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Yield and Water Use of Siberian Wildrye with Ridge and Furrow Planting in Northern China

W. Zhang, Z. Li,* Y. Gong, X. Lu, and D.C. Nielsen

ABSTRACT

Siberian wildrye (*Elymus sibiricus* L.) is a perennial grass that is widely planted in semiarid northern China, but yield is often low due to insufficient soil water supply. Field experiments were conducted from 2009 to 2011 to study the effects of ridge and furrow planting (RFP) on yield, evapotranspiration, and water use efficiency (WUE) of Siberian wildrye grassland under rainfed conditions. The treatments included bare flat bed planting (FB), bare ridge with bare furrow (BRB), bare ridge with naked oat (*Avena nuda* L.) straw mulch in furrow (BRM), plastic mulch on ridge with bare furrow (MRB), and plastic mulch on ridge with straw mulch in furrow (MRM). In the RFP system, the ridge and furrow were each 30 cm wide. Total forage yield with MRB and MRM each year was 46 to 111% and 50 to 135% greater, respectively, than with FB (2580 kg ha^{-1} yr^{-1}). These two treatments also increased total WUE each year by 79 to 121% and 80 to 150%, respectively, compared with FB (10.8 kg ha^{-1} mm^{-1} yr^{-1}). The BRB and BRM treatments increased total forage yield by 47 and 81% and total WUE by 51 and 81%, respectively, compared with FB only in 2010. The addition of straw mulch did not result in a further increase in total yield or WUE. Therefore, the MRB planting system will be recommended in Siberian wildrye production for achieving relatively high forage yield and WUE.

Siberian wildrye is a perennial forage grass widely used in semiarid northern China for its good forage quality and excellent drought and cold tolerance (Mao et al., 2003; Wang et al., 2009a); however, it frequently has low yields that do not meet the demands of the livestock industry. A main reason for the low yields is that the wet period from July to August does not coincide with the critical growth period from May to June (Sun et al., 2003; Wang et al., 2006a, 2009a).

Ridge and furrow planting has been shown to be an effective rainfall harvesting method (Reij et al., 1988; Wang et al., 2005) and is widely used in arid and semiarid areas to increase crop yield (Boers et al., 1986). Li et al. (2000) reported that the ridge and furrow water harvesting system combined with gravel mulch increased corn (*Zea mays* L.) yield and WUE under semiarid conditions in northwestern China. The benefits of the RFP method for yield of potato (*Solanum tuberosum* L.), corn, wheat (*Triticum aestivum* L.), and alfalfa (*Medicago sativa* L.) forage in northwestern China have been reported (Tian et al., 2003; Jia et al., 2006; Liu et al., 2009; Wang et al., 2009b). The effects of a plastic mulch ridge with a bare furrow on the forage height, plant density, and yield of Siberian wildrye have also been studied in northern China (Li et al., 2010a, 2010b); however, the effect of bare ridges on the growth and yield of Siberian wildrye and the effects of RFP on evapotranspiration (ET) and WUE have not been studied.

Plastic film mulch is beneficial to crop productivity in semiarid regions (Zhou et al., 2009). It reduces the exchange of heat and water between the soil and atmosphere, thereby reducing soil evaporation (Tian et al., 2003) and increasing soil water availability (Reij et al., 1988), soil temperature (Li et al., 2001; Wang et al., 2005), crop transpiration (Wang et al., 2003), and WUE (Zhao et al., 1995; Zhou et al., 2009). Maintaining or applying straw mulch is another management practice that reduces soil water evaporation and increases WUE and yield (Gill et al., 1996; Cook et al., 2006; Dahiya et al., 2007). Eckstein and Donath (2005) also showed that under a limited water supply, straw mulch increased seedling emergence for several perennial hemicryptophyte species (e.g., *Galium boreale* L., *Viola elatior* Fr.) due to the conservation of soil water; however, few researchers have reported the effects on forage production and water use of straw mulch in the furrow in an RFP system.

The water balance method used to calculate ET for RFP treatments in previous studies (Li and Gong, 2002; Wang et al., 2008, 2009b) is

$$\mathrm{ET_{old}} = \Delta \mathrm{SW_{old}} + P + P \times \mathrm{RE} + I - D \qquad [1]$$

where $\mathrm{ET_{old}}$ is field evapotranspiration (mm), P is precipitation (mm), RE is runoff efficiency (%), I is irrigation (mm), D is drainage (mm), $\Delta \mathrm{SW_{old}}$ is the change in soil water storage (mm) in the soil profile between two rows for FB or only in the furrow area for RFP treatments from the beginning to the end

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Abbreviations: BRB, bare ridge with bare furrow; BRM, bare ridge with straw mulch in furrow; ET, evapotranspiration; FB, flat bed planting; MRB, plastic mulch on ridge with bare furrow; MRM, plastic mulch on ridge with straw mulch in furrow; RFP, ridge and furrow planting; SWC, soil water content; WUE, water use efficiency.

Table 1. Soil properties for the experimental site.†

Depth	BD	WP	FC	pH	OM	N	P	K
cm	g cm^{-3}	——— m^3 m^{-3} ———			g kg^{-1}	——— mg kg^{-1} ———		
0–15	1.40	0.088	0.268	8.2	28.9	99.2	2.7	90.9
15–30	1.49	0.087	0.275	8.3	25.0	84.3	1.6	67.6
30–45	1.63	0.044	0.184	8.4	16.9	51.5	0.9	54.7
45–60	1.59	0.062	0.162	8.5	6.7	30.5	0.8	47.1

† BD, bulk density, measured by the undistributed soil core method; WP, wilting point, soil water content at matrix potential of –1.5 MPa; FC, field capacity; pH (1:2.5 soil/water), measured by a pH meter; OM, organic matter, measured by the potassium dichromate titrimetric method; N, NO_3–N + NH_4–N, measured by the alkali diffusion method; P, available P, measured by the Olsen method; K, exchangeable K, measured by NH_4OAc extraction flame photometric method.

