EFFECTS OF IRRIGATION AMOUNT ON ALFALFA YIELD AND QUALITY WITH A CENTER-PIVOT SYSTEM

M. Li, Y. Liu, H. Yan, R. Sui

ABSTRACT. *Irrigation amount is one of the most important factors that need to be considered in the management of center-pivot irrigation systems for alfalfa producers. In 2014 and 2015, a field study was conducted at Saiwusu, Inner Mongolia, China. Three irrigation levels (100%, 80%, 60% ET) were used to evaluate the effects of irrigation amount on alfalfa yield and quality. For assessing the effects of water distribution variation of center-pivot systems on alfalfa yield and quality, the water application depth, alfalfa yield, and quality between the first span, second span, overhang, and end gun were also compared. The results showed no significant difference in annual yield between the 100% and 80% ET irrigation levels. Compared to irrigation at 100% and 80% ET, irrigation at 60% ET caused significant reductions in yield of 10% and 11%, respectively. As the irrigation amount decreased, total crop water use significantly declined from 617 to 405 mm, and water use efficiency (WUE) increased from 21.8 to 29.8 kg ha^{-1} mm^{-1}. The water production functions of alfalfa were parabolic for each harvest. The proportions of seasonal actual water applied to each cutting were approximately 25%, 32%, and 43%, with contributions to annual yield accounting for 54%, 30%, and 16%, respectively, indicating that the third harvest of alfalfa had great potential for improving WUE and saving water. Irrigation level had a noticeable effect on the relative feed value (RFV) but no effect on crude protein (CP) concentration. The 60% ET irrigation level was conductive to increased CP concentration and RFV of alfalfa but was of no help to improve alfalfa quality grade. The spatial distributions of annual yield and quality were highly related to the spatial distribution of water for the center-pivot system. The coefficients of variation (CVs) for annual yield, RFV, and CP of the whole system were 5% to 12%, 2% to 8%, and 1% to 8%, respectively, while the CVs for actual irrigation amount ranged from 11% to 13%. Over-irrigation caused by the end gun slightly increased alfalfa annual yield, but it reduced the quality and WUE. Therefore, the end gun in a center-pivot irrigation system should be carefully selected for improving the uniformity of water application. The 80% ET irrigation level in the first and second cuttings and the 60% ET irrigation level in the third cutting are recommended for alfalfa production in semi-arid regions, such as western Inner Mongolia in China.*

Keywords. *Alfalfa, Center-pivot irrigation, Quality, Water management, Yield.*

Alfalfa is often considered an extravagant use of water compared with other crops due to its greater evapotranspiration rates (Schneekloth and Andales, 2009; Krogman and Hobbs, 1965). However, over 70% of alfalfa production in China is concentrated in arid and semiarid regions, with 3.7 million ha of alfalfa (China, 2015). In recent years, the use of center-pivot irrigation systems has gradually increased in China (Li et al., 2016) because of advantages in irrigation efficiency, coverage of irrigated area, automation, and labor costs (Valín et al., 2012). It was estimated that over 70,000 ha of irrigated alfalfa were equipped with center-pivot systems in the semi-arid region of Inner Mongolia, which is one of the largest commercial grass zones of China. Irrigation has become one of the major limiting factors for alfalfa production in Inner Mongolia because of severe water shortages and declines in the water table in that region (Meng et al., 2013).

Alfalfa yield and quality are both related to irrigation amount. Deficit irrigation has been an effective way to provide irrigation management for water shortage areas (Hanson et al., 2007; Lindenmayer et al., 2011), although many studies have shown that alfalfa yield benefits from irrigation (Pembleton et al., 2009). Reducing the irrigation amount caused a reduction in yield (Lindenmayer et al., 2011) but improved water use efficiency (WUE) and alfalfa quality (Lindenmayer et al., 2008; Ismail and Almarshadi, 2013; Carter and Sheaffer, 1983). Water stress was generally highly favorable for alfalfa quality because drought delayed alfalfa maturation (Halim and Buxton, 1989). The crude protein (CP) concentration declined when the alfalfa biomass yield significantly increased, especially during the growth period from the branching stage to harvest (Zhang, 2007). It is difficult to balance quality and yield, but both factors are important for alfalfa growers. The relationships between irrigation amount, alfalfa yield, and quality should be established to improve irrigation management strategies for al-

Submitted for review in January 2017 as manuscript number NRES 12239; approved for publication by the Natural Resources & Environmental Systems Community of ASABE in May 2017. Presented at the 2016 ASABE Annual Meeting as Paper No. 162460633.

