

Research Article

Spatial and Seasonal Variation in Rain Use Efficiency in Semiarid Grasslands of Inner Mongolia

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Rain use efficiency (RUE) is an important indicator for identifying the response of plant production to variation in precipitation patterns, especially in semiarid ecosystem grasslands of Inner Mongolia. We have investigated the response and spatial patterns of RUE to precipitation patterns based on five years (2006, 2007, 2008, 2012, and 2013) of records from semiarid ecosystem sites across Inner Mongolia. Our results showed that RUE_{ADM} was lowest in the wettest year (2012) and highest in the year following the driest year (2008). There was no significant correlation between RUE_{ADM} and RUE_{TDM} in typical and desert steppe. RUE_{TDM} was strongly correlated with both annual precipitation (AP) and growing season precipitation (GSP) compared to RUE_{ADM} . RUE_{ADM} , therefore, cannot be used in place of RUE_{TDM} . RUE_{ADM} increased with species richness. The relationship between RUE_{ADM} and species richness was significantly correlated in meadow steppe, typical steppe, and desert steppe. Our findings can shed light on the spatial utilization pattern of seasonal rainfall in semiarid grassland ecosystems.

1. Introduction

In arid and semiarid ecosystems, precipitation is an important factor in controlling biodiversity and ecosystem functioning [1]. Rain use efficiency (RUE) is defined as the amount of biomass produced per unit of precipitation and is the key indicator for measuring the response of plant production to precipitation [2–4]. Previous studies conducted in semiarid ecosystems have shown that RUE decreases over time with increasing annual precipitation [5–8]. In addition to precipitation, factors such as vegetation composition, soil condition, and biogeochemical constraints may also affect rain use efficiency [2, 3, 5, 7]. Higher diversity of plant species and functional groups may have greater RUE through increased productivity [4, 7, 9–12]. However, the interaction of RUE with seasonal precipitation patterns and spatial patterns of both above ground dry matter (ADM) and total dry matter (TDM) is not fully understood. Total dry matter is the sum of ADM and below ground dry matter (BDM).

In early studies [4, 12], the assessment of RUE was based on above ground net productivity, but not on total

net productivity, which includes root systems [13]. Rain use efficiency based on above ground dry matter (RUE_{ADM}) is sometimes used to evaluate rain use efficiency based on total plant dry matter (above ground + below ground) (RUE_{TDM}). But it is debatable whether RUE_{ADM} can significantly represent RUE_{TDM} (Gao, 2013). The inclusion of root systems is equally important, since below ground biomass is directly related to soil conservation [13]. In particular, in drought prone sites, root systems are important for carbon sinks, which may not correspond to the carbon uptake of above ground plant organs [14]. Therefore our study aims to evaluate the correlation between RUE_{ADM} and RUE_{TDM} . Estimates of RUE based on above ground dry matter, therefore, may be biased if used as a proxy to estimate total plant biomass productivity and carbon fixation efficiency relative to water uptake (Ying, 2013). This study was designed to (1) investigate the spatial patterns of rain use efficiency based on both above ground dry matter and total dry matter, (2) investigate RUE responses to seasonal precipitation, (3) evaluate the correlation between RUE_{ADM} and species richness, based on a five year precipitation and above ground dry matter data

