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Grazing decreased water use efficiency in Central Asia from 1979 to 2011

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ABSTRACT

Accurate predictions of water vapor at large temporal and spatial scales are particularly important in global studies. In recent years, Central Asian grasslands have been subject to both intensive grazing and variability in climatic conditions. However, uncertainties about grazing on water cycling under climate change still exist. Therefore, the Biome-BGC grazing model was applied to assess the effects of grazing on evapotranspiration (ET) and water use efficiency (WUE). Three grassland types were studied during the period 1979–2011: forest meadow (FM), temperate grassland (TG) and desert grassland (DG). ET shows a gradual decreasing trend from FM (365.65 ± 36.86 mm m^{-2} yr^{-1}) to DG (183.32 ± 21.15 mm m^{-2} yr^{-1}), and WUE ranging from 0.62 ± 0.03 g C kg^{-1} H_2O in FM to 1.12 ± 0.10 g C kg^{-1} H_2O in TG, with an average of 0.83 ± 0.05 g C kg^{-1} H_2O. Although there was a significant decrease in ET of 1.47–2.72 mm m^{-2} yr^{-1}, WUE increased at a rate of 0.004 g C kg^{-1} H_2O yr^{-1} in Central Asia. From 1979 to 2011, grazing lowered ET by 7.47% in Central Asia; the reduction rates for FM, TG and DG were 3.10%, 12.70% and 7.42%, respectively. In general, grazing decreased WUE by 3.60%. From non-grazed to grazed scenario, WUE increased by 6.86% for FM, but WUE decreased by 7.27% and 5.61% for TG and DG. An over-compensation of GPP under grazing might account for the higher WUE under certain grazing intensities. In order to achieve maximum utilization of water efficiency, proper grazing intensity for TG, DG and FM should be limited to 0.17, 0.39 and 0.38 head/ha, respectively.

1. Introduction

In global climate studies, it is particularly important to be able to accurately predict the exchange of water vapor and carbon dioxide between the atmosphere and terrestrial ecosystems, over both long periods of time and over large areas (Li et al., 2006). Evapotranspiration (ET) is water vapor exchange between the atmosphere and terrestrial ecosystems and, notwithstanding precipitation, ET forms one of the largest parts of the overall hydrological budget (Brutsaert, 1982). Closely linked to ET are the growth of vegetation and possible future photosynthetic carbon (C) uptake (Brümmer et al., 2012). Water use efficiency (WUE) is the ratio of photosynthetic carbon taken up per unit of water loss by transpiration (Cowan and Farquhar, 1977). Therefore, the study of ET and WUE among a variety of terrestrial ecosystems is therefore fundamental to understanding their role in local, regional and global water cycles and water vapor exchange between the Earth's surface and the atmosphere.

ET and WUE are controlled by canopy architecture and development, soil characteristics, and a variety of in situ environmental variables (Bremer et al., 2001; Hupet and Vanclooster, 2005). Human activities, as, for example, large-scale changes in land cover and land use, will affect ET in a variety of ways. These may include modifications to surface roughness length, the amount of vegetation covering the land and moisture in the soil (Alfieri et al., 2007; Hidy et al., 2012; Lapitan and Parton, 1996; Li et al., 2006).

A great part of Central Asia is characterized by semiarid or arid climate which is fragile and sensitive to both changes in climate and anthropogenic disturbances (Kerven et al., 2011). Of the land-use practices in grasslands in this region, grazing is the most frequently encountered (Polley et al., 2008). Grazing removes green leaf area and changes the microclimate of the surface which may affect ET and WUE (Li et al., 2000; Luo et al., 2010; Song et al., 2014). To cite an example, Cattle (*Bos taurus*) spring grazing a tallgrass prairie site reduced season-long ET by 6.1% compared with an ungrazed site (Bremer et al., 2001). Likewise, the Northern Great Plains semiarid grasslands of the US exhibited a three-year average ET that was 7% less when it was grazed than when left ungrazed (Frank, 2003). On the other hand though, another study reported heavy grazing by prairie dogs actually increased

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ET when compared to a lightly grazed site (Day and Detling, 1994). Additionally, Stewart and Verma (1992) reported no differences in ET from grazing in a tallgrass prairie even when leaf area index (LAI) differences were large and soil water was nonlimiting (Stewart and Verma (1992). While the effects of grazing on water cycles are related to vegetation cover, energy availability and soil water conditions, uncertainties regarding these effects still exist.

Therefore, the Biome-BGC grazing model was applied in this study to assess ecological effects of grazing on the grasslands in central Asia under climate change, specifically, (1) characterize the spatial and temporal dynamics of the actual ET and WUE from 1979 to 2011 among different grassland types; (2) analyze how and to what extent does grazing affect grassland ET and WUE. This quantification can provide a reference for maintaining dry grassland stability and improving resistance to potential climate changes.

2. Data and methods

2.1. Study area

Our study area includes five republic countries of Central Asia (i.e., Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, and Uzbekistan) and Xinjiang in China, occupying an area of nearly 5.7 million km^2 and have low precipitation, high evapotranspiration, arid and semi-arid climate (Cowan, 2007). Precipitation decreases toward the center and south of Aral Sea, and increases toward the north, east, and southern edges of the region (Buslov et al., 2007). Grasslands fall into one of three different bio-geographic types along the vertical gradients; forest meadow (FM) was obtained when the elevation above 1650 m a.s.l. and depending on the climate, grassland below 1650 m a.s.l. was further subdivided into desert grassland (DG) and temperate grassland (TG). Grassland production in northern Kazakhstan was more determined by temperature than precipitation so this region was classified as TG. Southern Kazakhstan and the desert areas of Xinjiang suffer from a deficiency of water and were therefore classified as DG (Luo et al., 2012). 63% of this land area are rangelands with an arid climate. The vast rangelands of Central Asia form the world's largest contiguous area of grazed land. (Fig. 1).