Mention of company or trade names is for description only and does not imply endorsement by the USDA. The USDA is an equal opportunity provider and employer.

The authors are **Maona Li,** Doctoral Student, **Yang Liu,** Doctoral Student, and **Haijun Yan,** Professor, College of Water Resources and Civil Engineering, China Agricultural University, Beijing, China; **Ruixiu Sui, ASABE Member,** Research Agricultural Engineer, USDA-ARS Crop Production Systems Research Unit, Stoneville, Mississippi. **Corresponding author:** Haijun Yan, China Agricultural University, No. 17 Tsinghua East Road, Beijing 100083, China; phone: +86-10-62737196; e-mail: yanhj@cau.edu.cn.

Vol. 60(5): 1633-1644 2017 American Society of Agricultural and Biological Engineers ISSN 2151-0032 https://doi.org/10.13031/trans.12239

falfa producers. Although some researchers (Carter and Sheaffer, 1983; Peterson et al., 1992) have studied the effects of irrigation amount on alfalfa yield and quality indexes (e.g., CP, acid detergent fiber, etc.) separately, few studies have focused on the relationships between irrigation amount, yield, and quality simultaneously. An understanding of the integrative response of alfalfa yield and quality to irrigation level is needed.

Crop yield and quality are also highly related to the water distribution uniformity of the irrigation system (Pair, 1968; Warrick and Gardner, 1983; Montazar, 2010). Over-irrigation can contribute to soil saturation and root waterlogging, which limits alfalfa root respiration, decreases growth rate, reduces yield, and can lead to pest outbreaks (Tovey, 1964; Barta and Sulc, 2002). Conversely, alfalfa yield can also be reduced by insufficient irrigation. End guns are widely used to increase the irrigated area (Sadeghi and Peters, 2013) of center-pivot systems, but improper selection and abnormal operating status can lead to non-uniform water distribution (Li et al., 2015). In addition, off-design working conditions of a system, such as declines in the water table, are relatively common in the management of irrigated alfalfa in Inner Mongolia (Yan et al., 2009). Off-design working conditions can cause non-uniform water distribution by the system, and they are not conducive to alfalfa growth. Therefore, it is necessary to study the effects of water distribution variations of center-pivot irrigation systems on alfalfa yield and quality.

The objectives of this field study were to: (1) investigate the effects of irrigation amount on the yield, quality, and WUE of alfalfa, and (2) evaluate the effects of the water distribution variation of the center-pivot irrigation system on alfalfa yield and quality.

Materials and Methods

Experimental Site Description

This research was conducted in 2014 and 2015 at Saiwusu, on the Inner Mongolian Plateau in northwest China (38° 56′ N, 106° 49′ E). The climate is a typical temperate continental semiarid monsoon climate with a summer precipitation pattern. More than 50% of the precipitation occurs from July to September, and the long-term (2003-2014) average annual precipitation is approximately 250 mm. The soil type is sandy loam with a bulk density of 1.3 g cm^{-3} and pH of 8.5. The field capacity (FC) and permanent wilting point of the topsoil layer (0 to 30 cm) were 0.257 and 0.104 cm^3 cm^{-3}, respectively. The saturated hydraulic conductivity of the topsoil layer was 5.0×10^{-4} m s^{-1}.

Irrigation System and Water Distribution Test

A center-pivot irrigation system (Valley, Valmont Industries, Inc., Omaha, Neb.) with R3000 sprinklers and 20 psi (138 kPa) pressure regulators was used in this study. The system consisted of just two spans, with a single-span length of 54.9 m and an overhang with a length of 25.1 m, because of the low capacity of the well. A Komet Twin 101 end gun with no booster pump was installed at the end of the overhang to increase the irrigated area and reduce the costs. A water distribution test was conducted on 13 October 2013 before the alfalfa irrigation experiment, in accordance with ASAE Standard S436.1 (ASAE, 1996) and ISO Standard 11545 (ISO, 2009). In the test, water collectors were placed in two straight lines with an angle of 7°. The distance between the distal ends of the two lines was 20 m. The catch cans, with an opening diameter of 0.23 m and a height of 0.24 m, were spaced 3 m apart uniformly along the two lines and perpendicular to the travel direction of the system. The wind speed was measured every 15 min with a three-cup anemometer (model DEM6, Zhonghuan TIG Meteorological Instruments Co., Ltd., Tianjin, China); the average wind speed during the test was 1.1 m s^{-1}. The test was investigated with percent timer settings of 30%. The flow rates of the whole system and of the end gun were calculated based on the measured water application depth and irrigated area. During the test, the calculated flow rates of the whole system and the end gun were 59 and 28 m^3 h^{-1} at a system operating pressure of 414 kPa.

