et al. 2012, Schaffrath et al. 2013, Schaffrath & Bernhofer 2013).

The results of Schaffrath et al. (2011), Vetter et al. (2012) and Schaffrath et al. (2013) mainly contribute to the first objective in chapter 1, which was the development of a method for the time-dependent identification of spatial evapotranspiration. The second objective of this thesis, the determination of the spatial and temporal dynamics and variability as well as the annual and long-term spatial patterns of ET, was achieved by Schaffrath & Bernhofer (2013). Here, we briefly summarise the results based on the most important findings of the thesis and provide additional spatial plots (Figs. 2 to 12). The spatial results are presented starting with the results of the long-term analysis (10 years). Then, the spatial results of single years are shown to reveal the interannual variability of P and ET. Eventually, exemplarily findings based on the eight-day resolution are shown to demonstrate the dynamics of ET.

It was possible to derive spatial ET for the grasslands of the Xilin river catchment despite ET being measured only at a few field sites and despite the high spatial and temporal variability of P and green vegetation. The second publication (Vetter et al. 2012) presents the parameterisation of the hydrological model BROOK90 and the results of modelled ET for a small sample area in the vicinity of ET measurements. Schaffrath et al. (2013) modified the approach to derive spatial ET for the complete grassland area of the Xilin River catchment.

The gap between the high spatiotemporal variability of water budget components in this area and a few point-scale-based ET measurements was successfully bridged using MODIS data products. They presented a general good agreement with field data and were available with a high temporal resolution of eight days. MODIS data were used and manipulated to obtain spatial information on vegetation state and P as well as minimum and maximum air temperatures (cp. Vetter et al. 2012, Schaffrath et al 2013, Schaffrath & Bernhofer 2013).

The analysis of MODIS LAI data in the Xilin river catchment revealed the mean LAI varies according to P at various time scales. In high P years, e.g., 2003, the mean MODIS LAI was substantially higher (0.72) than in dry years, e.g., 2005 (0.52). Figure 15 in Schaffrath et al. (2011) shows the sensitivity of MODIS LAI to precipitation at several sites in the study area and Figure 16 of Schaffrath et al. (2011) reveals the existence of a relationship between mean annual P and LAI in the study area from 2000 to 2008. Spatial P was estimated from a relationship found between measured cumulative P from six P stations within the study area and the corresponding mean cumulative LAI gain of a surrounding 3x3 pixel area of the MODIS MOD15 data product (cp. section 2.5.1 of Schaffrath et al. 2013). An advanced version of this relationship with 270 observations was used to model ET for the ten-year period in the grasslands of the Xilin River catchment. This relationship using changes of the eight-day MODIS LAI as a proxy for P translates into the following relationship: 11.3 mm of P resulted in a LAI gain of 0.1 and consequently a LAI gain of 0.1 per 11.3 mm of P (R^2=0.80, n=270). For details see the section 'Estimation of spatial precipitation' and Figure 3 in Schaffrath & Bernhofer (2013). The estimation of spatial minimum and maximum air temperatures was based on a relationship between measured air temperatures and MODIS surface temperatures (R^2=0.92 and R^2=0.87, n=81). For details on the estimation of minimum and maximum air temperatures see Fig. 2 of Vetter et al. (2012) and the section 'Estimation of spatial air temperatures' in Schaffrath & Bernhofer (2013).

An important parameter for the parameterisation of BROOK90 is maximum canopy conductance, as it determines transpiration. It was set to 6 mm s^{-1} after calculation and review of ET field measurements from 2005 and 2006 (cp. Vetter et al. 2012). Albedo was set to 0.2 and roots were parameterised for temperate grassland according to Jackson et al. (1996). Because BROOK90 derives soil hydraulic parameters from the soil texture of soil horizons, field data of more than 30 samples of the MAGIM project was used and analysed for model parameterisation. There are differences in texture within the study area, but the investigations indicated sand to be the dominating texture class (cp. Table 1 and Fig. 7 of Schaffrath et al. 2013). The parameterisation of

BROOK90 as well as tests and results of the parameterisation are shown in detail by Vetter et al. (2012) and in sections 2.3 and 3.2.1 of Schaffrath et al. (2013). For the spatial application of BROOK90, each pixel was calculated by a separate model run. Thus, there is no interaction between adjacent pixels. A flowchart of input data sources and their organisation is summarised in Figure 1.

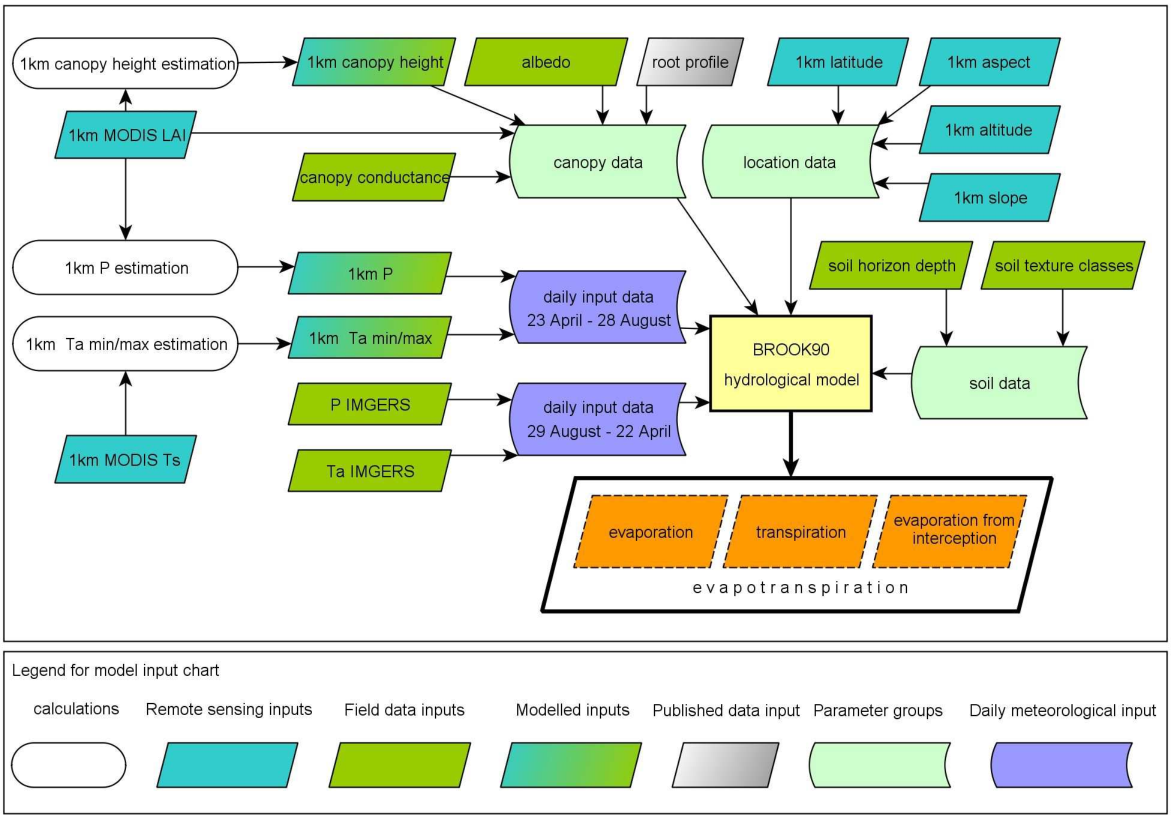

Figure 1 Organisation of input data for BROOK90. Daily input of P, minimum and maximum air temperature were provided separately for every pixel during the study period (23 April – 28 August). Station data from IMGERS were used between 29 August and 22 April because P estimation from MODIS LAI changes is not possible during this period and snow cover may not allow for consistent MODIS surface temperatures (a smaller version of this figure is also presented by Schaffrath & Bernhofer 2013)

Figure 2 summarises the mean spatial distribution of modelled ET, estimated P and MODIS LAI of the growing seasons of 2002 to 2011 (128 days from 23 April to 28 August). Based on a land use classification described in section 2.4 of Schaffrath et al. (2013), these spatial plots show the land use unit 'typical steppe' at 1-km resolution (927 m), which is referred to as 'the grasslands of the Xilin River catchment' in this thesis.