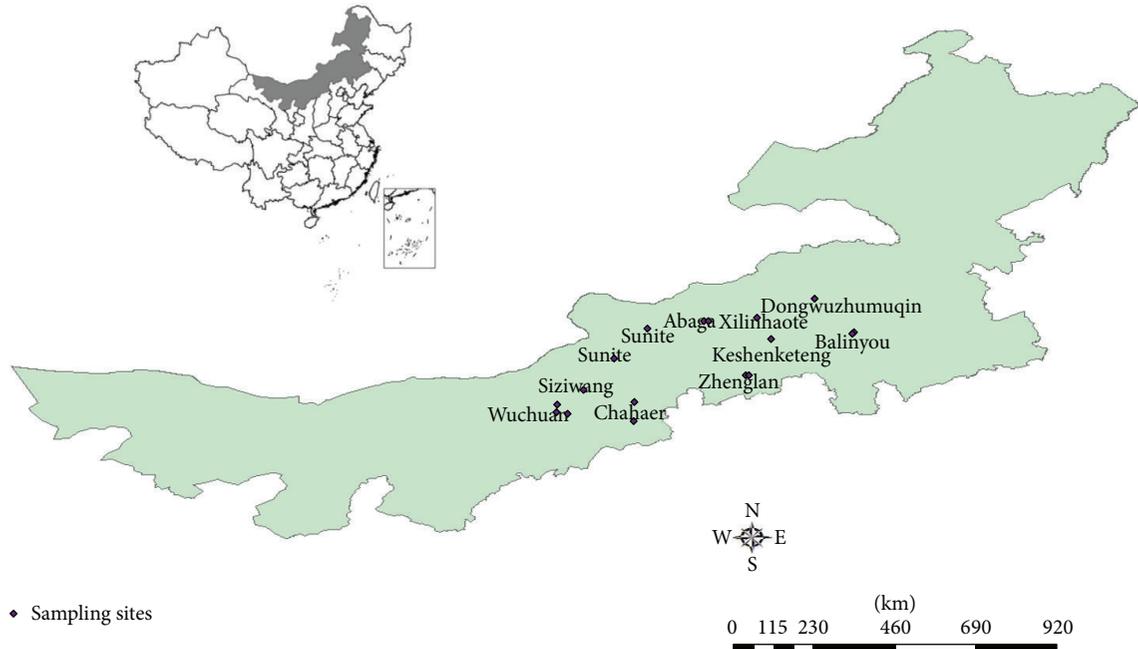


FIGURE 1: Study area and sampling sites in semiarid grassland, Inner Mongolia, China.

set, and (4) evaluate the correlation between RUE_{ADM} and RUE_{TDM} based on precipitation and total dry matter of one year data set across the Inner Mongolian region of China (Figure 1).

2. Materials and Methods

2.1. Study Area. The study was conducted in grasslands of Inner Mongolia, China (Figure 1), during the period from 2006 to 2013. A total of 34 semiarid sites were selected on an east–west transect, running from $N40^{\circ}46'26''$ to $N49^{\circ}16'31''$ latitude and $E108^{\circ}59'38''$ to $E122^{\circ}11'58''$ longitude (see the Appendix). The samples were collected from three vegetation types: meadow steppe, typical steppe, and desert steppe. A strong rainfall gradient partitions the region into a series of vegetation zones from the wetter east to the drier west. Meadow steppe, in the wettest part of the precipitation gradient, is the tallest and most productive of grassland types. Typical steppe consists of mid-height grass cover, whereas the driest of the three, desert steppe, is marked by patches of grass and shrubs separated by bare soil. Meadow steppe primarily covers the eastern part of the region, typical steppe stretches across the middle part of the region, and desert steppe covers the western region of Inner Mongolia (Figure 1). All the field sites are characterized by a continental, semiarid climate [15]. Mean annual precipitation of meadow, typical, and desert steppe ranges from 350 to 450 mm, 250 to 350 mm, and 200 to 250 mm, respectively; likewise mean annual temperature of meadow, typical, and desert steppe ranges from -4 to 5°C , -2 to 5°C , and 4 to 6°C , respectively (Fan, 2009). Amount and seasonal distribution of precipitation varied across the 5 years of the study period where 2012 was the wettest year (411.5 mm) and 2007 was the driest year (227.6 mm) (Figure 2).

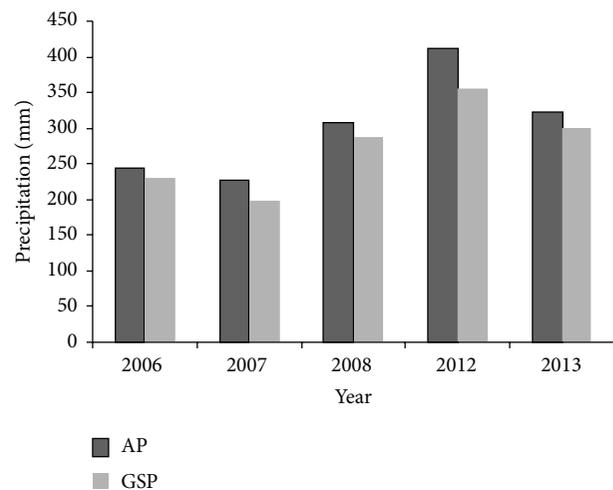


FIGURE 2: (AP) Annual precipitation (mm) growing season precipitation (mm) (GSP) of the study site in 2006, 2007, 2008, 2012, and 2013.