of a given period. Drainage for a rainfall or irrigation event was often neglected, and capillary rise and canopy interception were not considered. In these studies, RE was measured at a runoff plot nearby without plants. When rainfall runoff occurred, troughs collected the runoff and conveyed it into a bucket (Tian et al., 2003). There are two main disadvantages for this ET calculation method, however. One is that ET is determined only from the soil water content (SWC) in the planted area for the RFP treatments by assuming that the rainfall harvest area was independent of the planted area (Critchley and Siegert, 1991). Water flow between the rainfall harvest area and the planted area should not be neglected for the RFP treatments (Bargar et al., 1999), and the ET should be determined based on the SWC in both the rainfall harvest area and the planted area. The second disadvantage is that the constant and underestimated RE used for the whole growth period overestimates ET. In fact, RE values change with the shape of the ridge, the soil density of the ridge, and the intensity of precipitation (Li et al., 2000, 2007; Tian et al., 2003; Wang et al., 2008). Additionally, the ridge shape can change with time due to wind and water forces. The range in RE was 1 to 27% for bare ridge treatments and 31 to 93% for mulched ridge treatments in the studies of Tian et al. (2003). Li et al. (2007), and Wang et al. (2009b). Wang et al. (2008) reported that the RE for plastic mulched ridge treatments was higher than that for bare ridge treatments because of the plastic film's smooth, nonleaking surface (Wang et al., 2008). Furthermore, it is difficult to estimate the actual RE for different field topography and rainfall conditions.

Further research is needed on the effects of the RFP system and straw mulch in the furrow on forage yield, ET, and WUE of Siberian wildrye. In addition, improvements to the old ET calculation method for the RFP system are needed. Therefore, the objectives of this study were to evaluate the effects of RFP and mulch on soil water, ET, forage yield, and WUE of Siberian wildrye in semiarid northern China and to evaluate the estimation of field ET under RFP using a modified soil water balance method by measuring the SWC in both the ridge and furrow areas.

MATERIALS AND METHODS

The field experiment was performed in 2009 to 2011 at the Yu'ershan Demonstration Pasture of the National Grassland Ecosystem Station located on the Bashang Plateau of northern China (41°45′ N, 116°11′ E, 1460 m asl). This site has a semiarid, continental, monsoon climate with a long-term (1979–2008) mean annual temperature of 1°C, annual cumulative temperature over 10°C of 1980°C, a 119-d frost-free period, annual precipitation of 338 mm, and annual pan evaporation of 1736 mm. The long-term mean monthly temperature in January and July was –18.6 and 17.6°C, respectively. The average precipitation during the growing period (May–September) was 288 mm. These meteorological data were obtained from the nearest local meteorological station (Guyuan Station, 1412 m asl). The soil at the experimental site is a coarse loamy, mixed, superactive, frigid Typic Haplustoll with sandy loam texture throughout the entire 0- to 60-cm depth, formed from diluvial deposits, with gravel below 60 cm. Periodic observations of root development showed no root growth below 60 cm. Table 1 shows the characteristics of this soil.

The treatments evaluated for Siberian wildrye production were (i) BRB, bare ridge with bare furrow, (ii) BRM, bare ridge with naked oat straw mulch in the furrow, (iii) MRB, plastic mulch on the ridge with bare furrow, (iv) MRM, plastic mulch on the ridge with naked oat straw mulch in the furrow, and (v) FB, bare flat bed planting. The RFP treatments consisted of an approximately semicircular ridge (15 cm high, 30 cm wide) as the rainfall harvesting area and a furrow (30 cm wide) as the planted area (Fig. 1) in plots that were 3.3 m wide by 6 m long, with a 1.5-m buffer zone between plots. The RFP treatments were constructed using the following four steps. First, the soil was tilled to a depth of 15 cm using a rotary cultivator (Kaiyuanwang 1GQN-300, Shenghe Agricultural Machinery Co.) on 10 July. Second, nylon ropes were fixed on the ground to identify the boundaries of ridges or furrows. Third, the ridges and furrows in the RFP systems were made by hand using shovels from 24 to 25 July. And finally, an impervious, transparent anti-aging polyethylene film (0.08-mm thickness, 2-m width of product, Qingzhou Lu Guan Plastic Factory) with a 66-cm width was placed over the ridges by hand before planting. Damaged ridges were fixed and damaged film areas were replaced by hand in the early spring each year (about 90% of the film was replaced annually). Naked oat straw was applied at an approximate thickness of 5 cm at the end of the growing season in 2008 and was applied again at the end of the growing season every year. All plots were arranged in a randomized complete block design with three replicates. Siberian wildrye was planted at a 2-cm depth and a seeding rate of 25 kg ha^{-1} using a drill on 26 July 2008. Weeds were hoed annually by hand every 2 or 3 wk from the end of May to mid-September. Harvest in the planting year occurred on 7 Oct. 2008. Chemical fertilizers (130 kg ha^{-1} urea with 46% N and 70 kg ha^{-1} diammonium phosphate with 21% N and 23% P) were applied on the soil surface by hand before planting in 2008 and in a rainfall event each May from 2009 to 2011.

The first forage harvest was at the heading stage (11 July in 2009 and 2010; 17 July 2011), and the second harvest was at

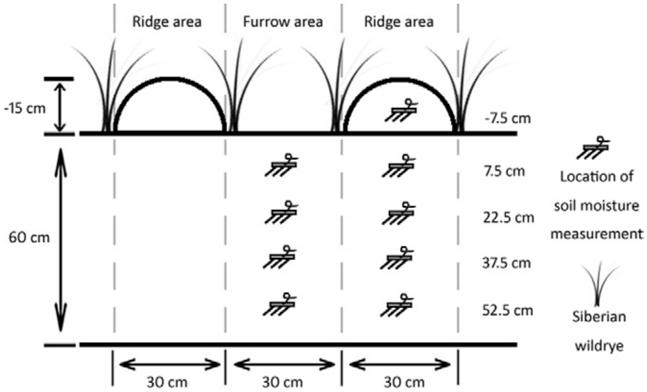

Fig. 1. Schematic diagram of ridge and furrow planting.

the end of the regrowth period (22 Sept. 2009, 26 Sept. 2010, and 27 Sept. 2011). The forage grass was carefully harvested by hand using a sickle at a stubble height of approximately 5 cm after each harvest. The samples were dried at 75°C for 72 h in an oven to calculate the dry forage yield (Ercoli et al., 1999; Wang et al., 2009a). Precipitation was measured using rain gauges at the experimental site.