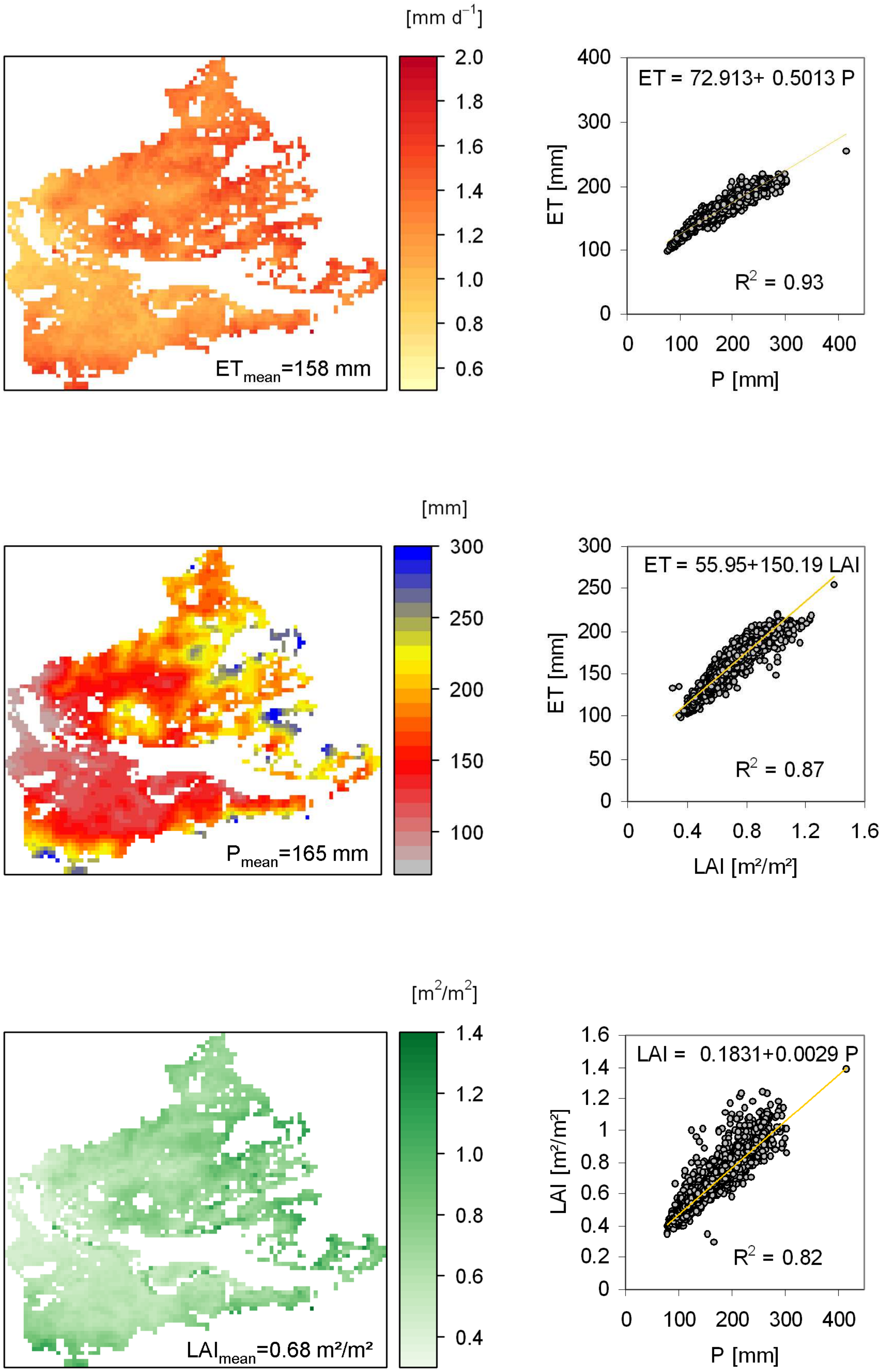

Figure 2 Long-term spatial patterns of modelled ET, estimated P and MODIS LAI in the grasslands of the Xilin River catchment from 2002 to 2011

Figure 2 also provides an overview of the average conditions revealing the general local differences of P, ET and LAI in the 2600 km² area. The pattern of, e.g., LAI, can be explained partly by altitude (R^2=0.43, n=3029) but also by longitude (R^2=0.38, n=3029): LAI and ET are generally lower in western directions and at lower altitudes. Schaffrath & Bernhofer (2013) demonstrated that altitude and longitude explain about 50% of ET differences (R^2=0.49, n=3029), whereas latitude has little influence on ET (R^2=0.07, n=3029). This is attributed to the higher elevation in the east and to the large-scale circulation patterns in the region with moist air entering from eastern directions.

Figure 2 implies a quantification of the magnitude of the general spatial differences: low values of P, ET and LAI are roughly one-third of their highest values, indicating enormous disparities of the general conditions in the study area. The relationships and regressions between P, ET and LAI display a strong entanglement, as local P drives local ET (R^2=0.93, n=3029) and largely controls local LAI (R^2=0.82, n=3029) (cp.with results of Schaffrath et al. 2011). Figure 2 also presents one outlier pixel with a high LAI (1.4) and P (above 400 mm). It is located in the north-west of the study area and is most likely attributed to a different land use type (marshland) or to a conversion of grassland to arable land. However, the impact of this outlier on the results can be neglected.

The interannual differences of P distribution are shown in Figure 3. Here, the spatial plots of the estimated P sums from 2002 to 2011 reveal the high interannual and spatial variability of P in the study area. Extraordinarily high P occurred in 2003, with a mean value of 301 mm. However, the plot indicates some areas with very little P of around only 100 mm (grey colour) and, in contrast, large areas with extremely high P over 450 mm indicating the characteristic non-uniform distribution and spatial variability of P in these grasslands. Though the 2003 data exemplarily shows how strong these disparities can be within the study area, the annual P patterns of the other years indicates these differences as well, but in a less pronounced manner. The western and north-western part of the study area often received less P than other areas, e.g., 2003 – 2006. However, in 2007, the P sum was higher in the west than in the eastern parts of these grasslands. In 2009, the driest growing season of the study period (P=116 mm), significantly higher amounts of approximately 200 mm mainly occurred in the eastern part of the grasslands.

The spatial plots of the modelled annual ET are shown in Figure 4. On an annual basis, the spatial patterns of ET have an inherent similarity to the spatial patterns of P (cp. with Fig. 3) showing the impact of P on ET. However, the magnitude of ET can differ from P. This is most notable in 2003, as high ET values are much lower than the corresponding P values. The gap between P and ET in this year is also clear from the mean values of the study area: whereas the mean P was 301 mm, the mean ET was only 199 mm in 2003. A general increase of soil moisture (+25 mm) and the vertical flow of water through the parameterised soil profile (77 mm) account for the discrepancy between P and ET in this year. In addition, 2003 may have been a year with additional surface runoff and a year with potential ground water recharge. Soil moisture decreased in all other years and the vertical flow through the parameterised soil profile was much smaller in general (mean value=16 mm) and insignificant in a very dry year such as 2009 (1.5 mm). Table 2 of Schaffrath & Bernhofer (2013) contains a detailed overview of modelled annual results, including the annual and mean evaporative ratios (ET/P), which is 0.99 for the ten-year period, indicating a simple water balance of P = ET in the long run.