2.2. Data Collection and Sampling Methods. Above ground biomass sampling was done in August in 2006, 2007, 2008, 2012, and 2013. Vegetation was sampled at 6 sites in meadow steppe, 18 sites in typical steppe grassland, and 10 sites in desert steppe (see the Appendix). At each site, three 1×1 m quadrats were sampled at intervals of 30 m along a 100 m transect. This gave 18 sampled quadrants (6×3) in meadow steppe, 54 (18×3) sampled quadrants in typical steppe, and 30 (10×3) sampled quadrants in desert steppe. For calculation and analysis based on above ground dry matter, the mean value for 5 years was taken. For some sites data were not measured for all 5 years (see the Appendix).

TABLE 1: Differences in RUE_{ADM} and RUE_{TDM} ($\text{g m}^{-2} \text{mm}^{-1}$) between grassland type and precipitation years.

Year	Meadow	Typical	Desert	Year mean
RUE_{ADM} ($\text{g m}^{-2} \text{mm}^{-1}$)				
2006	0.62 ± 0.06	0.51 ± 0.02	0.19 ± 0.01	0.44 ± 0.07^A
2007	0.52 ± 0.04	0.41 ± 0.02	0.55 ± 0.03	0.49 ± 0.02^A
2008	0.86 ± 0.08	0.46 ± 0.03	0.43 ± 0.03	0.58 ± 0.07^A
2012	0.53 ± 0.04	0.43 ± 0.03	0.23 ± 0.01	0.39 ± 0.04^A
2013	0.37 ± 0.04	0.48 ± 0.02	0.38 ± 0.02	0.41 ± 0.01^A
Grassland type mean	0.58 ± 0.04^X	0.45 ± 0.01^{XY}	0.35 ± 0.03^Y	0.46 ± 0.03
RUE_{TDM} ($\text{g m}^{-2} \text{mm}^{-1}$)				
2013	3.80 ± 0.30^X	2.76 ± 0.14^Y	1.64 ± 0.10^Z	2.73 ± 0.13

Note. Significant differences in mean RUE_{ADM} among years within grassland type are indicated by letters A and significant differences among grassland type by letters X–Z, respectively. Standard error = \pm SE.

Plants were harvested in each sampling quadrat in order to measure above ground biomass. Plant materials were clipped at ground surface and litter was collected by hand. Below ground biomass sampling was done only in August of 2013. The soil profile was separated into soil depth intervals of 0–10 cm, 10–20 cm, 20–30 cm, and 30–40 cm. Roots and other below ground biomass were separated from soil by washing with water through a 0.3 mm-mesh sieve. The clipped above ground plant materials and below ground root materials were oven-dried at 80°C for 24 hours and then weighted (g m^{-2}). Meteorological data from 2006 to 2013 were obtained from 15 instrumental weather stations within and adjacent to the study area from the China Meteorological Administration (<http://www.cma.gov.cn/2011qx/fw/>).

2.3. Data Analysis. RUE_{ADM} and RUE_{TDM} for each sampling plots were calculated by using (1) and (2), respectively. Analysis of variance (ANOVA) was applied to test year (Y) and grassland types (S). To assess how each ecosystem responded, we further analyzed the relationship between both RUE_{ADM} and RUE_{TDM} with seasonal precipitation patterns such as annual precipitation and growing season precipitation by using correlation analysis. We conducted correlation analysis to investigate the relationship of RUE_{ADM} to RUE_{TDM} and the relationship of RUE_{ADM} to species richness. All statistical analysis was performed using software package of SPSS 16.0 (SPSS Inc., Chicago, IL, USA):

$$RUE_{ADM} = \frac{ADM}{AP}, \quad (1)$$

$$RUE_{TDM} = \frac{TDM}{AP}. \quad (2)$$

3. Results and Discussion

3.1. Grassland Type and Year Effects on RUE. In general, RUE tends to decrease with increasing aridity and potential evapotranspiration, both of which are closely related to ecosystem-level water balance [2]. We found that RUE_{ADM} , based on above ground dry matter, varied from 0.19 to $0.86 \text{ g m}^{-2} \text{mm}^{-1}$ and was highest in meadow steppe and lowest in desert steppe (Table 1). Similarly RUE based on total dry

TABLE 2: F values and the probability of ANOVA analysis of RUE_{ADM} and RUE_{TDM} .