Volumetric SWC was measured by time domain reflectometry (15-cm TDR CS630 probes, Campbell Scientific) at soil depths of 7.5, 22.5, 37.5, and 52.5 cm between rows for the FB treatment and in both the ridge area and furrow area, with the ridge at 7.5 cm above the furrow surface, for the RFP treatments (Fig. 1). The "0" reference level for time domain reflectometry waveguide placement was considered to be the soil surface for the FB treatment and the surface of the furrow area for the RFP treatments. The horizontal waveguide installation was facilitated by digging a soil trench. All 15 experimental plots (three replications of five treatments) were instrumented for soil water measurements. Soil water measurements were made every 5 d and before and after rainfall events throughout the growing season in 2010 and 2011. In 2009, soil volumetric water contents were measured only seven times, including the beginning of the growing period and after the first and second harvests.

Evapotranspiration was determined by an improved soil water balance equation (Allen et al., 1998):

$$\mathrm{ET_{new}} = \Delta \mathrm{SW_{new}} + P + I - D - \mathrm{RO} + \mathrm{CR} - I_\mathrm{n} \quad [2]$$

where $\mathrm{ET_{new}}$ is ET by an improved method (mm), $\Delta \mathrm{SW_{new}}$ is the change in soil water storage (mm) between two rows for the FB or the weighted average method based on the soil water storage of both the furrow area and the ridge area for RFP treatments from the beginning to the end of a given period, P is precipitation (mm), I is irrigation (mm), D is drainage below the root zone (mm), RO is surface runoff (mm), CR is capillary rise into the root zone (mm), and I_n is canopy interception (mm). Irrigation (I) was 0 mm for this experiment because no irrigation was applied to any treatment. The weighted average of the soil water storage in the ridge and furrow areas is the simple average in this case because the fraction of field area occupied by furrows equaled the fraction of the field area occupied by ridges. Because the groundwater table was 7 m below the soil surface, CR was neglected. Surface runoff was not observed during the experiment due to the small amount of rainfall. When soil water storage in the root zone (0–60 cm) and the rainfall amount were above field capacity, it was assumed that excess water percolated into the deeper zones (D = the amount of water storage at the 0–60-cm soil depth before rainfall + rainfall amount – field capacity of the soil profile). Canopy interception was about 1 mm for each rainfall event according to Li et al. (2000) and Wang et al. (2006b). In this study, SWC was mainly affected by precipitation, plant transpiration, soil surface evaporation, and ridge and furrow runoff and interception.

Soil water storage in the soil profile (0–60 cm) for Eq. [2] was calculated for RFP treatments as

$$\mathrm{SW_{new}} = \sum_{i=1}^{n} \theta_i Z_i + \theta_\mathrm{x} Z_\mathrm{x} 0.78 \times 0.5 \quad [3]$$

and for the FB treatment as

$$\mathrm{SW_{new}} = \sum_{i=1}^{n} \theta_i Z_i \quad [4]$$

where $\mathrm{SW_{new}}$ is soil water storage in the profile (mm), Z_i is the ith soil layer depth (mm), θ_x is the SWC inside the ridge ($\mathrm{m^3\ m^{-3}}$,) Z_x is the height of the ridge (mm), 0.78 is the shape factor of the ridge, and 0.5 is the ratio of the ridge area to the total field area. The SWC of the ith layer (θ_i) for the RFP treatments was calculated using a new equation:

$$\theta_i = \frac{\theta_{\mathrm{R}i} + \theta_{\mathrm{F}i}}{2} \quad [5]$$

where θ_i is the SWC of the ith layer ($\mathrm{m^3\ m^{-3}}$), and $\theta_{\mathrm{F}i}$ and $\theta_{\mathrm{R}i}$ are the SWC of the ith soil layer in the furrow area and the ridge area ($\mathrm{m^3\ m^{-3}}$), respectively. For the FB planting treatment, the SWC of the ith layer (θ_i) was the measured value between two rows based on the assumption that the SWC within a soil layer in the FB planting treatment was homogeneous and SWC differences between the row and interrow were negligible (Hupet and Vanclooster, 2005).

Water use efficiency was calculated using the following equation (Uçan et al., 2007):

$$\mathrm{WUE} = \frac{Y}{\mathrm{ET}} \quad [6]$$

where WUE is water use efficiency ($\mathrm{kg\ ha^{-1}\ mm^{-1}}$), Y is yield ($\mathrm{kg\ ha^{-1}}$), and ET is actual evapotranspiration (mm), which equals $\mathrm{ET_{new}}$ in Eq. [2].

In this study, replication was considered as a random effect in all statistical procedures. Forage yield ET and WUE for the first growth, the second growth, and the total growing period were analyzed via the MIXED procedure of SAS (SAS Institute) with fixed effects of management practice (treatment) and year. Differences in forage yield ET and WUE between the first and second growth phases were evaluated using repeated measures (Littell et al., 2006). Soil water contents for each year were analyzed using the MIXED procedure of SAS, with monitoring date as a repeated measure and monitoring date, depth, treatment, and position (ridge or furrow) as fixed effects. A first-order autoregressive covariance structure was used for the repeated measures analysis. Soil water storage in the 0- to 60-cm depth was analyzed using the MIXED procedure of SAS, with monitoring date as a repeated measure and monitoring date and treatment as fixed effects. Means were compared using Fisher's protected LSD at the 0.05 probability level.

