Effects of Grazing on Net Primary Productivity, Evapotranspiration and Water Use Efficiency in the Grasslands of Xinjiang (Postprint)

Authors: HUANG, Xiaotao, LUO, Geping, YE, Feipeng, HAN, Qifei

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Abstract

Grazing is a main human activity in the grasslands of Xinjiang. It is vital to identify the effects of grazing on the sustainable utilization of local grasslands. However, the effects of grazing on net primary productivity (NPP), evapotranspiration (ET) and water use efficiency (WUE) in this region remain unclear. Using the spatial Biome-BGC grazing model, we explored the effects of grazing on NPP, ET and WUE across the different regions and grassland types in Xinjiang during 1979–2012. NPP, ET and WUE under the grazed scenario were generally lower than those under the ungrazed scenario, and the differences showed increasing trends over time. The decreases in NPP, ET and WUE varied significantly among the regions and grassland types. NPP decreased as follows: among the regions, Northern Xinjiang (16.60 g C/(m2 • a)), Tianshan Mountains (15.94 g C/(m2 • a)) and Southern Xinjiang (−3.54 g C/(m2 • a)); and among the grassland types, typical grasslands (25.70 g C/(m2 • a)), swamp meadows (25.26 g C/(m2 • a)), mid-mountain meadows (23.39 g C/(m2 • a)), alpine meadows (6.33 g C/(m2 • a)), desert grasslands (5.82 g C/(m2 • a)) and saline meadows (2.90 g C/(m2 • a)). ET decreased as follows: among the regions, Tianshan Mountains (28.95 mm/a), Northern Xinjiang (8.11 mm/a) and Southern Xinjiang (7.57 mm/a); and among the grassland types, mid-mountain meadows (29.30 mm/a), swamp meadows (25.07 mm/a), typical grasslands (24.56 mm/a), alpine meadows (20.69 mm/a), desert grasslands (11.06 mm/a) and saline meadows (3.44 mm/a). WUE decreased as follows: among the regions, Northern Xinjiang (0.053 g C/kg H2O), Tianshan Mountains (0.034 g C/kg H2O) and Southern Xinjiang (0.012 g C/kg H2O); and among the grassland types, typical grasslands (0.0609 g C/kg H2O), swamp meadows (0.0548 g C/kg H2O), mid-mountain meadows (0.0501 g C/kg H2O), desert grasslands (0.0172 g C/kg H2O), alpine meadows (0.0121 g C/kg H2O) and saline meadows (0.0067 g C/kg H2O). In general, the decreases in NPP and WUE were more significant in the regions with relatively high levels of vegetation growth because of the

high grazing intensity in these regions. The decreases in ET were significant in mountainous areas due to the terrain and high grazing intensity.

Full Text

Preamble

Effects of Grazing on Net Primary Productivity, Evapotranspiration and Water Use Efficiency in the Grasslands of Xinjiang

HUANG Xiaotao[1,2], LUO Geping[1*], YE Feipeng[3], HAN Qifei
[1] State Key Laboratory of Desert and Oasis Ecology, Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, Urumqi 830011, China
[2] Nanjing University of Information Science & Technology, Nanjing 210044, China