Source	Df	RUE_{ADM} (F value)
Grassland type (GT)	2	8.62**
Year	4	2.89*
Year* (GT)	8	3.87**
Source	Df	RUE_{TDM} (F value)
GT	2	10.57**

Note. RUE_{ADM} = rain use efficiency based on above ground dry matter, RUE_{TDM} = rain use efficiency based on total dry matter, and Df = degrees of freedom. ** $P < 0.001$ and * $P < 0.05$.

matter (RUE_{TDM}) varied between 1.64 and $3.80 \text{ g m}^{-2} \text{mm}^{-1}$ and was highest in meadow steppe and lowest in desert steppe. Our result was consistent with Bai et al. [4], who show that RUE tends to increase with MAP from desert in the west to the meadow steppe in the east. In support of our results, some previous studies also show that drier sites tend to have lower and less variable RUE because of low plant density, low production potential, high evaporation potential, and high tolerance to water stress [7, 16, 17].

For rain use efficiency based on above ground dry matter (RUE_{ADM}), there was a significant interaction between precipitation year and grassland type (Table 2). This was true for species richness, with a significant interaction between precipitation year and grassland type (Table 3). The general trend is that with a decrease in precipitation, there is a decrease in above ground dry matter, leading to higher RUE in dry year. RUE_{ADM} was lowest in 2012, which is the wettest year of our study period. However, previous studies also showed that a dry year following a wet year usually has high RUE for a given site (Le Houérou et al. 1984 [18]). Gao et al. [19] found that RUE based on above ground biomass was highest in the dry year 2005. This result was not consistent with our findings, as RUE_{ADM} was not highest in dry year 2007, but in 2008, the year following the dry year. Bai et al. [4] reported that above ground productivity increases during wet years more than it declines in dry years. This was because soil water storage of the previous year's precipitation was available in the subsequent dry year.

TABLE 3: F values and the probability of ANOVA results on species richness.

Source	Df	RUE_{ADM} (F value)
GT	2	28.26**
Year	4	19.19*
Year* (GT)	8	4.18**

Note. RUE_{ADM} = rain use efficiency based on above ground dry matter, GT = grassland type, and Df = degrees of freedom. ** $P < 0.001$ and * $P < 0.05$.

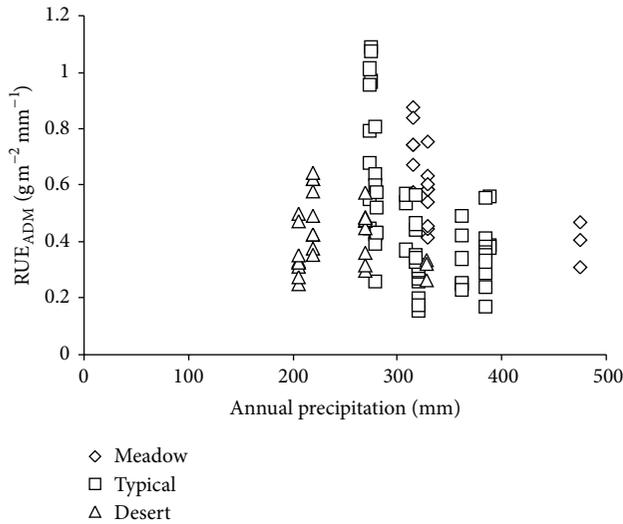


FIGURE 3: Relationship of RUE_{ADM} ($g\ m^{-2}\ mm^{-1}$) with annual precipitation (mm) in meadow steppe, typical steppe, and desert steppe across the grasslands of Inner Mongolia. RUE_{ADM} = rain use efficiency based on above ground dry matter.