RESULTS AND DISCUSSIONS

Weather Conditions

Precipitation during the growing season in 2009, 2010, and 2011 (from early May to the end of September) was 172, 346, and 257 mm, respectively. According to the classification method of precipitation years in the Chinese National Standard GB/T 21986–2008 (Standardization Administration of the People's Republic of China, 2008), annual precipitation patterns are divided into normal (precipitation anomaly percentage, PAP [(actual precipitation – average precipitation)/average precipitation × 100%]), dry (PAP < –15%), and wet (PAP > 15%) patterns. The growing season was relatively dry (PAP = –40%) in 2009, wet (PAP = 20%) in 2010, and normal (PAP = –11%) in 2011.

In 2009, there was a normal July, a wet June, and dry May, August, and September (Fig. 2a). In 2010, there was a normal July, wet May and September, and dry June and August. In 2011, there were normal June and September, a wet May, and dry July and August.

Mean air temperatures during the growing season were similar, with 14.8, 14.7, and 14.9°C in 2009, 2010, and 2011, respectively. Siberian wildrye experienced relatively warmer beginning and ending of the growth period in 2009 than in 2010 and 2011 (Fig. 2b).

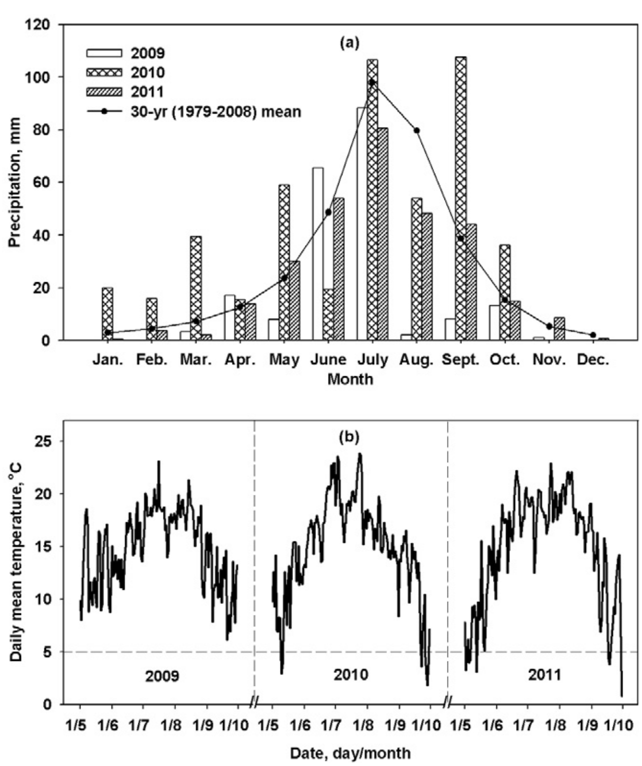

Fig. 2. (a) Monthly mean precipitation and (b) daily temperature at the study site in 2009, 2010, and 2011.

Soil Water Content

For the RFP treatments, SWC was affected significantly by treatment, position, depth, monitoring date, and most of interactions for these four fixed effects. Soil water content was not affected significantly by a monitoring date × treatment × depth interaction in 2010 or a monitoring date × treatment × depth × position interaction in either year (Table 2). The difference in SWC between the ridge and furrow locations for all RFP treatments was significant ($P < 0.001$) for all four treatments and largest at the 7.5-cm depth; the maximum difference was 0.16 $m^3 m^{-3}$. Small differences less than 0.09 $m^3 m^{-3}$ occurred at the 22.5-cm depth. The differences in SWC at the 22.5-cm depth between ridge area and furrow area were significant ($P < 0.05$) under the BRB and BRM treatments in both years. The differences at the 37.5- and 52.5-cm soil depths were not significant ($P > 0.05$) and negligible (Fig. 3 and 4). Soil water content at the 7.5-cm depth was greater under the furrow area than under the ridge area after rainfall events. This difference probably resulted from rainfall runoff from the ridge into the furrow, where greater infiltration occurred (Bargar et al., 1999). Differences in SWC between the ridge and furrow locations at the 22.5- and 37.5-cm depths were mixed (Fig. 3 and 4); however, these differences in SWC between the ridge area and the furrow area should not be neglected when the soil water balance for the whole field is considered.

Siberian wildrye dry matter yield was affected by available soil water in the root zone, primarily in the planted (furrow) area. In general, soil water storage in the 0- to 60-cm soil layer for each individual year was affected significantly by management practice ($P < 0.001$) and monitoring date ($P < 0.001$).Total soil water storage in the 0- to 60-cm soil layer for the RFP treatments was above the critical soil water storage

Table 2. The *P* values of volumetric soil water content for the flat bed planting (FB), bare ridge with bare furrow (BRB), bare ridge with straw mulch in furrow (BRM), plastic mulch on ridge with bare furrow (MRB), and plastic mulch on ridge with straw mulch in furrow (MRM) treatments in 2010 and 2011.

	***P* of soil water content**	
Fixed effects	**2010**	**2011**
Date (D)	<0.001	<0.001
Treatment (Tr)	<0.001	<0.001
Depth (Dp)	<0.001	<0.001
Position (Po)	<0.001	<0.001
D × Tr	0.043	<0.001
D × Dp	<0.001	<0.001
D × Po	<0.001	<0.001
Tr × Dp	<0.001	<0.001
Tr × Po	<0.001	<0.001
Dp × Po	<0.001	<0.001
D × Tr × Dp	0.992	0.045
D × Tr × Po	<0.001	<0.001
D × Dp × Po	<0.001	<0.001
Tr× Dp × Po	<0.001	<0.001
D × Tr × Dp × Po	0.899	0.998

[CSW, wilting point (WP) + 0.4(field capacity – wilting point) for 0- to 60-cm profile; Allen et al. (1998); Wang et al. (2009a)] and WP (soil water content at a matric potential of –1.5 MPa, from Panigrahi and Panda, 2003) for a longer period than for the FB treatment during 3 yr (Fig. 5). The MRB and MRM treatments resulted in greater soil water storage than the BRB and BRM treatments after most rainfall events, except for the period in 2010 after the middle of August ($P < 0.05$). Straw mulch in the furrow did not consistently increase soil water storage for either the bare ridge system or the mulch ridge system.