Cultural Practices and Harvest Procedures

Alfalfa (*Medicago sativa*) cultivar ‘Zhongmu No. 1’ was seeded on 15 May 2009 with a grain drill in rows 0.3 m apart. Spring green-up began on 5 April 2014 and 15 April 2015. Alfalfa was harvested in the early flowering stage, when 10% of the alfalfa had bloomed. Three harvests in 2014 occurred sequentially on 5 June, 18 July, and 30 August. Three harvests in 2015 occurred sequentially on 12 June, 22 July, and 2 September. Three squares (1 m × 1 m) of fresh alfalfa were collected in the diagonals of each plot and weighed for estimating the alfalfa yield in each plot. The final alfalfa yield per unit area was determined after oven-drying the samples at 105°C for 1 h and then at 65°C for 72 h. The alfalfa samples were analyzed for CP concentration and relative feed value (RFV). The CP concentration was measured using near-infrared reflectance spectroscopy (NIR-TR-3750, Foss, Eden Prairie, Minn.) (Shenk and Westerhaus, 1991). RFV was calculated from estimates of dry matter digestibility (DDM) and dry matter intake (DMI) (Rohweder et al., 1978). DDM and DMI were calculated from the concentrations of neutral detergent fiber (NDF) and acid detergent fiber (ADF), which were also measured using near-infrared reflectance spectroscopy.

Experimental Design

For evaluating the effects of irrigation amount on alfalfa yield and quality, three irrigation levels were designed to replace 100%, 80%, and 60% of the calculated crop evapotranspiration (ET_c) minus the effective precipitation. For assessing the effects of water distribution variation of the center-pivot irrigation system on alfalfa yield and quality, test plots were spaced under the first span, second span, overhang, and end gun, respectively (fig. 1). All treatments were replicated three times. Irrigation was scheduled by ET_c, which was calculated using reference evapotranspiration (ET_o) and crop coefficients (K_c). ET_o was calculated from the weather data last event using the Penman-Monteith approach (Allen et al., 1998). Daily K_c was generated using FAO-56 (Allen et al., 1998), with the calculated parameters and actual growing period lengths adjusted to the Inner Mon-