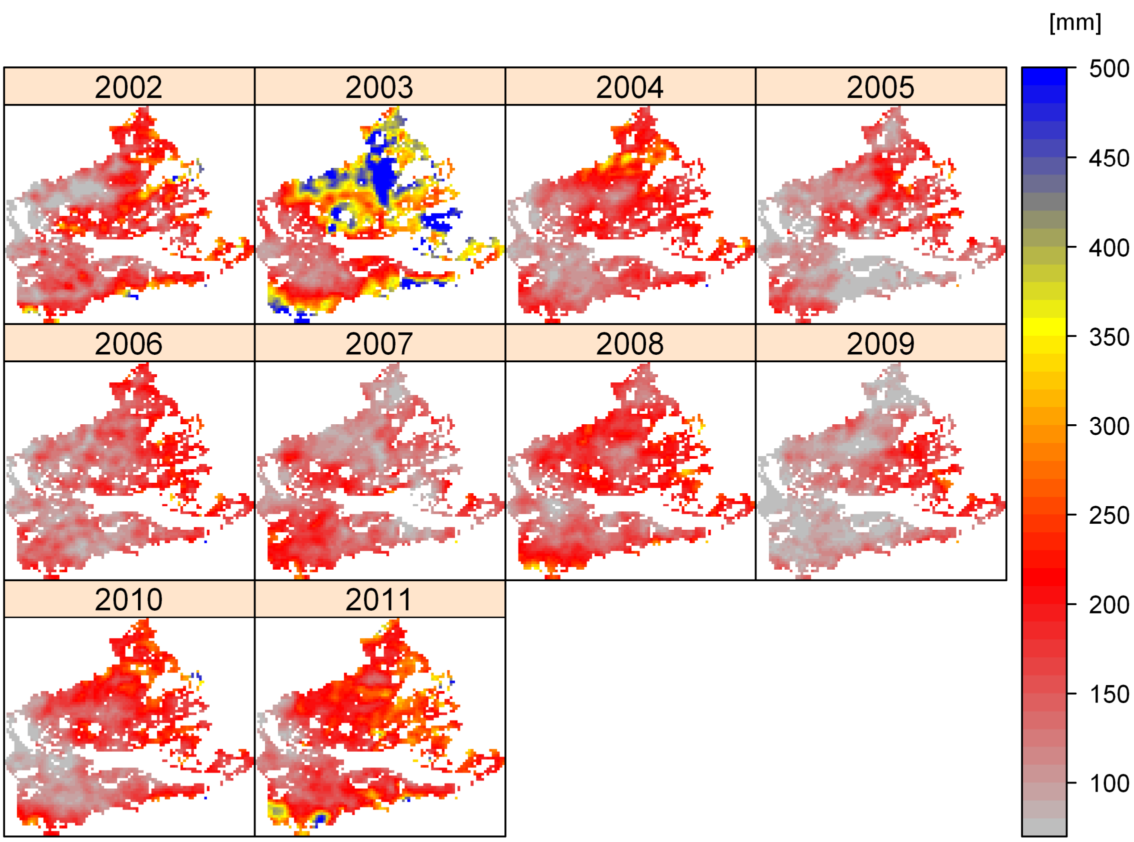

Figure 3 Spatial representation of the modelled annual precipitation from 2002 to 2011 in the grasslands of the Xilin River catchment

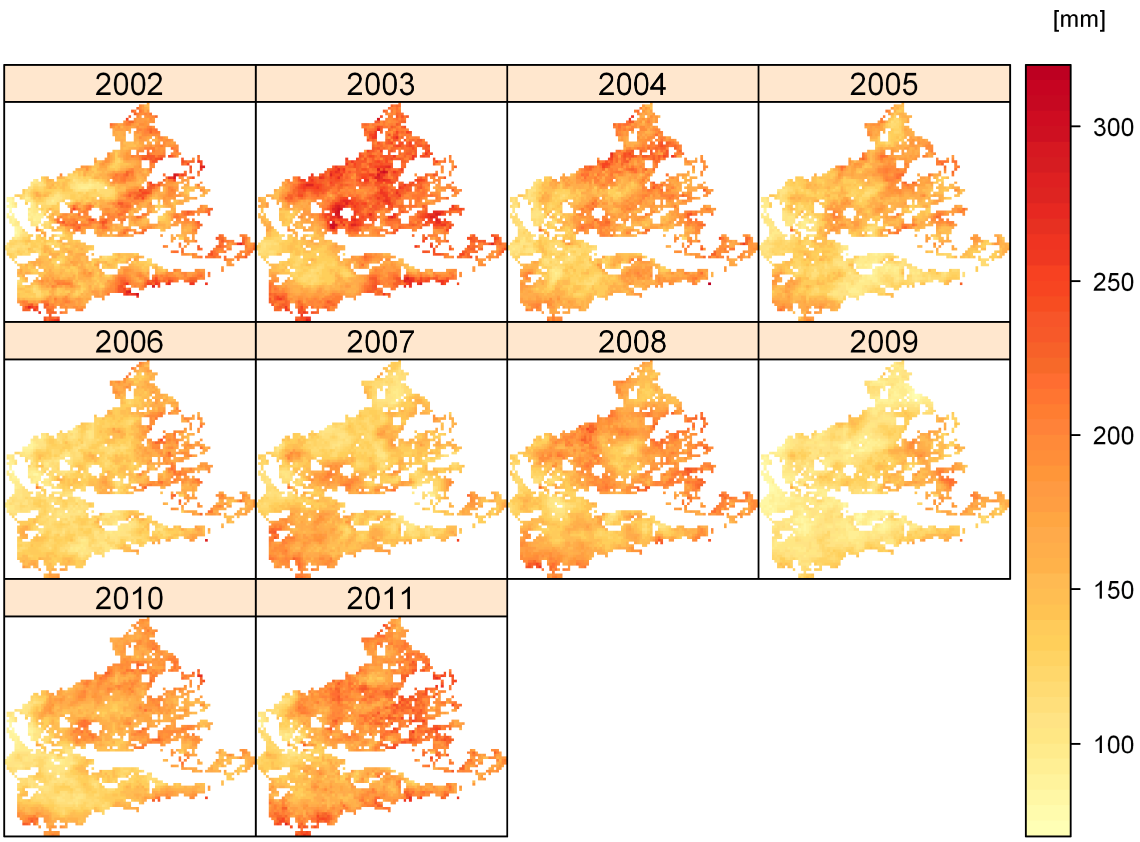

Figure 4 Spatial plots of the modelled annual evapotranspiration from 2002 to 2011 in the grasslands of the Xilin River catchment

The important role of soil moisture storage and its interannual variation is exemplarily shown in Figure 5. Demonstrating the impact of P on soil water conditions, Figure 5 shows the initial values of soil moisture for the first 60 cm of the soil profile for 1 January of two contrasting years. On one hand relatively high matrix potential (approx. -35 kPa) indicates soil moisture to be approximately 20% at the end of 2003. These values resulting from the wet conditions of 2003 were assigned to the beginning of 2004. On the other hand, 2009 was a very dry year resulting in very low matrix potential and lower soil moisture (approximately 15%) at the beginning of 2010.