3.2. Relationship between Seasonal Precipitations with RUE_{ADM} . Our analysis shows that RUE_{ADM} decreased with both increased annual precipitation and growing season precipitation. RUE_{ADM} was significantly correlated with annual precipitation in meadow steppe ($R = -0.628$, $P < 0.05$, Figure 3) and typical steppe ($R = -0.540$, $P < 0.05$, Figure 3). Likewise RUE_{ADM} was significantly correlated with growing season precipitation in meadow steppe ($R = -0.778$, $P < 0.001$, Figure 4) and typical steppe ($R = -0.652$, $P < 0.001$, Figure 4). However, in desert steppe RUE_{ADM} does not significantly correlate with either annual precipitation or growing season precipitation. This may be due to the constraints on growth in vegetation due to less rainfall in desert steppe compared to meadow and typical steppe. Above ground dry matter was more abundant at the wetter site. Mean relative biomass of above ground dry matter was 47.82% for meadow steppe, 30.33% for typical steppe, and 21.83% for desert steppe.

3.3. Effects of Seasonal Precipitation on RUE_{TDM} . RUE_{TDM} decreased significantly with increasing annual precipitation and growing season precipitation. Our result showed that RUE_{TDM} was strongly correlated with annual precipitation in meadow steppe ($R = -0.833$, $P < 0.001$, Figure 5), typical

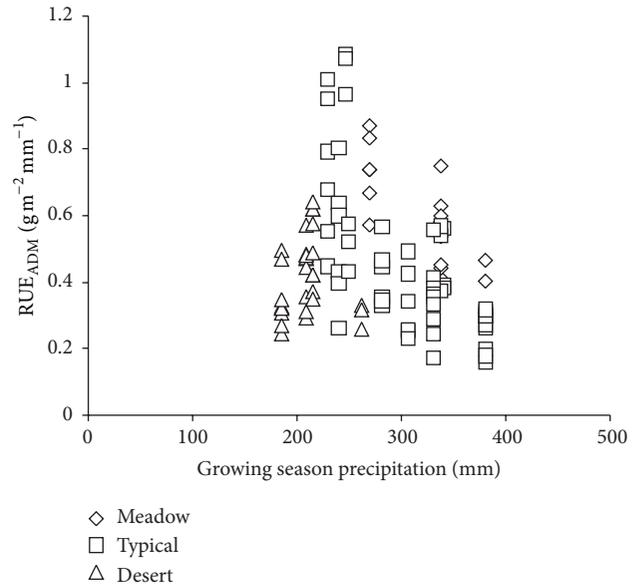


FIGURE 4: Relationship of RUE_{ADM} ($g\ m^{-2}\ mm^{-1}$) with growing season precipitation (mm) in meadow steppe, typical steppe, and desert steppe across the grassland of Inner Mongolia. RUE_{ADM} = rain use efficiency based on above ground dry matter.

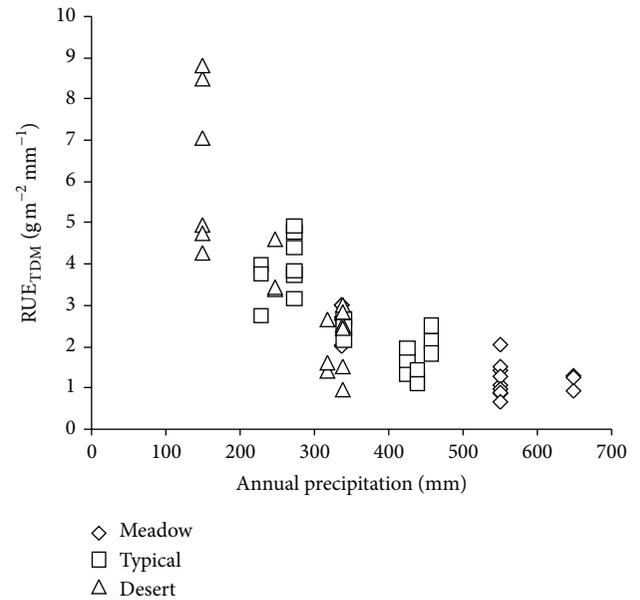


FIGURE 5: Relationship of RUE_{TDM} ($g\ m^{-2}\ mm^{-1}$) with annual precipitation in meadow steppe, typical steppe, and desert steppe across the grassland of Inner Mongolia. RUE_{TDM} = rain use efficiency based on total dry matter.

steppe ($R = -0.824$, $P < 0.001$, Figure 5), and desert steppe ($R = -0.842$, $P < 0.001$, Figure 5). Likewise, the relationship between RUE_{TDM} with growing season precipitation (GSP) is strongly correlated in all three grassland type meadow steppe ($R = -0.833$, $P < 0.001$, Figure 6), typical steppe ($R = -0.835$, $P < 0.001$, Figure 6), and desert steppe ($R = -0.840$, $P < 0.001$).