The yield of Siberian wildrye mainly depends on the soil water status at the stem elongation stage (following jointing) during June in semiarid northern China (Wang et al., 2009a). Soil water storage at this stage was lower than the CSW for all treatments in all 3 yr (Fig. 5). The RFP treatments had greater soil water storage during this period than the FB treatment. The MRB and MRM treatments had greater soil water storage than the BRB and BRM treatments after most rainfall events. Among the 3 yr of this study, soil water status was lowest at the stem elongation stage in 2010, when it decreased below the WP (Fig. 5).

Evapotranspiration

Because of the differences in SWC found between the ridge area and the furrow area (Fig. 3 and 4), it was necessary to use the improved soil water balance method (Eq. [2]) to calculate ET for the RFP treatments. The improved method used the area-weighted mean SWC in the ridge and furrow areas (Eq. [2]) to replace the SWC only in the furrow as was done in the old method of Wang et al. (2005) (Eq. [1]). Canopy interception was also considered in the improved method. For

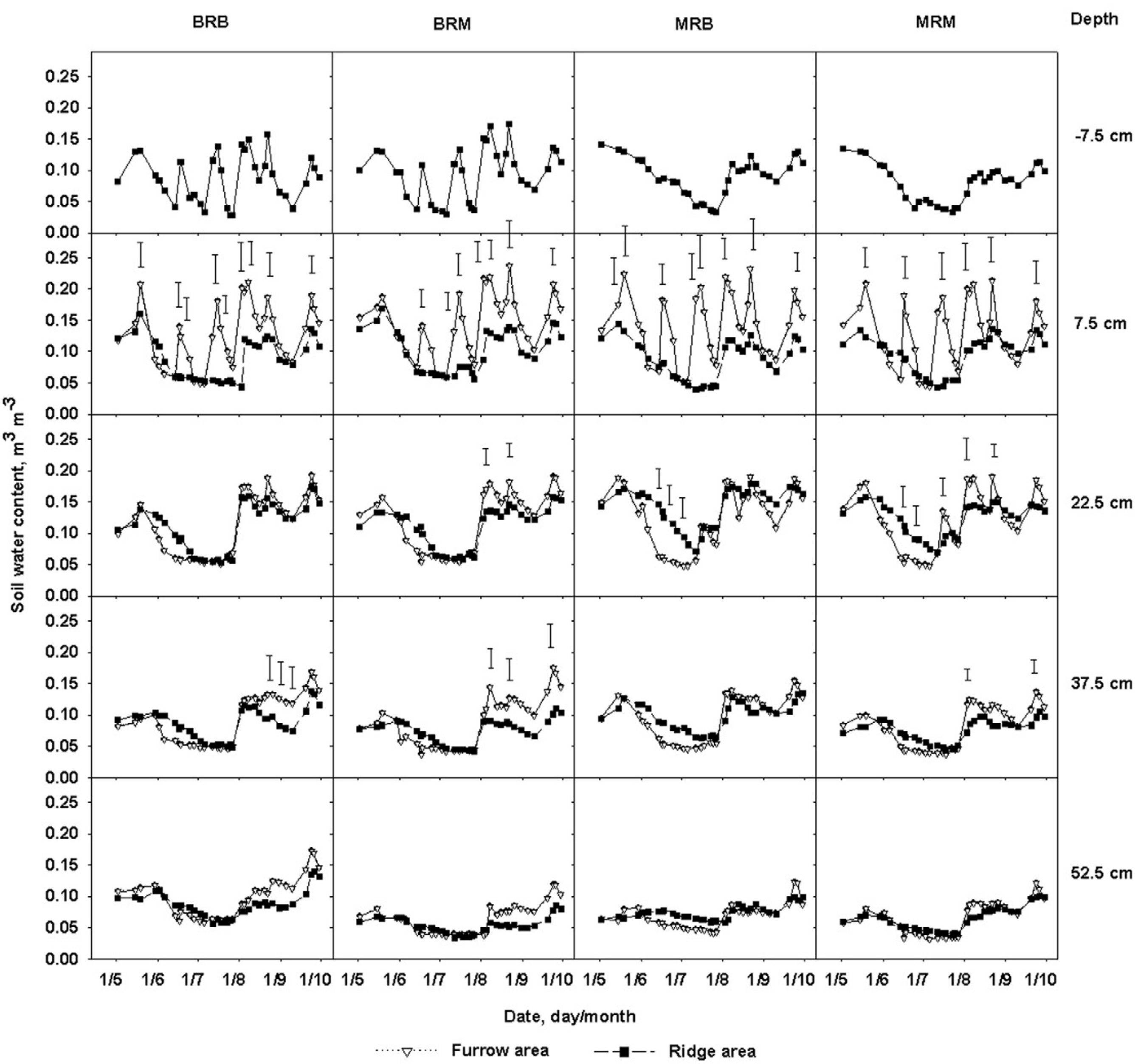

Fig. 3. Soil water content by depth for the bare ridge with bare furrow (BRB), bare ridge with straw mulch in furrow (BRM), plastic mulch on ridge with bare furrow (MRB), and plastic mulch on ridge with straw mulch in furrow (MRM) treatments in 2010. Data points are the average of three replications. Bars are the LSD at the 0.05 probability level.