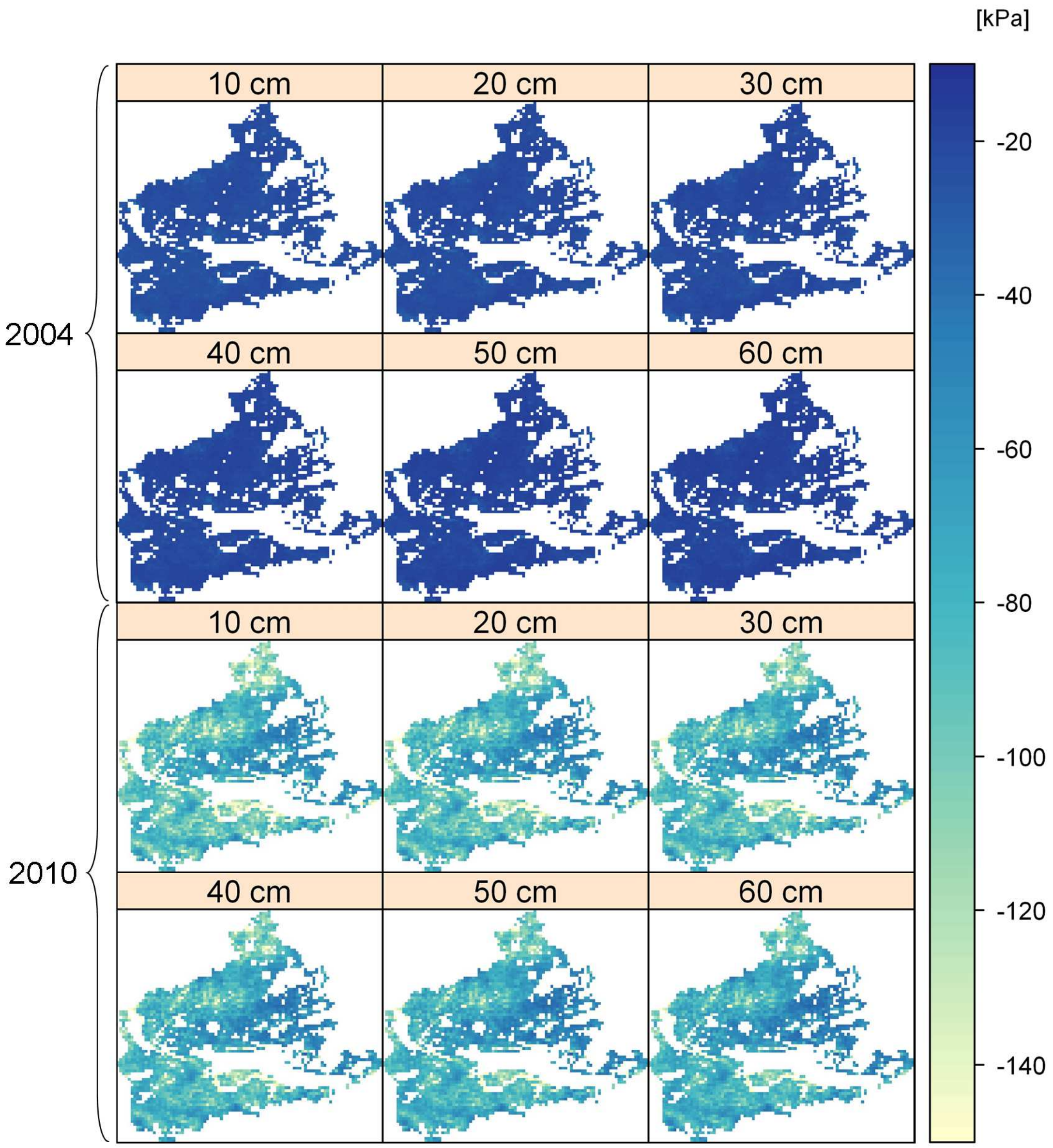

Figure 5 Spatial plots of the modelled initial soil water conditions of the first 60 cm in the grasslands of the Xilin River catchment in 2004 and 2010

Next, the dynamics of P and ET on the eight-day resolution are presented exemplarily for the year 2008. In the growing season of 2008, P was 162 mm and ET was 165 mm, which is approximately average for the ten-year period (cp. table 2 in Schaffrath & Bernhofer 2013). Figure 6 provides insight into the spatial and temporal distribution of estimated P of 2008. It shows only little P occurred until the beginning of June (DOY 153-160).

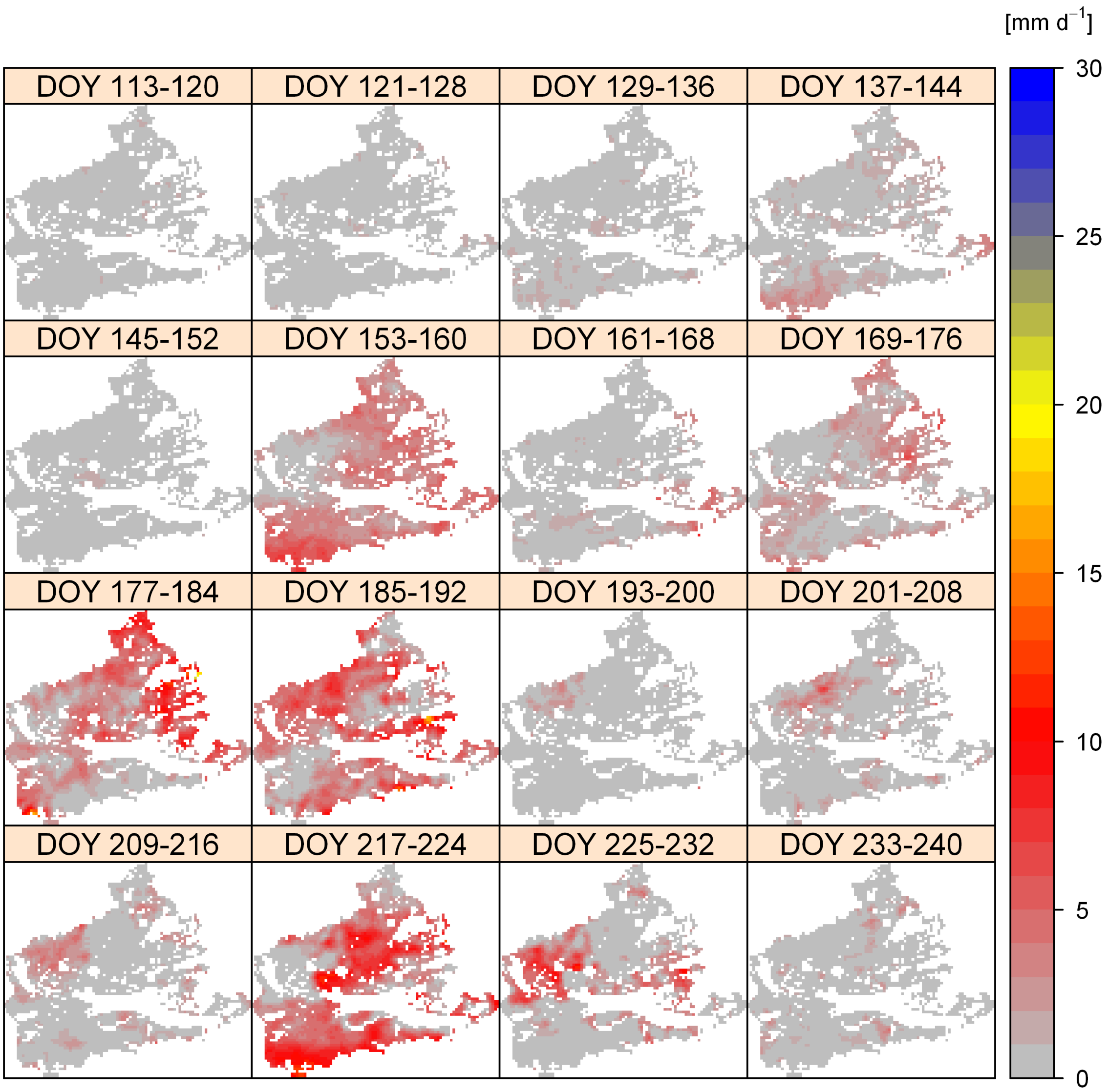

Figure 6 Modelled spatial precipitation (eight-day resolution) in the grasslands of the Xilin River catchment in 2008

During this eight-day period, the grasslands received 24 mm of P on average, with higher values up to 62 mm (7.75 mm d^{-1}) in the south of the study area. However, P did not occur evenly distributed over the grasslands. The central and north-western parts received little to no P at that time. The next significant P pulses occurred at the end of June (DOY 177-184) and at the beginning of July (DOY 185-192).

The modelled ET of 2008 is shown in Figure 7. ET was very low until the beginning of June, when the first significant P pulse occurred in 2008.