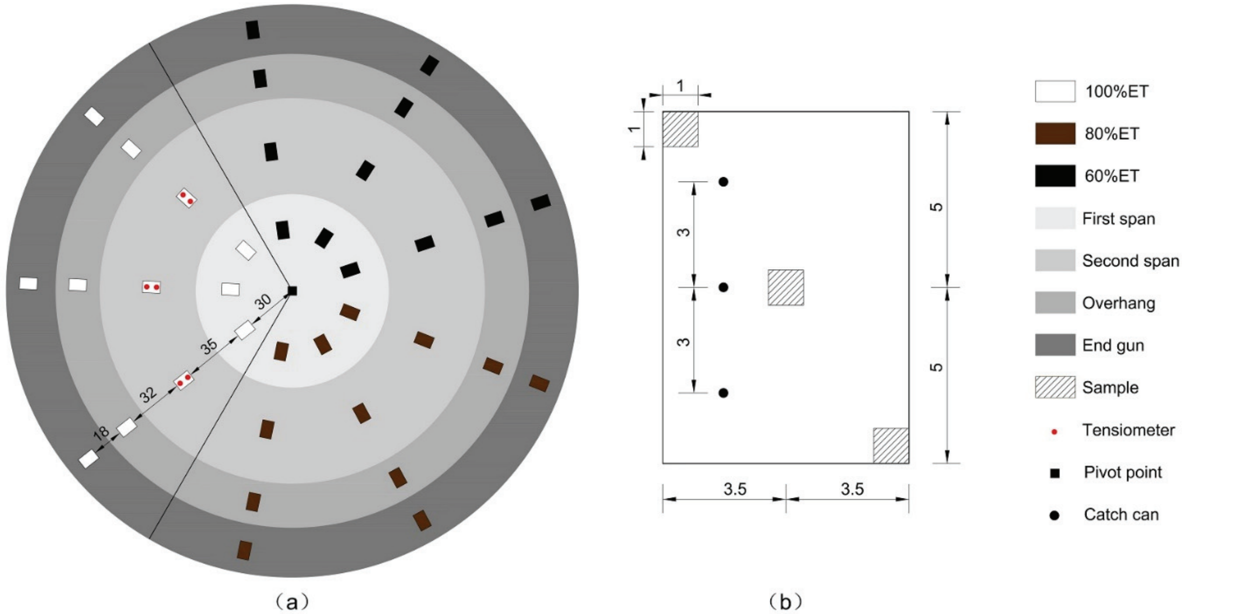

Figure 1. (a) Schematic diagram of center-pivot system and layout of plots, catch cans, and tensiometers, and (b) layout of samples and catch cans in a plot for measuring actual irrigation amount (units are meters).

golian Plateau. Specifically, K_c values were allowed to increase linearly from 0.3 to a maximum of 1.28, remain at 1.28 until harvest, and then increase linearly from 0.3 to a maximum of 1.25 in the subsequent harvest. Irrigation in this study was not applied at regular intervals. Instead, irrigation was scheduled based on soil water depletion. All plots started to receive irrigation when the soil water content in the topsoil layer (0 to 30 cm) for the 100% ET irrigation level in the second span was as low as 60% FC (0.154 cm^3 cm^{-3}). All plots received the same irrigation amount during the first irrigation event in 2014. The end gun was used during the water distribution test and alfalfa irrigation experiment.

Weather and Water-Related Data and Calculated Parameters

Collected data included weather data, actual irrigation amount, soil water content, alfalfa yield, and alfalfa quality.

Weather Data

Weather data, including precipitation, wind speed, temperature, relative humidity, and solar radiation, were collected with a portable weather station (U30, HOBO) installed approximately 700 m from the study field. The method of Guo and Xu (1997) for calculating precipitation infiltration was adopted to estimate the effective precipitation, as follows:

$$P_o = \alpha P \tag{1}$$

where P_o is the precipitation infiltration (i.e., effective precipitation), α is the coefficient of precipitation infiltration, which is usually related to soil type, precipitation amount, precipitation intensity, precipitation duration, etc., and P is the precipitation amount (mm). This empirical formula has been widely used for estimating effective precipitation, especially in the north of China (Liu et al., 2007; Li et al., 2003; Hu et al., 2013). Commonly, α is equal to 0, 0.8 to 1, or 0.7 to 0.8 when precipitation is <5 mm, 5 to 50 mm, or >50 mm, respectively. Precipitation of less than 5 mm seldom gets into the soil due to evaporation and canopy interception. However, precipitation with a relatively low amount and intensity can be conserved in the soil. Therefore, α was equal to 0 (precipitation <5 mm) or 1 (precipitation of 5 to 50 mm) in this study.

Coefficient of Uniformity

The coefficient of uniformity for a center-pivot irrigation system was calculated with the modified formula of Heermann and Hein (ASAE, 1996), given by:

$$\mathrm{CU}_H = \left[1 - \frac{\sum_{i=1}^{N} \left|D_i - \overline{D}_w\right| S_i}{\sum_{i=1}^{N} D_i S_i}\right] \times 100 \tag{2}$$

where CU_H is the Heermann and Hein coefficient of uniformity (%), N is the number of catch cans used in the data analysis, i is a number assigned to identify a particular catch can, normally beginning with the catch can located nearest the pivot point (i = 1) and ending with i = N for the catch can farthest from the pivot point, D_i is the application depth of water collected in the ith catch can (mm), S_i is the distance of the ith catch can from the pivot point (m), and $\overline{D}_w$ is the weighted average application depth of water collected (mm), calculated as:

$$\overline{D}_w = \sum_{i=1}^{N} D_i S_i \Big/ \sum_{i=1}^{N} S_i \tag{3}$$

Irrigation Amount

Three catch cans were placed above the plants in each plot to measure actual irrigation amount (fig. 1).

Soil Water Content

Tensiometers (TEN30, Beijing Waterstar Tech Co., Ltd., China) were installed at 0.25 m depth in the 100% ET plots in the second span for monitoring the lower limit for irrigation. For calculating the change in soil water storage (ΔW) in the root zone (1 m), the soil water content to 1 m depth in 0.2 m increments was measured by oven-drying at one day before and after irrigation events.