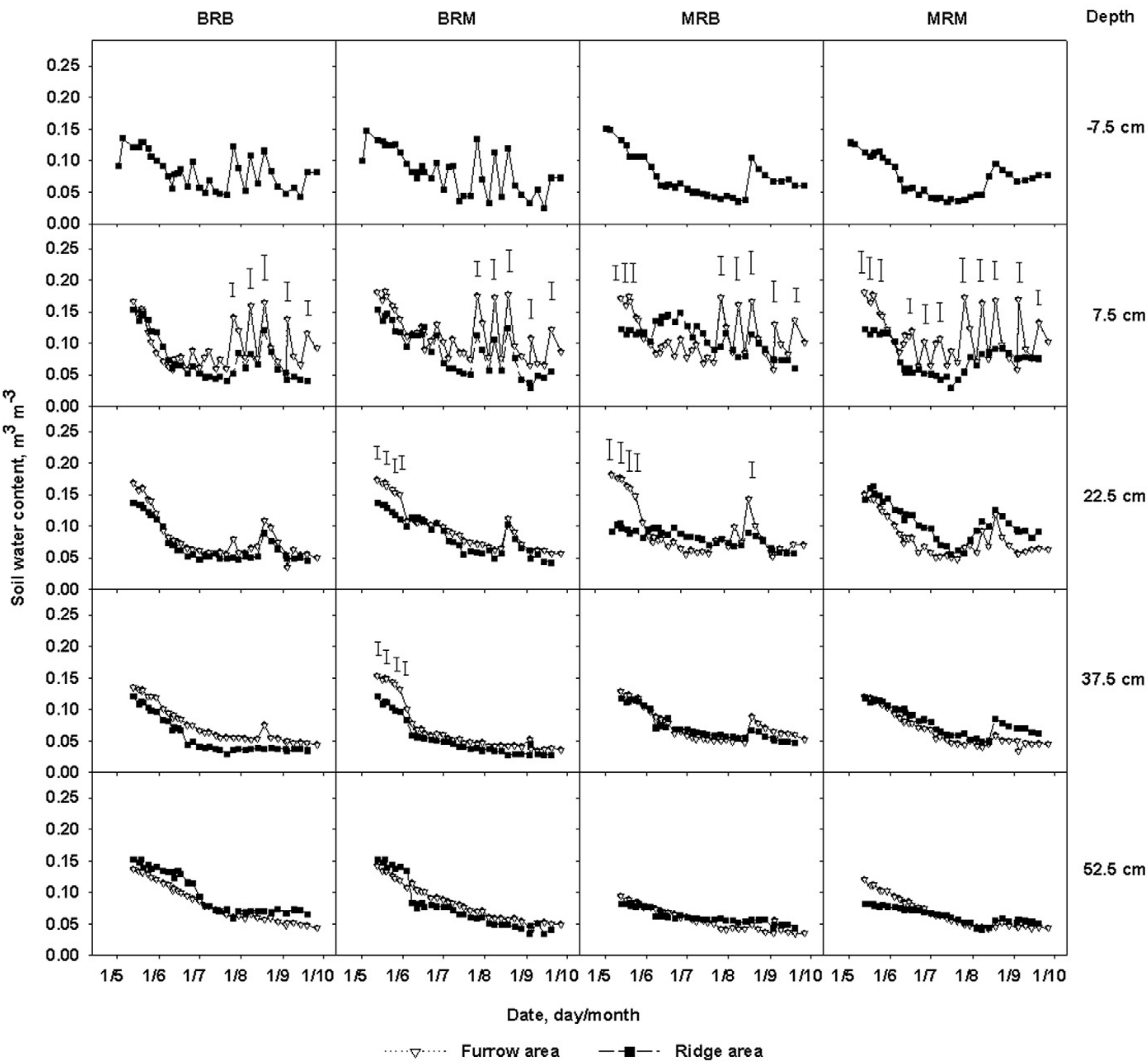

Fig. 4. Soil water content by depth for the bare ridge with bare furrow (BRB), bare ridge with straw mulch in furrow (BRM), plastic mulch on ridge with bare furrow (MRB), and plastic mulch on ridge with straw mulch in furrow (MRM) treatments in 2011. Data points are the average of three replications. Bars are the LSD at the 0.05 probability level.

the FB treatment, the difference between the two methods is that canopy interception was considered in the improved method.

A comparison of ET by the two methods (Fig. 6) indicates that the improved method resulted in lower calculated ET than the old method for the first and second cutting periods and for the total growing season. The data points in Fig. 6 nearest the 1:1 line were from the FB, BRB, and BRM treatments, and they averaged 12% lower with the improved method than the old method. The ET differences between the calculation methods was much greater for the MRB and MRM treatments (points farthest from the 1:1 line), with ET calculated by the improved method averaging 45% of the ET calculated by the old method.

Evapotranspiration calculated by the improved soil water balance (Eq. [2]) during the first growth period, the second growth period, or the whole growing period was affected significantly by management practice (Table 3). The ET of Siberian wildrye grown under BRB and BRM treatments was not different from the FP treatment in any of the 3 yr. A possible reason was that infiltration in the entire field for the BRB and BRM treatments was similar to that for the FP treatment although the distribution of infiltration was different between the FP system and the RFP systems. The MRB and MRM treatments had lower total growing season ET than the FB treatment in 2009 and 2011, probably because the plastic film mulch in the MRB and MRM treatments decreased the area of soil water evaporation. Straw mulch in the furrow did not provide an additional effect on ET because no significant differences in ET were found between the BRB and BRM treatments or between the MRB and MRM treatments. The ET was also affected significantly by year. The total ET