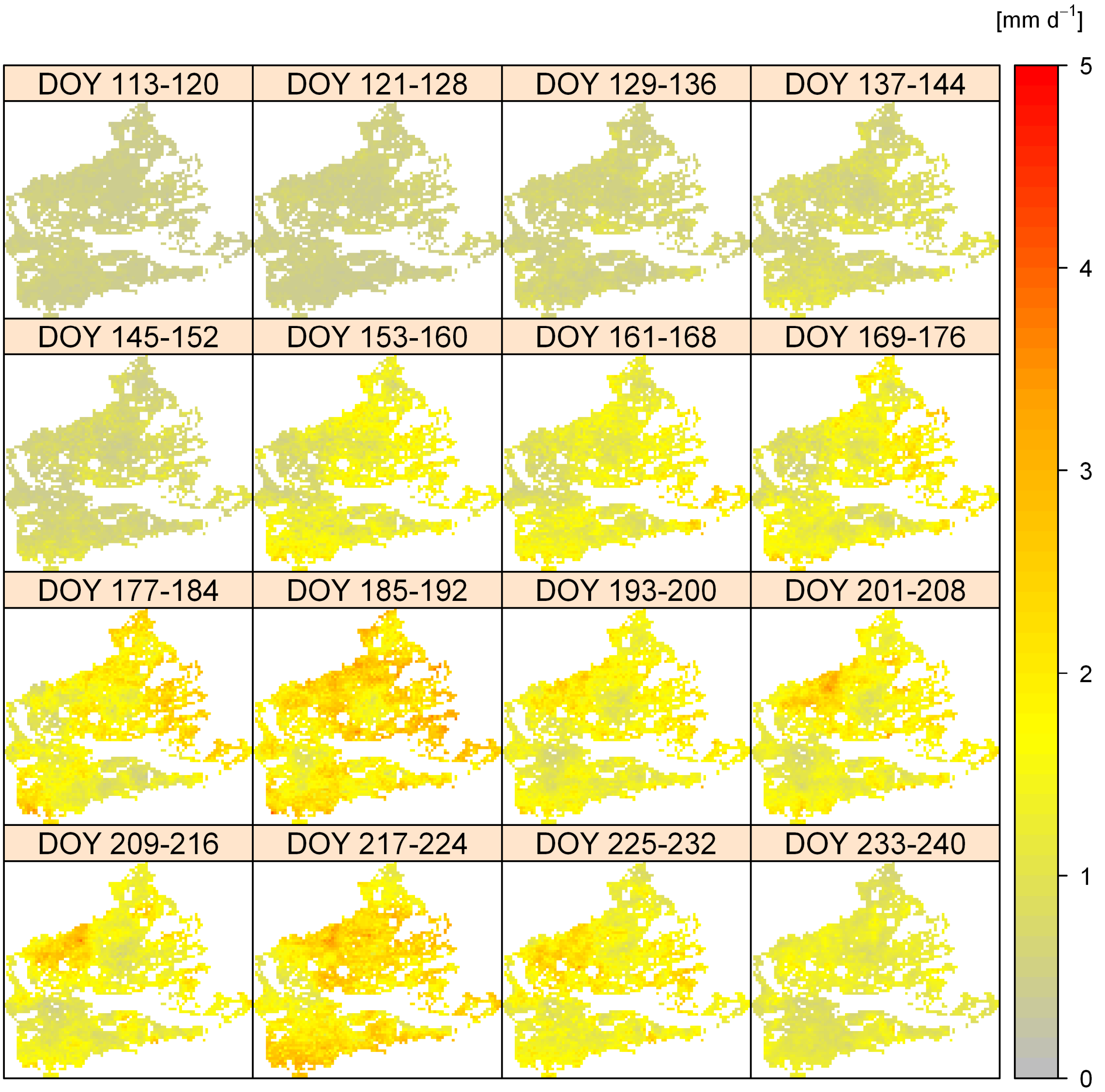

Figure 7 Modelled spatial eight-day ET in the grasslands of the Xilin River catchment in 2008

Before this event, ET was 0.72 mm d^{-1} (DOY 145-152). ET was roughly doubled in the period of DOY 153-161 (1.33 mm d^{-1}). The maximum ET for single pixels increased up to 2.73 mm d^{-1} during that period.

However, ET did not increase in areas that received no or only little P (cp. Fig. 5). During the following eight-day interval (DOY 161-169), no considerable P occurred, but the ET pattern and amount did not decrease significantly (mean ET=1.32 mm d^{-1}). This was different in July, when high ET decreased quickly in response to the dry period from DOY 193-200. The mean values dropped from 2.12 mm d^{-1} (DOY185-192) to 1.54 mm d^{-1} (DOY 193-200). The rapid decrease of ET within an eight-day period indicates the high PET in summer. The maximum ET for a single pixel was 4.03 mm d^{-1} in 2008 in the period from DOY185-192. The quick response of ET to P is typical for the grasslands of the Xilin River catchment and occurred in other years as well.

The spatial ET changes of consecutive eight-day periods of 2008 are presented in Figure 8 in more detail. As Figure 8 shows, ET may increase in some parts of the study area, even when it is decreasing in other parts in the same period. In addition, ET of individual pixels increased up to 2 mm d^{-1} or decreased up to -1.75 mm d^{-1} from one eight-day period to another, indicating the highly dynamic nature of the ET in the grasslands of the Xilin River catchment.

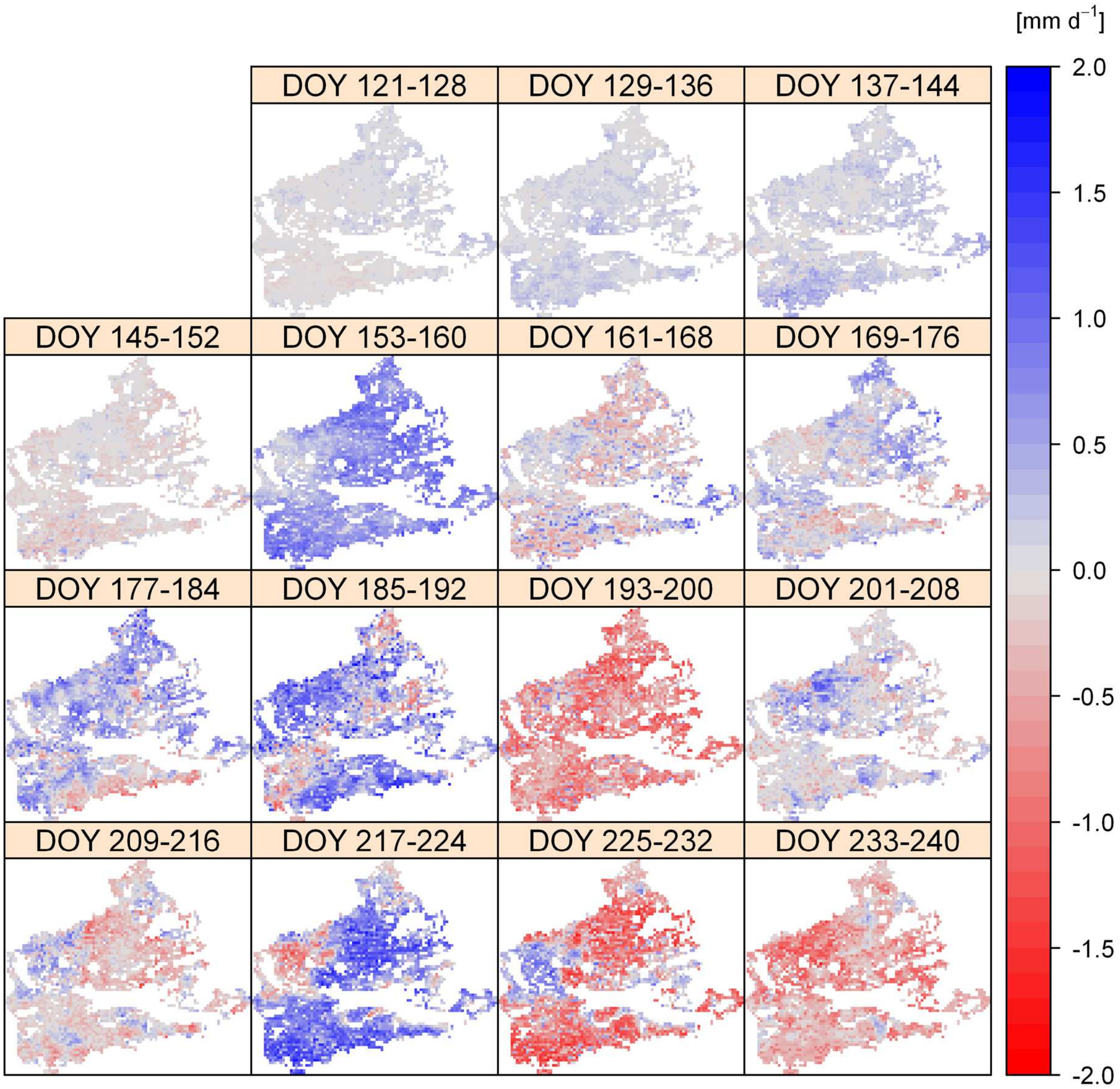

Figure 8 Spatial plots of eight-day ET changes in the grasslands of the Xilin River catchment in 2008

The eight-day distribution of the main components of ET, soil evaporation (E) and transpiration (T), are shown as probability density functions (PDF) in Figure 9 for 2008. Fig. 9 shows E and T as well as their spatial differences to be low at the beginning of the study period. E is generally slightly higher than T in the first part of the growing season, whereas T dominates E from mid-July on. The more stretched shape of the PDF indicates that spatial differences start to increase substantially in the period of DOY 153-161, when the first large P-event occurred.