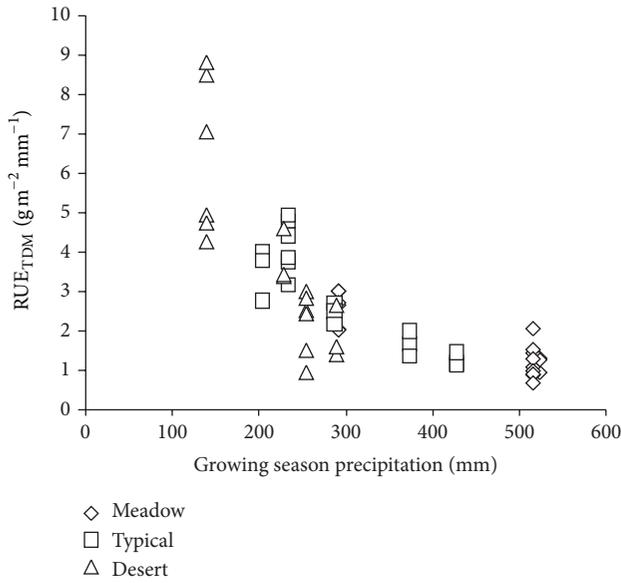


FIGURE 6: Relationship of RUE_{TDM} ($g\ m^{-2}\ mm^{-1}$) with growing season precipitation in meadow steppe, typical steppe, and desert steppe across the grassland of Inner Mongolia. RUE_{TDM} = rain use efficiency based on total dry matter.

Although there was a significant correlation between RUE_{ADM} and RUE_{TDM} at sites of meadow steppe ($R = 0.725$, $P < 0.05$, Figure 7), the correlation between RUE_{ADM} and RUE_{TDM} in typical and desert steppe was not significant. Our results show that rain use efficiency based on total dry matter was strongly correlated to the precipitation gradient compared to rain use efficiency based on above ground dry matter. Thus, our results suggest that RUE_{ADM} does not reflect RUE_{TDM} in semiarid grassland of Inner Mongolia. In contrast to our results, Gao et al. [19] observed that RUE based on above ground productivity can be used as a proxy for RUE based on total productivity in ungrazed and winter grazing sites. Although our results showed that RUE_{ADM} does not reflect RUE_{TDM} , the limitation of our study is that RUE_{TDM} was measured only for one year. The relative percentage of below ground dry matter in our study was 84.69%, and there was inconsistent partitioning between shoot and root systems. Rain used efficiency, based on total dry matter, therefore, is not significantly correlated with rain used efficiency based on above ground dry matter.

3.4. Species Richness and RUE_{ADM} . RUE_{ADM} also increased with species richness indices. The relationship between RUE_{ADM} with species richness was significantly correlated in meadow steppe ($R = 0.713$, $P < 0.05$, Figure 8), typical steppe ($R = 0.458$, $P < 0.05$, Figure 8), and desert steppe ($R = 0.398$, $P < 0.05$). According to Bai et al. [4] plant species richness in Inner Mongolia increased linearly with annual precipitation (AP) and above ground biomass. Our results show that with an increase in species richness, there was increase in RUE_{ADM} . Yang et al. [12] observed that RUE in both Alpine steppe and meadow steppe increased with species richness, which is consistent with our results. This was mainly because more species may mean more biomass [20],