Abstract: Grazing is a primary human activity in the grasslands of Xinjiang and plays a vital role in the sustainable utilization of these ecosystems. However, the effects of grazing on net primary productivity (NPP), evapotranspiration (ET) and water use efficiency (WUE) remain unclear. Using the spatial Biome-BGC grazing model, we explored grazing effects on NPP, ET and WUE across different regions and grassland types in Xinjiang from 1979–2012. NPP, ET and WUE under grazed scenarios were generally lower than under ungrazed scenarios, with these differences showing increasing trends over time. The decreases varied significantly among regions and grassland types. NPP decreased most in Northern Xinjiang (16.60 g C/(m^2·a)), the Tianshan Mountains (15.94 g C/(m^2·a)), and Southern Xinjiang (−3.54 g C/(m^2·a)). Among grassland types, NPP reductions followed the order: typical grasslands (25.70 g C/(m^2·a)), swamp meadows (25.26 g C/(m^2·a)), mid-mountain meadows (23.39 g C/(m^2·a)), alpine meadows (6.33 g C/(m^2·a)), desert grasslands (5.82 g C/(m^2·a)) and saline meadows (2.90 g C/(m^2·a)). ET decreased most in the Tianshan Mountains (28.95 mm/a), Northern Xinjiang (8.11 mm/a) and Southern Xinjiang (7.57 mm/a). Among grassland types, ET reductions were: mid-mountain meadows (29.30 mm/a), swamp meadows (25.07 mm/a), typical grasslands (24.56 mm/a), alpine meadows (20.69 mm/a), desert grasslands (11.06 mm/a) and saline meadows (3.44 mm/a). WUE decreased most in Northern Xinjiang (0.053 g C/kg H O), the Tianshan Mountains (0.034 g C/kg H O) and Southern Xinjiang (0.012 g C/kg H O). Among grassland types, WUE reductions were: typical grasslands (0.0609 g C/kg H O), swamp meadows (0.0548 g C/kg H O), mid-mountain meadows (0.0501 g C/kg H O), desert grasslands (0.0172 g C/kg H O), alpine meadows (0.0121 g C/kg H O) and saline meadows (0.0067 g C/kg H O). Generally, NPP and WUE decreases were more significant in regions with relatively high vegetation growth due to high grazing intensity, while ET decreases were significant in mountainous areas due to terrain and high grazing intensity.

Keywords: grazing effect; grassland type; net primary productivity; evapotranspiration; water use efficiency; Biome-BGC grazing model

Introduction

Grazing is a common practice in grasslands worldwide and significantly affects ecosystem functions. The interactions between grassland ecosystems and herbivores are highly complex, involving numerous factors, making grazing a popular yet challenging research topic in grassland ecology. However, studies examining grazing effects on NPP, ET and WUE across different grassland types remain limited at regional scales, particularly in arid regions.

NPP, ET and WUE are three key factors reflecting grassland ecosystem functions. NPP indicates production capacity and is highly sensitive to climate change and human activities. ET represents the primary form of water loss in arid grasslands, and the balance between precipitation and ET is crucial for determining ecosystem structure, function and productivity. WUE reflects plant water-use efficiency for biomass production and serves as an indicator of environmental suitability for plant growth. Compared with humid grasslands, arid grasslands exhibit unique ecological processes in response to water stress, making studies of NPP, ET and WUE particularly important in dry regions.

Grazing affects plant growth through vegetation removal and feces deposition, influences ET through vegetation removal, and may alter WUE. Recent studies show that NPP and ET responses to grazing differ under varying environmental conditions, suggesting diverse effects across regions and grassland types. Understanding these large-scale effects is essential for developing appropriate grazing management strategies tailored to different grassland ecosystems.

Xinjiang, located in the arid Eurasian hinterland, contains widely distributed grassland ecosystems where grazing is the main anthropogenic disturbance. Increasing grazing intensity over recent decades has caused widespread degradation. Research on grazing effects on NPP, ET and WUE is therefore vital for sustainable grassland resource utilization in Xinjiang. The region' s distinct variations in elevation, climate, grassland type and grazing management create spatial heterogeneity in these parameters, making it ideal for studying grazing effects under different environmental conditions in arid areas.

Model simulation is currently considered the most effective method for studying large-scale grazing effects, as it allows evaluation of different scenarios. The process-based Biome-BGC grazing model can effectively estimate grazing impacts on carbon and water fluxes and storage in grassland ecosystems. This study aims to determine grazing effects on NPP, ET and WUE in Xinjiang grasslands from 1979–2012 across different regions and grassland types using the spatial Biome-BGC grazing model.

Study Area

Xinjiang covers 1.66×10 km^2 and represents an important livestock production region. The climate is temperate with arid characteristics, featuring a mean annual temperature of 10.4°C and mean annual precipitation of 188 mm. The Tianshan Mountains divide Xinjiang into Northern and Southern Xinjiang [Figure 1: see original paper]. Southern Xinjiang receives 20–100 mm annual precipitation with temperatures of 10.0–13.8°C, while Northern Xinjiang receives 100–500 mm with temperatures of 4.0–8.8°C. Grasslands comprise 34.4% of Xinjiang' s territory, including alpine meadows (1.09×10 km^2), mid-mountain meadows (3.14×10 km^2), typical grasslands (3.35×10 km^2), desert grasslands (3.63×10 km^2), saline meadows (3.01×10 km^2) and swamp meadows (5.4×10 km^2). Most grasslands are grazed, though intensity varies significantly among types. Increasing grazing intensity has caused severe deterioration across large areas.