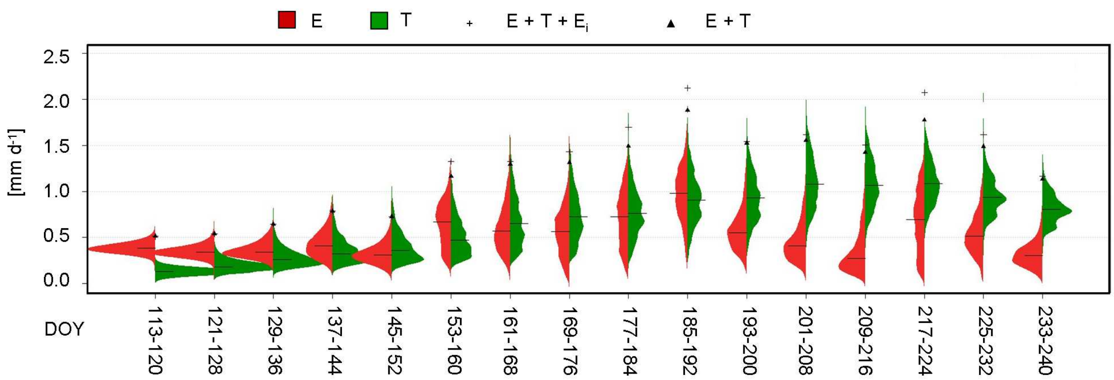

Figure 9 Probability density functions of the modelled spatial distribution of ET components in 2008. The black horizontal line depicts the median; soil evaporation is shown on the left side in red colour and transpiration is shown on the right side in green. E_i is evaporation from intercepted rain; the + shows ET as sum of its components and the triangle shows ET without E_i

The main contributions to these changes in ET are changes in E, whereas variations in T are less pronounced, as Figures 10 and 11 show. The differences of E of two consecutive eight-day periods were up to ±1.5 mm d^{-1} for individual pixels in 2008, whereas the range of variations of T was between ± 0.7 mm d^{-1}. These results indicate the important role of unproductive E in the ET dynamics modelled for the grasslands of the Xilin River catchment as E is more sensitive to P pulses than T.

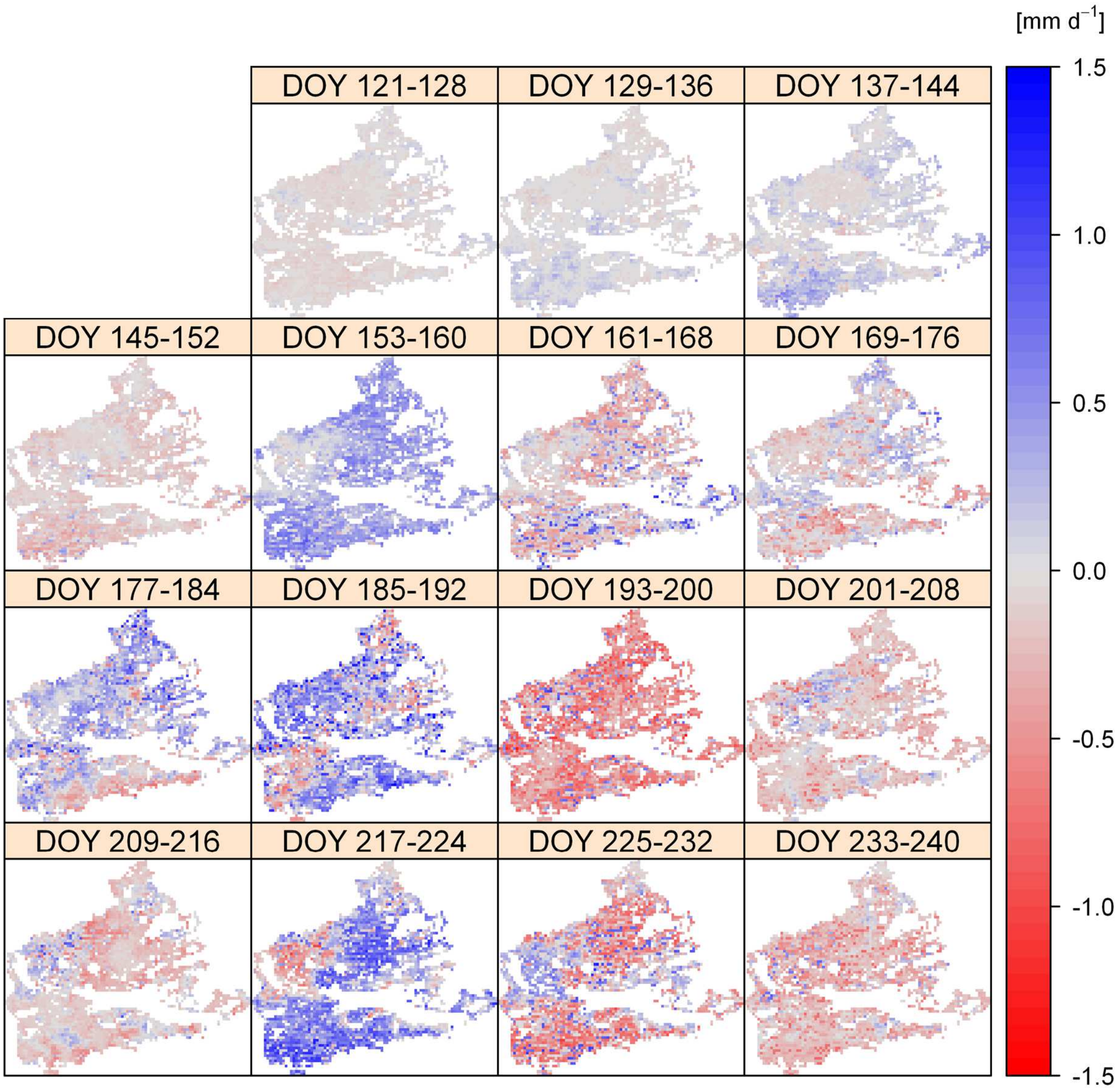

Figure 10 Spatial plots of changes in eight-day soil evaporation in the grasslands of the Xilin River catchment in 2008