Crop Water Use

The actual crop water use in the two different growing seasons was estimated using the water balance method (James, 1988; Kresović et al., 2016):

$$\text{ET}_a = \Delta\text{SW} + I + P_o + \text{GW} - D_p - R \tag{4}$$

where ET_a is actual crop water use (i.e., crop evapotranspiration) (mm), ΔSW is the change in soil water storage in the 1 m profile between different growth stages, I is the actual irrigation amount (mm), P_o is the effective precipitation (mm), GW is the groundwater contribution to water use (ignored in this study because of the 30 m depth of groundwater), D_p is deep percolation from the root zone, and R is surface runoff, which was ignored because of the small droplets produced by the R3000 sprinklers (King and Bjorneberg, 2009), the well-drained soils, and the small slope of the experimental field.

Water Use Efficiency

The WUE of alfalfa was calculated using the following equation:

$$\text{WUE} = \frac{Y}{\text{ET}_a} \tag{5}$$

where WUE is the water use efficiency of alfalfa (kg ha^{-1} mm^{-1}), Y is the dry alfalfa yield (kg ha^{-1}), and ET_a is the actual crop water use (mm).

Data Analysis

The alfalfa yield and quality for different treatments in the two years were subjected to one-way analysis of variance (ANOVA) in which treatments were separated using Fisher's protected LSD at the 5% level (SPSS 20.0).

Results and Discussions

Performance Evaluation of Center-Pivot System

The water application depth for the end gun was about 1.7 times the average values for the other sections of the center-pivot system. As shown in table 1, the overall CU_H (84%) of the data excluding the end gun is obviously larger than the value including the end gun (64%). The high kinetic energy of the water caused the water to spill to other cans, contributing to the fluctuating data for line 2 of the end gun. The fluctuating data resulted in a low application uniformity for the end gun (table 1), which decreased the application uniformity of the whole system. The greater application depth for the end gun was due to the flow rate of 28 m^3 h^{-1} at 414 kPa working pressure, which is greater than the recommended value (13 m^3 h^{-1}) based on the method of Von Bernuth (1983). This discrepancy was due to improper selection of the end gun. The abnormal data for the first span and overhang were probably due to wind drift (fig. 2).

Table 1. Water application depth and coefficient of uniformity (CU_H) for different irrigated areas in the center-pivot irrigation system.

	First Span	Second Span	Over-hang	End Gun	Overall: End Gun Excluded	Overall: End Gun Included
Application depth (mm)	5.6	4.7	5.5	8.8	5.1	6.4
CU_H (%)	82.9	89.3	84.8	63.5	83.6	64.3

The average water application depths and CU_H values for the first span, second span, and overhang were similar, with CVs of 9% and 4%, respectively. The second span had the highest uniformity, but the average application depth was 15% less than that of the other sections. The main reason for the non-uniform application depths was that the short length of the center-pivot system and the unequal spacing of the sprinklers, which made sprinkler configuration more difficult. Center-pivot systems with relatively short lengths (usually three spans or fewer) are widely used in the region due to the low capacity of the wells (40 to 60 m^3 h^{-1}) during the peak season of water use in summer. In addition, the sprinkler configuration started with #14 nozzles in accordance with the specifications of the selected sprinklers (Nelson R3000 Series), which caused excessive flow near the pivot and high average water application depths in the first span. Additionally, the overhang had higher application depths due to the narrower sprinkler spacing and more overlapping of sprinklers than in other sections of the system. Therefore, the center-pivot system had a low water application uniformity.

Weather Conditions and Irrigation

Weather conditions were more favorable for alfalfa growth in 2015 than in 2014. The accumulated ET_o in 2015 (599 mm) was 16% greater than in 2014 (517 mm) due to greater wind speeds and temperatures. Daily temperatures had similar trends in the two years, except that a cold spring occurred in the middle of May 2014. The average daily temperatures during the growing season were 19.3°C and 20.5°C in 2014 and 2015, respectively (fig. 3). The average

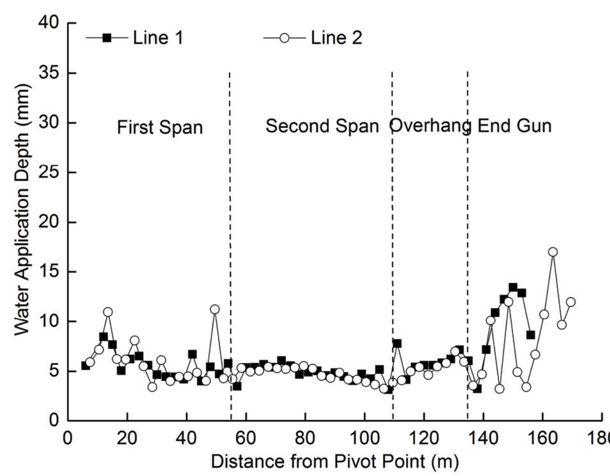

Figure 2. Water application depths of catch cans as measured from the pivot point of the center-pivot irrigation system.