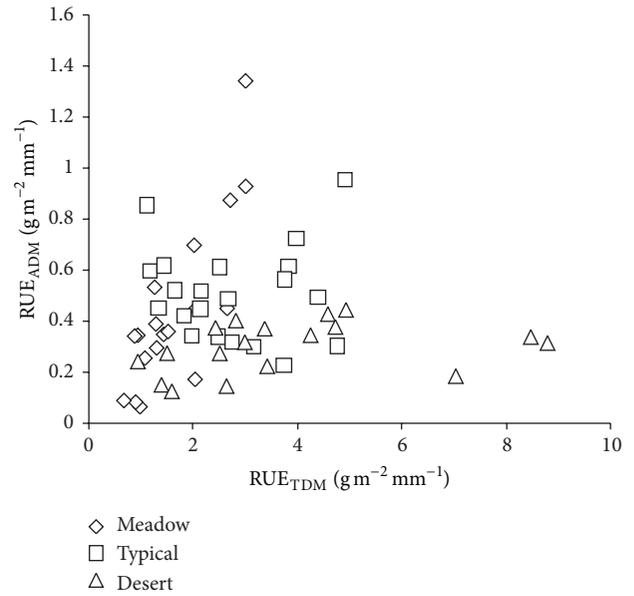


FIGURE 7: Relationship between RUE_{ADM} ($g\ m^{-2}\ mm^{-1}$) and RUE_{TDM} ($g\ m^{-2}\ mm^{-1}$) in meadow steppe, typical steppe, and desert steppe across the grassland of Inner Mongolia. RUE_{ADM} = rain use efficiency based on above ground dry matter, RUE_{TDM} = rain use efficiency based on total dry matter.

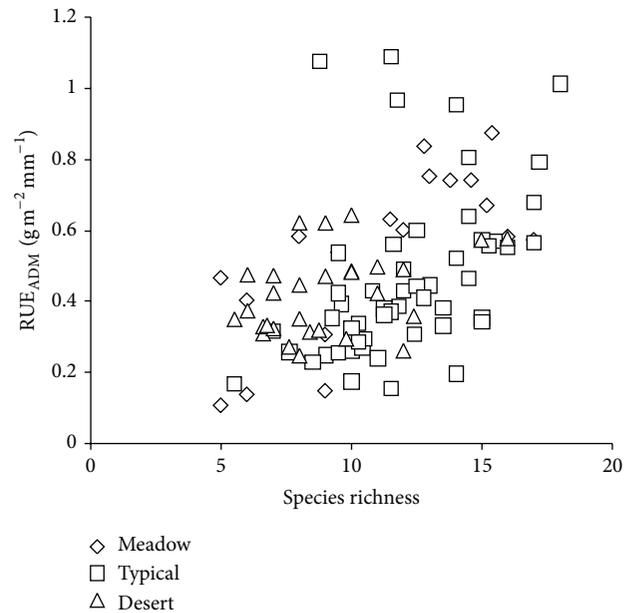


FIGURE 8: Relationship of RUE_{ADM} ($g\ m^{-2}\ mm^{-1}$) with species richness in meadow steppe, typical steppe, and desert steppe across the grassland of Inner Mongolia. RUE_{ADM} = rain use efficiency based on above ground dry matter.

resulting from complete use of available water due to niche partitioning. Another reason may be that high species rich ecosystems may contain functional groups which respond to higher precipitation. For example, ecosystems dominated by mesophytic grasses respond more strongly to precipitation than systems dominated by xerophytic grasses [7, 12].

TABLE 4: Geographical extent, climatic ranges, and above ground dry matter data measured year of sites sampled in Inner Mongolia.