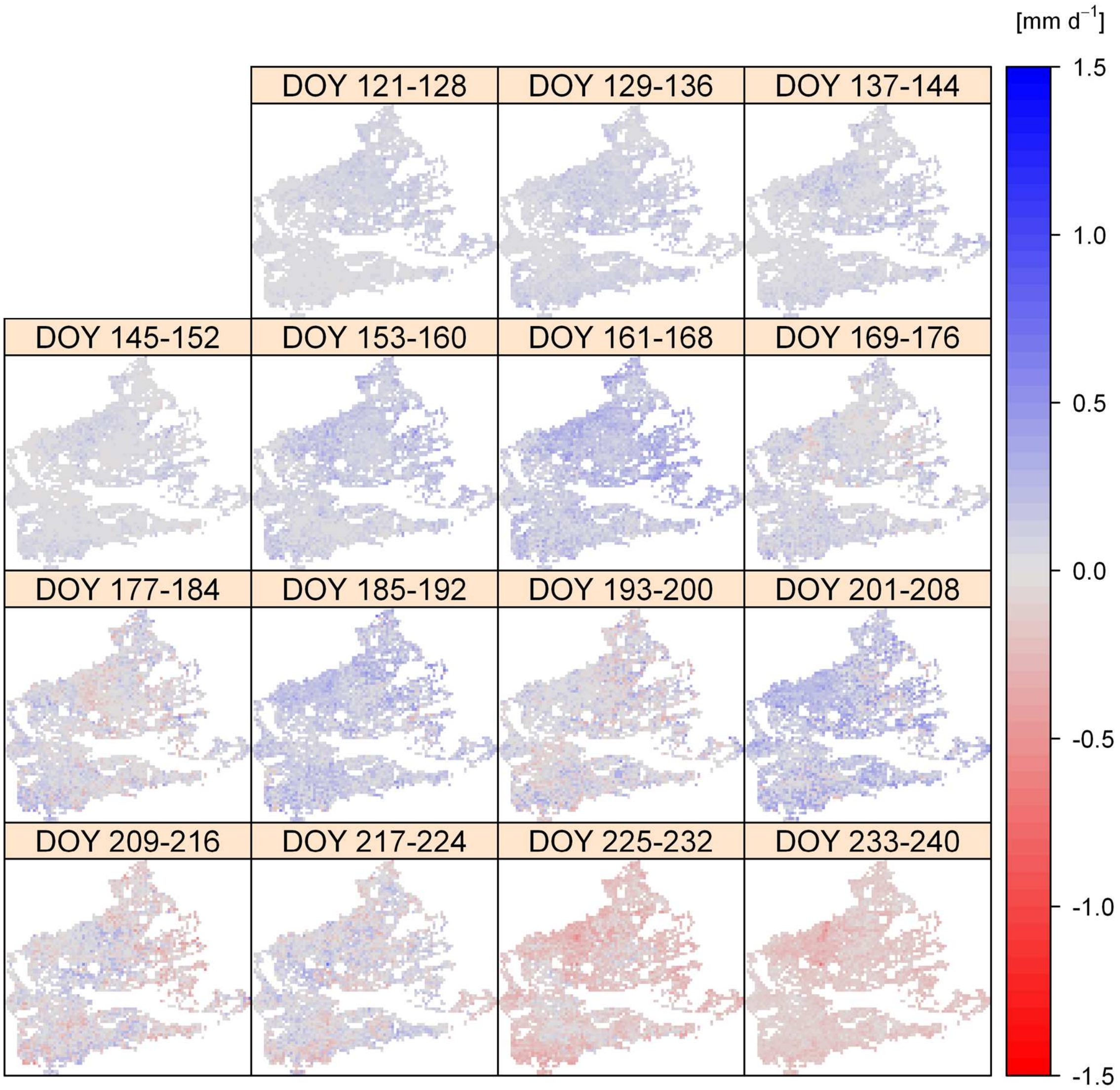

Figure 11 Spatial plots of changes in eight-day transpiration in the grasslands of the Xilin River catchment in 2008

The long-term variability of ET was quantified for the grasslands of the Xilin River by use of the coefficient of variation (CV). The mean CV of the eight-day ET in the study area ranges from 25% in the period from DOY 129-136 (9 May-16 May) to 40% in the period from DOY 153-160 (2 June–9 June). The temporal variability of ET is shown in more detail in Figure 5a of Schaffrath & Bernhofer (2013). A spatial plot of the spatiotemporal variability of eight-day ET is shown in Figure 6 of Schaffrath & Bernhofer (2013). The data of this figure were calculated from modelled ET data of 10 years (2002-2011). The CV of individual pixels has a broad range, up to 75% and the spatial pattern is highly variable over the growing season. Figure 9 of Schaffrath & Bernhofer (2013) presents the spatiotemporal variability of T, which displays different patterns than the results for ET. However, the variability of T is very high (up to 60%) in the northern part of the grasslands until July when it is slightly decreasing. The spatial pattern of the mean spatiotemporal variability of ET in the study area is shown in Figure 12. The mean CV of Fig. 12 is 32.5%, ranging from 23% to 44%. The CV is lower at the higher elevated areas in the east and south of the grasslands and in the vicinity of the Xilin River than in northern and less elevated areas (cp. with Fig. 1 of Schaffrath et al. 2011).

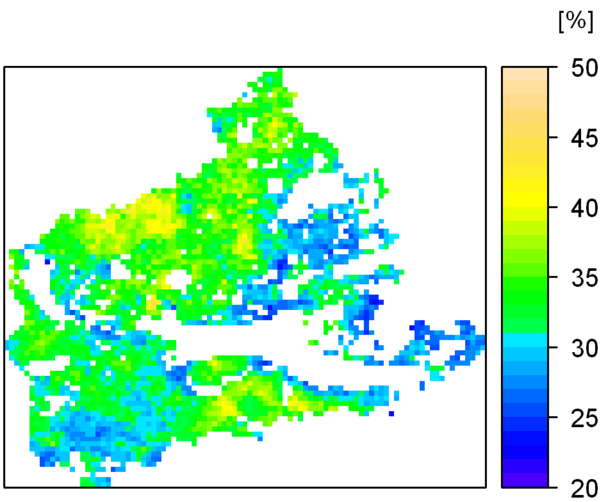

Figure 12 Spatial plot of the mean spatiotemporal variability of ET in the grasslands of the Xilin River catchment from 2002 to 2011

Modelled ET data were compared with the results of Hao et al. (2007, 2008), Huang et al. (2010) and Wang et al. (2012). The range and variation of modelled ET is in good agreement with these data, but the verification of modelled ET with field data is difficult because of the limited number of well-maintained long-term measurements. However, reasonable results were achieved with BROOK90, as the simulations with the calibrated model covered the day-to-day variations well (cp. Vetter et al. 2012). Schaffrath & Bernhofer (2013) also performed a comparison of modelled ET with the global ET product provided by the MODIS science team. The MODIS ET-product is calculated based on the work of Cleugh et al. (2007). The comparison of both data sets indicated the MODIS ET product to be in range of ET with our approach, but with lower values in spring (MODIS ET = Modelled ET x 0.8, R^2=0.63, n=160). In general, the spatial patterns of both data sets show similarities, but the contrast of the MODIS ET is higher (cp. with Figure 11 of Schaffrath & Bernhofer 2013). More detailed information on the MODIS ET product and the comparison with ET modelled in this thesis is provided by Schaffrath & Bernhofer (2013).

7. Discussion

Basically, this chapter discusses the implications of the results on grazing management and focuses on consequences including possible solutions for the problem of degradation of Inner Mongolian grasslands. In addition, different aspects of modelled results, e.g., their accuracy as well as uncertainties and potential error sources of the method, are discussed in the discussion section of chapter 5 (Schaffrath & Bernhofer 2013).

The combination of in situ data, remote sensing data products and hydrological modelling increased our knowledge of short- and long-term spatial water balance processes and demonstrated their interactions in semi-arid Inner Mongolian grasslands. Livestock husbandry, water management and the restoration of the degraded grasslands could benefit from the insights of this work because it has been performed for a large area of more than 2600 km² of natural grassland and not just for a few artificially created sites. In addition, it does comprise a comparatively long study period of 10 years. Thus, this thesis contributes to the demand for long-term studies of natural grassland ecosystems (Bai et al. 2004). In addition, the study reveals that field measurements – at best over several years – are important and useful for further extension into long study periods.

The analysis of the MODIS ET data product and the comparison with modelled ET by Schaffrath & Bernhofer (2013) did not just support the testing for plausibility of the results, but it also may encourage the scientific community to use the MODIS ET product for spatial applications in large rural areas, e.g., drylands. Although the MODIS ET data product does not separate ET into its components as our approach does, and although MODIS ET deviates from our results in spring due to missing information on soil moisture, the good agreement of the long-term spatial pattern with our data (R=0.79, n=3029) indicates the functioning of MODIS ET data for Inner Mongolian grasslands in general. However, transferring the matrix potential of the soil profile from 31 December to 1 January of the following year and the capability of ET separation into its components are two major advantages of the developed method over using the MODIS ET product. In addition, there are only a few studies using the MODIS ET data product thus far. Ruhoff et al. (2011) demonstrated monthly and annual ET of the MODIS ET data product to be consistent with EC data in tropical forests and rainforest when the land cover classification is correct. Otherwise, ET is less accurate. However, they conclude the global estimation of ET is a challenge as numerous surface and atmospheric parameters are required globally. Nevertheless, because important data on surface parameters, such as LAI and surface temperature, have been collected by MODIS globally since the year 2000, ET could also be modelled with the method developed in this thesis in other regions of the Eurasian steppe belt or in North America. An adaptation of BROOK90 to other study areas in e.g., China, Mongolia, Russia and Kazakhstan or in the North-American prairie could be achieved by model parameterisation with the data available via the FLUXNET network (http://fluxnet.ornl.gov, accessed January 2014). In addition, the results of our long-term analysis could be improved by integration of observations beyond 2011, as MODIS was still functioning through the year 2013.