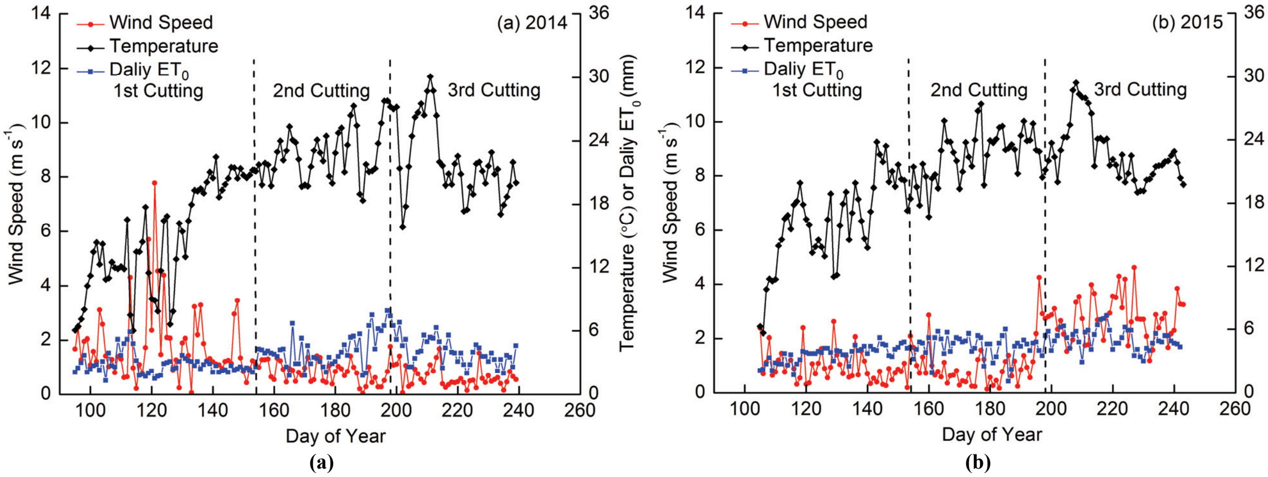

Figure 3. Daily wind speed, daily temperature, and daily ET_o during the alfalfa growing season in (a) 2014 and (b) 2015.

daily temperatures during the three cuttings were 16.3°C, 23.0°C, and 22.2°C, respectively. Hot and dry conditions during the second harvest, with a daily temperature of 23.0°C and little precipitation, were not conducive to alfalfa growth. The average daily wind speed during the third cutting was 2.77 m s^{-1} in 2015 but only 0.67 m s^{-1} in 2014, which might help to explain why the accumulated ET_o was higher in 2015 than in 2014 (Huo et al., 2004). The cold spring in the middle of May also caused lower accumulated ET_o in 2014. The maximum daily ET_o during the alfalfa growing season was 7.9 and 7.3 mm d^{-1} in 2014 and 2015, respectively, with average daily ET_o of 3.5 and 4.3 mm d^{-1}, respectively (fig. 4).

Averaged across the two years, the irrigation amounts were 440, 349, and 270 mm for the 100% ET, 80% ET, and 60% ET irrigation levels, respectively (fig. 4). Small differences were observed in total precipitation during the two growing seasons, but the precipitation distributions were different. The maximum precipitation for the two study years was 32.8 mm in 2015. Deep percolation from the root zone was zero because the soil water content did not reach field capacity after irrigation and precipitation. The effective precipitation was 73.4 and 68.9 mm during the growing season in 2014 and 2015, respectively, which is slightly more than half of the long-term (2003-2013) average of 126 mm. The seasonal effective precipitation for the three cuttings was 12.4, 23.2, and 37.8 mm, respectively, in 2014, but all effective precipitation for the 2015 growing season occurred during the third cutting. The seasonal irrigation amounts for full irrigation (100% ET level) for each cutting in 2014 were 118, 126, and 170 mm, with accumulated ET_c of 130, 151, and 200 mm, respectively. The seasonal irrigation amounts for the 100% ET level for each cutting in 2015 were 123, 171, and 172 mm, with accumulated ET_c of 133, 197, and 205 mm, respectively. The total irrigation amounts in the growing seasons for the 100% ET level were 414 and 466 mm in 2014 and 2015, with accumulated ET_c of 481 and 535 mm, respectively.