Data

Model Validation Data

Validation data for NPP and ET were collected from field observations and previous publications. Forty-eight plots provided annual NPP data, including six ungrazed enclosures and 42 grazed plots. Due to measurement difficulties, all grazed plot NPP data represent remaining NPP after grazing. Daily ET data (2013–2015) were obtained from a typical grassland in Urumqi County (43°33 N, 87°12 E; 1648 m a.s.l.) using an HL20 Bowen ratio system in a 100 m×100 m ungrazed enclosure. Additional daily ET data (October 2012–September 2013) came from an alpine meadow in Aksu (41°42 N, 80°10 E; 3550 m a.s.l.) using a microlysimeter in an ungrazed enclosure. Desert grassland ET data (22 July–2 September 2010) were collected using a Bowen ratio system in Qitai County (44°11 N, 89°26 E; 617 m a.s.l.) and from Yan et al. (2015).

Grazing Data

Elevation, precipitation and distance from residential areas distinguished pasture types. Summer pastures occurred above 2500 m in mountains or in plains with 630 mm mean annual precipitation. Spring-autumn pastures were located below 2500 m in mountains or in plains with 126 mm precipitation. Winter pastures were near permanent mountain settlements or in plains with light snowfall and 210 mm precipitation. Regional grazing intensity data were interpolated from global livestock numbers and environmental data provided by the United Nations FAO (http://www.fao.org/docrep/010/a1259e/a1259e00.htm) and corrected using Xinjiang statistical yearbook data for high precision. Field investigations provided grazing data at validation points.

Livestock (cattle, sheep, goats, horses, camels, yaks) were converted to sheep units using Ministry of Agriculture standards: 1 goat = 0.9 sheep, 1 cattle =

6.0 sheep, 1 horse = 6.0 sheep, 1 yak = 4.5 sheep, 1 camel = 8.0 sheep. Figure 2 shows interannual grazing intensity variation in Xinjiang grasslands from 1979-2012.

Meteorological Data

Required meteorological data included daily maximum/minimum air temperatures, average temperature, humidity, solar radiation, precipitation and day length. Regional data were extracted from the China Meteorological Forcing Dataset using C++, offering better precision than existing grid-based data for this region. With 10 km spatial resolution, these data are suitable for terrestrial modeling (http://www.tpedatabase.cn/portal/MetaDataInfo.jsp?MetaDataId=249369). Validation point meteorological data were collected through field observations.

Other Auxiliary Data

Elevation data were derived from WorldClim (Hijmans et al., 2005) (http://www.worldclim.org/download). Soil data (effective depth, sand/silt/clay percentages) came from the Harmonized World Soil Database (FAO/IIASA/ISRIC/ISS-CAS/JRC, 2012). A Xinjiang grassland type map was generated from vegetation type maps based on elevation and vegetation characteristics. Validation point elevation and soil data were obtained through field investigations.

The Biome-BGC Grazing Model

The Biome-BGC grazing model is a process-based ecosystem model that effectively simulates grazing effects on carbon and water fluxes and storage in grassland ecosystems over large areas. The grazing process is suitable for arid and semi-arid grasslands.

In the model, NPP is estimated by Equation 1 (Luo et al., 2012):

$$NPP = C'_{veg} + C_{litter} + D_r \quad (1)$$

where C'_{veg} (g C/(hm$^2 \cdot$ d)) is vegetative carbon, C_{litter} is litter carbon (g C/(hm$^2 \cdot$ d)), and D_r (g C/(hm$^2 \cdot$ d)) is carbon consumed by animals, calculated by Equation 2 (Luo et al., 2012):

$$D_r = G_e \times S_r \times (C_{leaf} - (C_{leaf})_U) \quad (0 < D_r < S_r D_x) \quad (2)$$

where G_e is livestock grazing efficiency (hm^2/(sheep $\cdot$ d)), S_r is grazing intensity (sheep/hm^2), C_{leaf} is leaf biomass carbon (g C/m^2), $(C_{leaf})_U$ is residual aboveground leaf carbon unavailable to livestock (g C/m^2), and D_x is livestock consumption rate based on satiation (g C/(sheep $\cdot$ d)).