2.2. Biome-BGC grazing model

Biome-BGC is a biogeochemical model that simulates above- and belowground carbon, water, and nitrogen cycles of different vegetation types (Running and Hunt, 1993; Thornton, 1998). For the water cycle, Biome-BGC calculates transpiration, interception and evaporation from the canopy, soil water content, snowmelt and outflow from the soil. For carbon cycles, the model calculates photosynthesis, growth respiration,

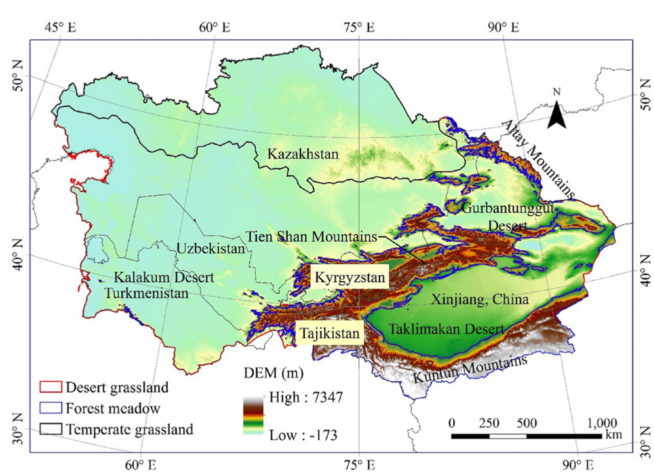

Fig. 1. Study area and distribution of major grassland types in Central Asia.

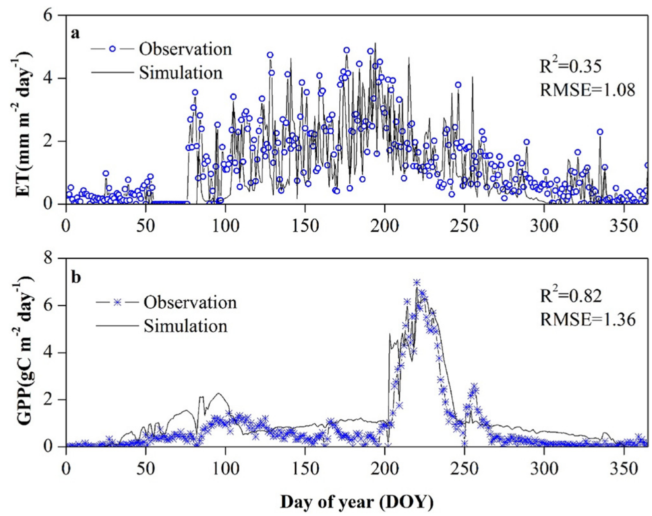

Fig. 2. Comparison of observed and simulated ET (a) and GPP (b).

maintenance respiration, allocation, litter-fall and decomposition. Finally, nitrogen cycling is represented by deposition, uptake, litter-fall and mineralization.

The original model has been recently modified to improve its performances when applied to grassland with herbaceous. A defoliation formulation developed by Seligman et al. (1992) was integrated into the Biome-BGC model (Luo et al., 2012), resulting in a Biome-BGC grazing model which describes the effects of grazing on the carbon cycle of grassland ecosystems. Han et al. (2016) give a detailed description of this model. In this model, Net Primary Productivity (NPP) is defined as the summation of the Gross Primary Productivity (GPP), autotrophic respiration (Ra) and defoliation rates (Dr).

$$NPP = GPP - Ra - D_r \quad (1)$$

$$D_r = G_e \times GI \times (C_{leaf} - (C_{leaf})_r) \quad (0 < D_r < G_i D_x) \quad (2)$$

where D_r is the defoliation rate (g C ha^{-1} d^{-1}), *Ge* is the grazing efficiency of the livestock (ha/d/sheep unit), *GI* is the grazing intensity (head/ha), C_{leaf} is the C in the leaf biomass (g C m^{-2}), $(C_{leaf})_r$ is the residual aboveground C_{leaf} that is unavailable to livestock (g C m^{-2}), and D_x is the satiation consumption rate of the livestock (g C d^{-1} head^{-1}) (NRC, 1985).

WUE is defined as the ratio of GPP to ET, i.e. the amount of carbon assimilated per unit of water loss by ET:

$$WUE = GPP/ET \quad (3)$$

2.3. Input datasets

Minimum and maximum air temperature, precipitation, solar radiation and vapor pressure deficit were some of the daily climate data required. These, along with other general information on the stands being studied, such as latitude, soil depth, soil water content, were then imported into the model. In addition to this, about 50 parameters describing the eco-physiological behavior of the species found in the forest stands were similarly required (Running and Hunt, 1993). Meteorology data was gathered over Central Asia on a daily basis from 1979 to 2011 and displayed on a grid at a resolution of 0.5 of latitude/longitude. The information originated from the Climate Forecast System Reanalysis (CFSR) (Environmental Modeling Center, 2010). By using linear interpolation for 1979 to 2011 and livestock numbers for the different regions based on FAO grazing intensity data for the year 2000, grazing data over this time period were obtained (Wint and Robinson, 2007). The grazer species including cattle, buffalo, sheep and goats according to Central Asian' husbandry situation. All the grazers