EFFECT OF IRRIGATION LEVEL ON YIELD, CROP WATER USE, AND WUE

Annual alfalfa yield was significantly affected by irrigation level in the two study years. The average yield was 13.4, 13.5, and 12.1 Mg ha^{-1} with average crop water use of 617, 506, and 405 mm for the 100% ET, 80% ET, and 60% ET irrigation levels, respectively (table 2). As a two-year average, no significant differences existed in yield between the 100% and 80% ET levels; however, compared with the

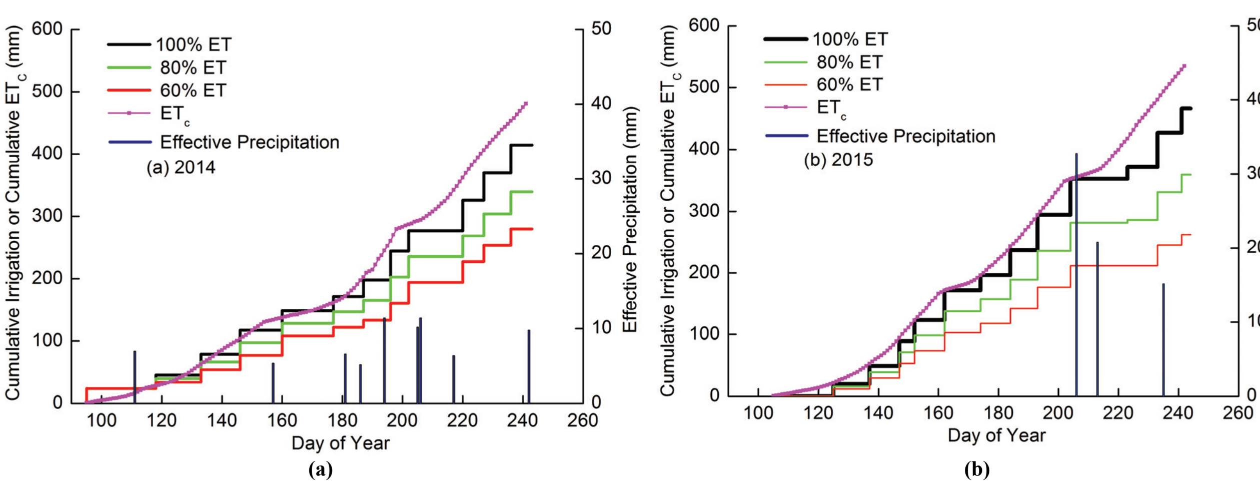

Figure 4. Cumulative ET_c values, irrigation amounts, and effective precipitation for different irrigation levels (100% ET, 80% ET, and 60% ET) during the alfalfa growing season in (a) 2014 and (b) 2015.

Table 2. Yield, crop water use, and water use efficiency (WUE) of alfalfa with different irrigation levels in the second span in 2014 and 2015.[a]