ET is calculated using the Penman-Monteith equation (Equation 3) (Running and Coughlan, 1988; Zhao and Zhao, 2014):

$$ET = \frac{\Delta(R_n - G) + \rho C_p(e_s - e_a)/r_a}{\Delta + \gamma(1 + r_s/r_a)} \quad (3)$$

where ET is actual evapotranspiration (mm/d), Δ is the slope of vapor pressure versus temperature curve (kPa/°C), R_n is net radiation (MJ/(m² · d)), ρ is air density (kg/m³), C_p is specific heat of air (MJ/(kg · °C)), e_s is saturation vapor pressure (kPa), e_a is actual vapor pressure (kPa), γ is the psychrometric constant (kPa/°C), r_s is bulk surface resistance (s/m), and r_a is aerodynamic resistance (s/m). Energy is divided into transpiration and evaporation components.

Grassland WUE was calculated by Equation 4 (Han et al., 2013):

$$WUE = \frac{NPP}{ET} \quad (4)$$

where WUE is expressed as g C/kg H O.

Two scenarios—grazed and ungrazed—were evaluated to assess grazing effects on NPP, ET and WUE in Xinjiang grasslands from 1979-2012.

Model Validation

The Biome-BGC grazing model was validated for NPP and ET estimates using field observations and published data from Xinjiang grasslands. The model accurately estimated annual NPP, with simulated data closely matching field observations under both grazed ($R^2 = 0.88$, RMSE=26.92) and ungrazed scenarios ($R^2 = 0.83$, RMSE=36.07). Due to measurement difficulties, NPP values represent remaining NPP after grazing.

ET validation compared simulated and observed data from: (1) a typical grassland in Urumqi County under ungrazed conditions ($R^2 = 0.76$, RMSE=0.67), (2) an alpine meadow in Aksu under ungrazed conditions ($R^2 = 0.66$, RMSE=0.76), and (3) a desert grassland in Qitai County under grazed conditions ($R^2 = 0.66$, RMSE=0.30). The model performed well in estimating ET [Figure 4: see original paper].

Impacts of Livestock Grazing on NPP

Spatial distribution of average annual NPP differences between grazed and ungrazed scenarios shows widespread decreases across Xinjiang from 1979-2012, indicating extensive grassland degradation [Figure 5: see original paper]. Significant NPP reductions occurred mainly in the Altay Mountains and parts of the Tianshan Mountains, while increases appeared at middle to low elevations on the northern Kunlun Mountains slope and in western Southern Xinjiang. Interannual fluctuations were similar between scenarios, with NPP showing a fluctuating increase under ungrazed conditions but a fluctuating decline under grazed conditions.

NPP decreases were most significant in Northern Xinjiang and the Tianshan Mountains, while Southern Xinjiang showed general increases . Among grassland types, NPP reductions followed the order: typical grasslands, swamp meadows, mid-mountain meadows, alpine meadows, desert grasslands and saline meadows. Decreases were more pronounced in grasslands with relatively good vegetation growth .

Impacts of Livestock Grazing on ET

ET under grazed scenarios decreased in most Xinjiang regions from 1979–2012 [Figure 6: see original paper]. Significant ET reductions occurred in parts of the Tianshan Mountains, while increases appeared in portions of Southern Xinjiang and northern Northern Xinjiang. ET was lower under grazed than ungrazed scenarios throughout the period, with similar interannual fluctuations between scenarios. A fluctuating ET increase occurred under ungrazed conditions, but not under grazed conditions.

ET decreases were most significant in the Tianshan Mountains, slightly larger in Northern than Southern Xinjiang, though percentage decreases were higher in Southern Xinjiang due to lower baseline ET values . Among grassland types, ET reductions followed the order: mid-mountain meadows, swamp meadows, typical grasslands, alpine meadows, desert grasslands and saline meadows. Percentage decreases followed a slightly different order: alpine meadows, mid-mountain meadows, typical grasslands, swamp meadows, desert grasslands and saline meadows. Mountainous grasslands showed the most significant ET decreases .

Impacts of Livestock Grazing on WUE

WUE under grazed scenarios decreased across most Xinjiang grasslands from 1979–2012 [Figure 7: see original paper]. Significant WUE reductions occurred in the northwestern Tianshan Mountains and eastern Altay Mountains, while increases appeared in the Altun Mountains, southwestern Tianshan Mountains, and northern Kunlun Mountains slope. Interannual WUE fluctuations were lower under grazed conditions, with a clear fluctuating decline observed under grazing but not under ungrazed conditions.