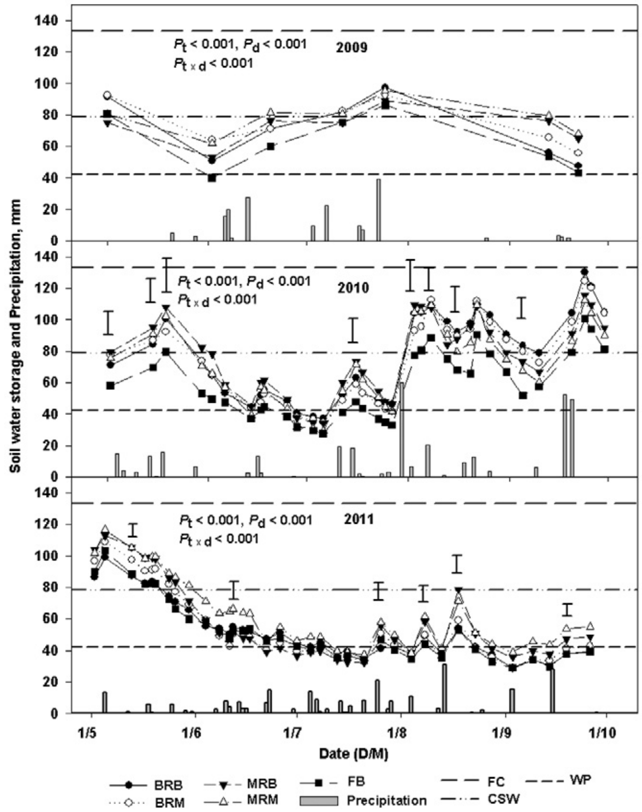

Fig. 5. Precipitation and soil water storage in the 0- to 60-cm depth in the planting area for the flat planting (FB), bare ridge with bare furrow (BRB), bare ridge with straw mulch in furrow (BRM), plastic mulch on ridge with bare furrow (MRB), and plastic mulch on ridge with straw mulch in furrow (MRM) treatments in 2009, 2010, and 2011. The field capacity (FC), wilting point (WP) and critical soil water storage (CSW) in the 0- to 60-cm depth are shown; P_t is the P value for the effect of treatment, P_d is the P value for the effect of monitoring date, and $P_{t \times d}$ is the P value for the treatment × monitoring date interaction. Bars are the LSD at the 0.05 probability level.

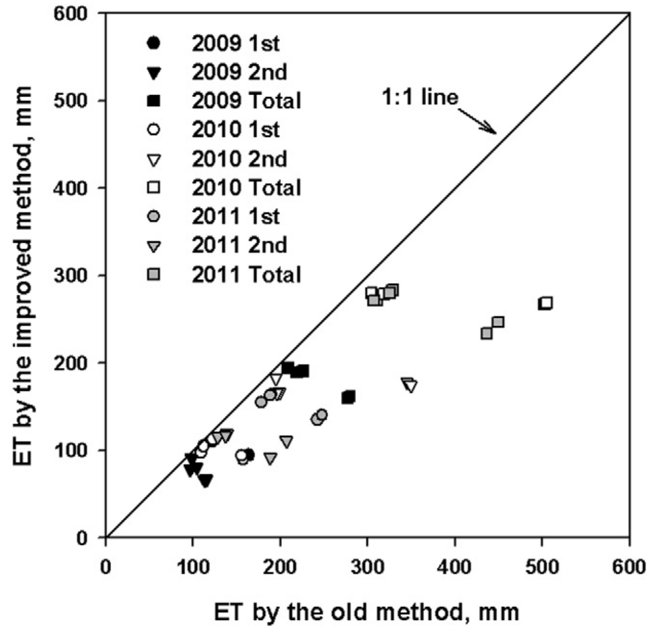

Fig. 6. Comparison of Siberian wildrye evapotranspiration (ET) calculated by the old water balance method, Eq. [1], and the improved soil water balance method, Eq. [2], for all treatments in 2009, 2010, and 2011. Data are shown for the first and second harvesting periods and for the total growing season.

in 2009 was 34 and 32% lower than that in 2010 and 2011, respectively. The majority of the total ET occurred during the first growth period in 2009 and 2011 (53–61% of total ET) and during the second growth period in 2010 (59–66% of total ET). Evapotranspiration was also affected by a management practice × year interaction except during the first harvest.

Forage Yield and Water Use Efficiency

Forage yield was low (300–600 kg ha^{-1}) during the establishment year (2008). The forage yield during both growth periods and the whole growing period was affected by management practice and year but not by a management practice × year interaction (Table 4). In all 3 yr, the majority of the total forage yield (62–79%) for all treatments came from the first harvest. The total forage yield of Siberian wildrye was not affected by the BRB and BRM treatments when compared with the FB treatment in 2009, 2011, and over the 3 yr; however, the BRB and BRM treatments increased the forage yield in 2010 by 47 and 81%, respectively. The plastic mulch on the ridge (MRB and MRM) increased the forage yield by 46 to 135% compared with the FB treatment in all 3 yr. Straw mulch in the furrow for the BRM treatment increased the forage yield by 23% compared with the BRB treatment in 2010 but not in 2009 or in 2011. In this study, relatively high forage yields were consistently obtained with the MRB and MRM treatments, ranging from 3990 to 6720 kg ha^{-1}. In comparison, the forage yield for the FB treatment was comparable to the yields reported by Wang et al. (2009a, 2010), which ranged from 2160 to 3850 kg ha^{-1} under dryland conditions. In this study, forage yield for the MRB and MRM treatments was lower than that reported by Wang et al. (2009a, 2010) with a single irrigation at the stem elongation (jointing) stage (5730–6880 kg ha^{-1}) and was lower than that reported by Wang et al. (2009a) under full irrigation (6490–7130 kg ha^{-1}).

Water use efficiency during both growth periods and the whole growing period was affected by management practice, but it was not affected by the interaction between management practice and year (Table 5). Water use efficiency during the second growth period and the whole growing period was also significantly affected by year. Water use efficiency during the first growth period was 81 to 362% higher than during the second growth period, primarily due to lower yield during the second period (Tables 4 and 5). The WUE values were not affected by bare ridge treatments (BRB and BRM) compared with the FB treatment in 2009 and 2011, but the BRB and BRM treatments increased forage WUE in 2010 by 51 and 81%, respectively (Table 5). The MRB and MRM treatments increased WUE by 79 to 150% compared with the FB treatment. Straw mulch in the furrow did not affect WUE under either the bare ridge or mulched ridge treatments. Plastic mulch on the ridge (MRB and MRM treatments) resulted in relatively high WUE values ranging from 15.0 to 28.8 kg ha^{-1} mm^{-1}, compared with WUE values ranging from 6.8 to 14.0 kg ha^{-1} mm^{-1} for the FB treatment. The WUE values for the FB treatment were comparable to those reported by Wang et al. (2009a, 2010) for rainfed conditions, ranging

Table 3. Evapotranspiration of Siberian wildrye for the flat bed planting (FB), bare ridge with bare furrow (BRB), bare ridge with straw mulch in furrow (BRM), plastic mulch on ridge with bare furrow (MRB), and plastic mulch on ridge with straw mulch in furrow (MRM) treatments in 2009, 2010, and 2011. Values were calculated by the improved soil water balance method (Eq. [2]).