Site name	Grassland type	Longitude	Latitude	MAP (mm)	MAT (°C)	ADM measured year
Alukeerqinqi	Meadow steppe	E119°58'36"	N43°50'18"	462.4	-2.29	2013
Zaluteqi	Meadow steppe	E121°1'24"	N44°39'4.3"	373.6	7.07	2013, 2012
Zaluteqi	Meadow steppe	E119°46'28"	N45°23'14"	373.6	7.07	2013
Keerqin youyi qianqi	Meadow steppe	E122°11'58"	N46°11'26"	373.6	7.07	2013
Xiwuzhumuqin	Meadow steppe	E117°49'35"	N44°39'15"	339.8	4.84	2013, 2012, 2008, 2007, 2006
Xiwuzhumuqin qi	Meadow steppe	E117°41'58"	N44°36'16"	339.8	4.84	2013, 2012, 2008, 2007, 2006
Balinyouqi	Typical steppe	E118°47'27"	N43°36'36"	385.1	3.23	2013, 2012, 2008, 2007, 2006
Dongwuzhumuqinqi	Typical steppe	E118°48'20"	N45°38'45"	259.2	6.52	2013, 2012, 2008, 2007
Chenbaerhuqi	Typical steppe	E119°4'39"	N49°16'31"	245.3	1.8	2013
Xilinhaote	Typical steppe	E116°19'25"	N44°07'5"	274.7	1.32	2013, 2012, 2006
Xilinhaote	Typical steppe	E115°56'50"	N43°56'28"	274.7	1.32	2013, 2012, 2008, 2007
Abagaqi	Typical steppe	E114°59'23"	N44°0'28"	244.5	2.37	2013, 2008, 2007, 2006
Abagaqi	Typical steppe	E115°03'48"	N44°00'6.0"	244.5	2.37	2012, 2008, 2007
Ewenkezu zizhiqi	Typical steppe	E119°42'39"	N49°4'13"	270.5	7.87	2013
Wuchuanxian	Typical steppe	E111°46'33"	N41°41'12"	352.4	5.82	2013, 2006
Wuchuanxian	Typical steppe	E111°12'09"	N41°07'53"	352.4	5.82	2012
Wuchuanxian	Typical steppe	E111°29'2"	N41°1'29"	352.4	5.82	2012, 2008
Chahaeryouyiqianqi	Typical steppe	E113°11'23"	N40°46'26"	363.9	4.65	2008, 2007, 2006
Chahaeryouyiqianqi	Typical steppe	E113°10'51"	N41°24'36"	363.9	4.65	2012, 2008, 2007
Keshenketengqi	Typical steppe	E116°41'29"	N43°26'54"	380	5.8	2008, 2007, 2006
Keshenketengqi	Typical steppe	E117°48'57"	N43°28'48"	380	5.8	2006
Zhenglanqi	Typical steppe	E116°02'54"	N42°16'1"	381.9	3.48	2012, 2008, 2007, 2006
Zhenglanqi	Typical steppe	E116°05'41"	N42°15'42"	381.9	3.48	2013, 2008, 2007, 2006
Zhenglanqi	Typical steppe	E116°05'33"	N42°15'33"	381.9	3.48	2008, 2007
Daerhanmamingan qi	Desert steppe	E111°12'13"	N41°20'50"	258.6	5.19	2013, 2012, 2008, 2007, 2006
Daerhanmamingan qi	Desert steppe	E110°29'51"	N41°37'37"	258.6	5.19	2012
Daerhanmamingan qi	Desert steppe	E110°23'32"	N41°34'56"	258.6	5.19	2012
Wulatezhongqi	Desert steppe	E109°32'34"	N41°25'05"	204	3.71	2013
Wulatezhongqi	Desert steppe	E108°59'38"	N41°28'59"	204	3.71	2013
Wulatezhongqi	Desert steppe	E108°31'14"	N41°31'19"	204	3.71	2012
Sunitezouqi	Desert steppe	E113°35'17"	N43°46'30"	185.1	4.25	2013, 2012, 2008, 2006
Sunitezouqi	Desert steppe	E112°40'7"	N42°48'13"	185.1	4.51	2013, 2012, 2008, 2007, 2006
Sunitezouqi	Desert steppe	E113°31'16"	N43°46'33"	185.1	4.51	2012, 2008, 2007
Siziwangqi	Desert steppe	E111°46'33"	N41°41'12"	169.9	4.77	2013, 2012, 2008, 2006

Note. MAP = mean annual precipitation, MAT = mean annual air temperature, and ADM = above ground dry matter. MAP and MAT values were averaged over 2006, 2007, 2008, 2012, and 2013.

4. Conclusions

This study provides a broad analysis of RUE based on both above ground dry matter and total dry matter in 3 semiarid grassland types in the Inner Mongolia of China. Our results show that rain use efficiency based on both above ground dry matter and total dry matter was significantly higher in meadow steppe and lower in desert steppe. RUE_{ADM} was found to be lowest in the wettest year (2012) and highest in the year following the driest year (2008). Rain use efficiency based on above ground dry matter was significantly correlated with precipitation in meadow and typical steppe. RUE_{TDM} was strongly correlated with both mean annual precipitation and growing season precipitation in comparison to RUE_{ADM} . Therefore, rain use efficiency based on above

ground dry matter cannot be used as proxy for rain use efficiency based on total dry matter. The relationship between RUE_{ADM} with species richness was significantly positive in meadow steppe, typical steppe, and desert steppe, as RUE_{ADM} increased with species richness. The differences in rain use efficiency in meadow steppe to desert steppe are due to differentiation in vegetation type. Future research should include a comprehensive analysis of biogeochemical components in relation with rain use efficiency in the semiarid grasslands of Inner Mongolia.

Appendix

See Table 4.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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