In this thesis, the high spatiotemporal variability of both water availability (P) and consumption (ET) were demonstrated according to the author’s knowledge for the first time in Inner Mongolian grasslands. However, the frequency of relatively wet growing seasons appears to be low. P sums were clearly higher (300 mm) than the calculated average of the ten-year study period (165 mm) only in one out of 10 years (2003). The very low P values as of 2009 (116 mm) also appear to be exceptional. The mean P of the study area varied between 136 mm and 175 mm in eight of 10 observed years only, but the spatial P plots (Fig. 3) display local differences of P, which were much higher and very variable. This indicates an interannual variability on the catchment level that supports sustainable grazing management with the traditional nomadic lifestyle.

In addition, the results indicate the dominant role of E in short-term ET dynamics (Figures 9 and 10). As the BROOK90 model does not consider non-green leaves, the ET simulations represent the typical conditions at grazed sites quite correctly. According to our observations of field sites in Inner Mongolia, permanently grazed sites are characterised by a very low fraction of dead plant material and litter. On the other hand, the proportion of dead plant material and litter was significantly higher at ungrazed and seasonally grazed sites. Su et al. (2005) demonstrated grazing exclusion enhanced litter accumulation, which we assume to decrease the proportion of unproductive E on ET.

The results of this work indicate an uncontrolled, intensive and sedentary livestock management to be inappropriate in this area. Thus, a reintroduction of nomadism in this area would be in alignment with the natural conditions of these grasslands but may be unrealistic under current political, economic and social structures.

However, interdisciplinary scientific research has improved the knowledge about Inner Mongolian grasslands substantially during the last decade. There is no doubt that heavy grazing has a strong impact on these sensitive grasslands, and the detrimental effects of continuous grazing on vegetation and soils are well known (Tong et al. 2004, Su et al. 2005, Jiang et al. 2006, Steffens et al. 2008, Han et al. 2009, Butterbach-Bahl et al. 2011). The vitality of Inner Mongolian grasslands is also affected by climate change, but the transformation from nomadism to recent land use practices with an 18-fold increase of livestock since 1949 (Jiang et al. 2006) is the main cause and trigger for grassland degradation in Inner Mongolia. Thus, establishing a sustainable livestock management in the grasslands of the Xilin River requires the drastic reduction of stocking rates and a change in spatial management of grazing. We suggest bringing stocking rates into alignment with the carrying capacity of very dry years to reduce and prevent further degradation. In this scenario, excess P during wetter years could be beneficial for the natural restoration of these grasslands, and the surplus of forage could be reserved. In addition, the spatial results of our long-term analyses (Fig.1 and Fig 12) can be used to support the calculation of local stocking rates. Stocking rates may be kept lower in zones of higher spatiotemporal variability of ET and low long-term ET than in areas of high long-term ET and low spatiotemporal variability of ET.

The adaptation of livestock management to the carrying capacity of the grasslands is crucial for the restoration and protection of the grasslands in Inner Mongolia. This approach may be supported by the establishment of an alternative property-rights-regime as proposed by Bijoor et al. (2006) or the re-location of rural population into surrounding cities to relieve grazing pressure as discussed by Jiang et al. (2003). The development of eco-tourism in this area can be a powerful tool as well (cp. Qian 2002).

Another promising approach for a sustainable grassland management might be the introduction of permaculture (Mollison 1988) at already degraded farms. The permaculture concept is a method developed in the 1970s for designing sustainable land-use systems based on balancing water, soil, plants and animals into complex landscape patterns using ecological principles (Mollison 1988, Holmgren 2011). The conservation of resources is a central issue to the holistic approach of permaculture (Mars 2003). By the efficient and intelligent use of natural energy and nutrient cycles, food, energy and shelter will be produced, whereas waste is recycled and the diversity of natural ecosystems will be restored. Permaculture also offers practical measures for e.g., healing gully erosion (Mollison 1988). However, the practical implementation of permaculture requires motivated, skilled and interested farmers. Thus, we would recommend the establishment of an exemplarily permaculture pilot farm in Inner Mongolia in cooperation with interdisciplinary scientists. Anthropological scientists may educate local farmers to increase their awareness of potential methods for the improvement of their lifestyle and about the sensitivity of the grassland environments, while natural scientists can apply their advanced methods to monitor the effects induced by the application of permaculture principles.

Observing the problem of grassland degradation from a different perspective makes clear that the ongoing shift from a plant-based diet to a high proportion of animal based food in China and in other emerging countries in general is the basic cause for the increasing demand of meat and thus for significant environmental problems (Steinfeld et al. 2006, Stehfest et al. 2009, De Vries & De Boer 2010). However, the increased intake of animal-based food caused an increased appearance of food-related health issues in China (Popkin & Du 2003). Although the subject is still controversial, and the public awareness about it is low, nutritional science has found high consumption of animal-based food negatively affect health: cardiovascular disease, obesity and cancer are associated with high consumption of red meat (Daviglus et al. 2008, Campbell et al. 1998, Popkin & Du 2003). If the public awareness could grow on this effect, the demand for meat may decrease in the future, which would simplify the responsible management of the grasslands in Inner Mongolia.

However, instead of controlling the causes, the Chinese government has invested huge amounts of money in large-scale afforestation programs, such as the Three-North Shelter Forest Program to protect the Chinese mainland from the negative effects of dust storms. However, the anticipated effects failed to appear (Jiang et al. 2006, Cao 2008) as many trees died and the impact of severe dust storms in Beijing and the Chinese mainland is still high. From the author's point of view, the financial support of a controlled and sustainable grassland management system should be considered to eventually re-establish the ecological function of Inner Mongolian grasslands as a barrier against the vast deserts of Central Asia. As the ungrazed field sites of IMGERS and the study of Su et al. (2005) proved, exclusion of grazing is promoting growth and ground coverage of vegetation. Therefore, the ability of grasslands to recover naturally is shown. The increased roughness length resulting from a large-scale grassland restoration program will, in turn, reduce the formation and impact of severe dust storms.

In conclusion, the studies on spatial ET in this thesis identified the high spatiotemporal variability of ET, indicating sedentary livestock management to be inappropriate in the Xilin River catchment. In addition, the long-term spatial results on ET, which integrate the distribution of P and its interaction with soils and vegetation, could support the sustainable adaptation of livestock management according to the environmental conditions in the grasslands of the Xilin River catchment. This work also underlined the recent research activities, e.g., the MAGIM project, increased the knowledge and understanding of causes and means of grassland degradation. The international scientific community identified non-sustainable land use practices to be the main cause for land degradation and desertification in this area. As a variety of approaches for grassland restoration have been developed recently, the author suggests further evaluation of strategies and political decision making based upon scientific findings are required to protect and restore the grasslands of Inner Mongolia. The combination of severe restrictions of stocking rates with restoration programs is inevitable for the protection and restoration of the grasslands of Inner Mongolia.

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Appendix

A.1 DOY-calendar table

Start DOY	End DOY	Start date*	End date*
113	120	23 April	30 April
121	128	1 May	8 May
129	136	9 May	16 May
137	144	17 May	24 May
145	152	25 May	1 June
153	160	2 June	9 June
161	168	10 June	17 June
169	176	18 June	25 June
177	184	26 June	3 July
185	192	4 July	11 July
193	200	12 July	19 July
201	208	20 July	27 July
209	216	28 July	4 August
217	224	5 August	12 August
225	232	13 August	20 August
233	240	21 August	28 August

*Note: The study period is from 22 April to 27 August in leap years (2004, 2008).