		Evapotranspiration		
Year	Treatment	First growth period	Second growth period	Total
		mm		
2009	FB	103 bA†	91 aB	194 a
	BRB	110 aA	81 bB	191 a
	BRM	110 aA	79 bB	189 a
	MRB	94 cA	66 cB	160 b
	MRM	95 cA	67 cB	162 b
2010	FB	98 abB	183 aA	281 a
	BRB	105 abB	167 bA	272 a
	BRM	113 aB	166 bA	279 a
	MRB	90 bB	178 abA	268 a
	MRM	94 abB	175 abA	269 a
2011	FB	155 abA	116 aB	271 a
	BRB	164 aA	119 aB	283 a
	BRM	163 aA	117 aB	280 a
	MRB	136 cA	111 bB	247 b
	MRM	141 bcA	92 cB	233 b
			P > F	
Treatment		<0.001	<0.001	<0.001
Year		<0.001	<0.001	<0.001
Treatment × Year		0.755	<0.001	0.012

† Means followed by the same lowercase letter in a column in a given year are not significantly different according to Fisher's protected LSD test at the 0.05 probability level. Means followed by the same uppercase letter in a row are not significantly different according to Fisher's protected LSD test at the 0.05 probability level.

Table 4. Yield of Siberian wildrye for the flat bed planting (FB), bare ridge with bare furrow (BRB), bare ridge with straw mulch in furrow (BRM), plastic mulch on ridge with bare furrow (MRB), and plastic mulch on ridge with straw mulch in furrow (MRM) treatments in 2009, 2010, and 2011.

		Yield		
Year	Treatment	First harvest	Second harvest	Total
		kg ha^{-1}		
2009	FB	2070 cA†	650 bB	2720 b
	BRB	2290 bcA	920 aB	3210 b
	BRM	2450 abcA	900 abB	3350 ab
	MRB	2970 abA	1010 aB	3980 a
	MRM	3020 aA	1050 aB	4070 a
2010	FB	1170 cA	730 dB	1900 d
	BRB	1820 bA	970 cB	2790 c
	BRM	2290 bA	1140 bcB	3430 b
	MRB	2800 aA	1210 bB	4010 a
	MRM	3060 aA	1410 aB	4470 a
2011	FB	2370 cA	760 cB	3120 c
	BRB	3370 bcA	910 bcB	4280 bc
	BRM	3260 bcA	1330 abB	4590 bc
	MRB	4200 abA	1660 aB	5860 ab
	MRM	5270 aA	1450 aB	6720 a
			P > F	
Treatment		<0.001	<0.001	<0.001
Year		<0.001	<0.001	<0.001
Treatment × Year		0.350	0.066	0.189

† Means followed by the same lowercase letter in a column in a given year are not significantly different according to Fisher's protected LSD test at the 0.05 probability level. Means followed by the same uppercase letter in a row are not significantly different according to Fisher's protected LSD test at the 0.05 probability level.

Table 5. Water use efficiency of Siberian wildrye for the flat bed planting (FB), bare ridge with bare furrow (BRB), bare ridge with straw mulch in furrow (BRM), plastic mulch on ridge with bare furrow (MRB), and plastic mulch on ridge with straw mulch in furrow (MRM) treatments in 2009, 2010, and 2011.

Year	Treatment	Water use efficiency		
		First growth period	Second growth period	Total
		kg ha^{-1} mm^{-1}		
2009	FB	20.1 bA†	7.1 cB	14.0 b
	BRB	20.8 bA	11.4 bB	16.8 b
	BRM	22.2 bA	11.5 bB	17.7 b
	MRB	31.7 aA	15.4 aB	25.0 a
	MRM	31.9 aA	15.6 aB	25.2 a
2010	FB	12.5 cA	4.0 dB	6.8 d
	BRB	17.3 bcA	5.8 cB	10.3 c
	BRM	20.3 bA	6.9 bB	12.3 b
	MRB	31.4 aA	6.8 bcB	15.0 a
	MRM	32.7 aA	8.1 aB	16.6 a
2011	FB	15.5 cA	6.5 dB	11.5 b
	BRB	20.5 bcA	7.7 cdB	15.1 b
	BRM	20.4 bcA	11.3 bcB	16.5 b
	MRB	31.0 abA	15.0 abB	23.8 a
	MRM	37.4 aA	15.7 aB	28.8 a
		P > F		
Treatment		<0.001	<0.001	<0.001
Year		0.311	<0.001	<0.001
Treatment × Year		0.784	0.059	0.217

† Means followed by the same lowercase letter in a column in a given year are not significantly different according to Fisher's protected LSD test at the 0.05 probability level. Means followed by the same uppercase letter in a row are not significantly different according to Fisher's protected LSD test at the 0.05 probability level.

from 9.0 to 13.0 kg ha^{-1} mm^{-1}. The WUE values for the MRB and MRM treatments were similar to the WUE values of 17.8 to 23.0 kg ha^{-1} mm^{-1} under a single irrigation at the stem elongation (jointing) stage reported by Wang et al. (2009a, 2010) and 17.0 kg ha^{-1} mm^{-1} with full irrigation (Wang et al., 2009a).

CONCLUSIONS

For the RFP, it is necessary to use the improved soil water balance method with SWC measured in both the ridge and furrow areas to accurately calculate ET because of the significant differences in SWC that result in ET being overestimated by the old water balance method. Results from this study indicated that the MRB treatment can improve the forage yield of Siberian wildrye by 46 to 111% and WUE by 79 to 121% compared with the FB treatment under rainfed conditions in semiarid northern China. The BRB treatment did not increase forage yield or WUE in all years. The addition of straw mulch in the furrow did not result in a further increase in yield and WUE compared with the mulch ridge or bare ridge treatments. In this region, the RFP planting with plastic mulched ridge and bare furrow treatment should be used in Siberian wildrye production based on its high forage yield and WUE. The effects of these management practices on profitability, soil fertility, nutrient management, and soil organic C should be studied in future research.

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