WUE decreases were most significant in Northern Xinjiang, least significant in Southern Xinjiang, and intermediate in the Tianshan Mountains. Percentage decreases were slightly higher in the Tianshan Mountains than Southern Xinjiang due to higher baseline WUE values . Among grassland types, WUE reductions followed the order: typical grasslands, swamp meadows, mid-mountain meadows, desert grasslands, alpine meadows and saline meadows. Decreases were more significant in grasslands with high vegetation growth .

Uncertainty Analysis

Biome-BGC grazing model simulations are suitable for arid and semi-arid grasslands and can effectively estimate Central Asian grassland carbon emissions. Our validation confirmed model reliability for Xinjiang grasslands. However, the grazing process is complex, and some components remain unconsidered, introducing inevitable uncertainty. For example, trampling effects are unclear and not effectively incorporated, though trampling-induced soil density changes can influence ecological processes. Future model improvements should address trampling effects.

Uncertainty also arises from input data. Meteorological data are major drivers influencing model results. This study used the China Meteorological Forcing Dataset, which offers higher precision than existing grid datasets for the region. Grazing data, key for simulating grazing effects, were obtained from FAO and corrected using Xinjiang statistical yearbook data to ensure high precision.

Effects of Livestock Grazing on NPP, ET and WUE

Results indicate that livestock grazing decreased NPP in Xinjiang grasslands from 1979–2012, reflecting unsustainable grazing practices and widespread degradation. However, NPP increases in some regions suggest moderate grazing may promote grass growth. Grazing effects varied among regions and grassland types due to climate and grazing intensity differences. Generally, NPP decreases were more significant in grasslands with high vegetation growth, attributable to high grazing intensity.

ET differences between scenarios increased with grazing intensity. In plain grasslands, ET decreases resulted primarily from reduced transpiration due to leaf removal. In mountainous grasslands, ET decreases were more significant than in plains due to higher grazing intensity and increased runoff from vegetation destruction, in addition to reduced transpiration.

WUE under grazed scenarios was lower than under ungrazed scenarios, with a strong fluctuating decline observed under grazing. Increased grazing intensity caused remarkable WUE decreases. Overgrazing removes excessive leaf area, the main photosynthetic organ, inhibiting grass growth. Widespread overgrazing has reduced WUE across most Xinjiang regions, with more significant decreases in grasslands with high vegetation growth associated with high grazing intensity.

Comparisons with Previous Studies

Previous studies have examined Xinjiang grassland grazing effects using various methods. Long et al. (2010) studied soil evaporation under different rainfall intensities in Qitai County. Yan et al. (2013) explored ET-environmental factor relationships in an *Achnatherum splendens* grassland. Luo et al. (2012) used Biome-BGC to estimate aboveground NPP at four northern Tianshan Mountain sites under different grazing intensities, finding moderate grazing could promote

ANPP under water stress. However, these site-based studies lacked large-scale understanding, particularly for complex surfaces. Han et al. (2014) provided the first regional carbon budget estimate for Xinjiang using the spatial Biome-BGC model, though grazing intensity data were lower than reality, reducing accuracy. Our study corrected grazing intensity using Xinjiang statistical yearbook data and estimated grazing effects on NPP, ET and WUE for different regions and grassland types, providing detailed spatial analysis of grazing effects.

Conclusions

NPP, ET and WUE in Xinjiang grasslands under grazed scenarios were generally lower than under ungrazed scenarios from 1979-2012, with differences increasing over time due to intensified grazing. Grazing transformed NPP trends from increasing volatility to decreasing volatility. Compared with ungrazed conditions, grazing slowed ET increases and caused more significant WUE declines.

Strong regional variations in NPP, ET and WUE differences occurred among regions and grassland types due to climate and grazing management variations. Widespread overgrazing contributed to NPP decreases in most regions. ET decreased in plains due to reduced transpiration from grazing, while mountainous grasslands experienced additional ET reductions from increased runoff. WUE decreased in most regions due to vegetation destruction from overgrazing. This study demonstrates that grazing significantly impacted carbon and water cycling in Xinjiang grassland ecosystems during 1979–2012.

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Note: Figure translations are in progress. See original paper for figures.