	Year	Irrigation Level	Cutting 1st	2nd	3rd	Total
Yield (Mg ha^{-1})	2014	100% ET	6.5 a ±0.2	4.1 a ±0.1	2.5 a ±0.2	13.2 a ±0.1
		80% ET	6.6 a ±0.2	4.3 a ±0.1	2.6 a ±0.1	13.4 a ±0.1
		60% ET	5.9 b ±0.2	3.7 b ±0.2	2.4 a ±0.3	12.0 b ±0.5
		Mean	6.3	4.0	2.49	12.9
		One-way ANOVA	** (p = 0.00)	** (p = 0.00)	NS (p = 0.53)	** (p = 0.00)
	2015	100% ET	8.0 a ±0.1	3.7 a ±0.3	2.0 a ±0.3	13.7 a ±0.4
		80% ET	7.8 a ±0.1	4.1 a ±0.3	1.7 a ±0.2	13.7 a ±0.2
		60% ET	7.3 b ±0.1	3.2 b ±0.1	1.7 a ±0.1	12.2 b ±0.2
		Mean	7.7	3.7	1.8	13.2
		One-way ANOVA	** (p = 0.00)	** (p = 0.00)	NS (p = 0.20)	** (p = 0.00)
Crop water use (mm)	2014	100% ET	205.3 a ±3.2	173.1 a ±13.1	229.1 a ±17.4	607.5 a ±12
		80% ET	173.0 b ±10.4	147.0 b ±5.2	191.2 b ±9.1	511.2 b ±15
		60% ET	129.2 c ±4.4	113.0 c ±8.3	157.0 c ±8.1	399.2 c ±16
		Mean	169.	144.3	192.4	506.0
		One-way ANOVA	** (p = 0.00)	** (p = 0.00)	** (p = 0.00)	** (p = 0.00)
	2015	100% ET	194.3 a ±19.1	186.5 a ±4.6	245.1 a ±12.0	625.9 a ±18.9
		80% ET	168.1 b ±4.1	151.1 b ±7.8	181.3 b ±13.4	500.5 b ±22.1
		60% ET	136.4 c ±5.9	114.0 c ±6.3	161.0 c ±8.2	411.4 c ±23.1
		Mean	166.3	150.5	195.8	512.6
		One-way ANOVA	** (p = 0.00)	** (p = 0.00)	** (p = 0.00)	** (p = 0.00)
WUE (kg ha^{-1} mm^{-1})	2014	100% ET	31.8 c ±1.1	23.9 c ±1.3	11.0 b ±0.5	21.7 c ±1.4
		80% ET	38.1 b ±1.9	29.0 b ±2.1	13.5 ab ±1.9	26.3 b ±0.7
		60% ET	45.6 a ±2.3	32.8 a ±1.5	15.0 a ±1.2	30.0 a ±1.7
		Mean	38.5	28.6	13.2	26.0
		One-way ANOVA	** (p = 0.00)	** (p = 0.00)	* (p = 0.02)	** (p = 0.00)
	2015	100% ET	41.3 c ±1.7	19.7 b ±1.3	8.1 a ±1.0	21.9 c ±1.2
		80% ET	46.6 b ±2.3	27.0 a ±1.8	9.6 a ±1.4	27.3 b ±0.3
		60% ET	53.5 a ±1.9	28.1 a ±0.7	10.4 a ±2	29.6 a ±1.6
		Mean	47.1	24.9	9.4	26.3
		One-way ANOVA	** (p = 0.00)	** (p = 0.03)	NS (p = 0.11)	** (p = 0.00)

[a] Treatments in the same column with the same letter are not significantly different at a probability level of $p < 0.05$. NS = not significant at a probability level of $p < 0.05$, * = significant at a probability level of $p < 0.05$, and ** = significant at a probability level of $p < 0.01$.

100% and 80% ET levels, the 60% ET level caused significant reductions in yield of 10% and 11%, respectively. Seasonal yields for each cutting were significantly affected by irrigation level ($p < 0.01$), except for the third cutting. This was probably because most of the precipitation occurred in the third cutting and closed the gap between the different irrigation treatments. Stomatal conductance and transpiration are reduced when alfalfa is under severe water stress (Mouradi et al., 2016). Thus, the water stress of the 60% ET level caused the alfalfa to stop growing and delayed maturation. Alfalfa stem density, stem height, and leaf size decrease (Brown and Tanner, 1983) at severe deficit irrigation of 60% ET. Therefore, the 60% ET irrigation level resulted in lower yield in comparison to the other irrigation levels. The annual yield was higher in 2015 mainly because the average seasonal yield for the first cutting was 23% higher in 2015. Lamb et al. (2014) confirmed that annual yield is determined by the seasonal yield for the first cutting. Significant differences and declines in alfalfa yield occurred with successive harvests, with nearly 50% or more of the seasonal yield for the first cutting. Compared with the other cuttings, a relatively long growth period (60 days in 2014 and 58 days in 2015) for the first cutting allowed the alfalfa to accumulate greater biomass. At the same time, low temperatures during the first cutting inhibited the growth of weeds and thus reduced competition for nutrients between the alfalfa and weeds. Higher temperatures and more irrigation during the third cutting greatly increased the growth of weeds. Hence, the first cutting had the highest seasonal yield. The growth period for the first cutting in 2014 was almost the same as that in 2015, but the seasonal yield may have been suppressed by the cold temperatures that occurred in the middle of May in 2014. That might be why the seasonal yield of the first cutting was higher in 2015 than in 2014.

Crop water use decreased significantly with decreased irrigation amount. Irrigation amount was the most important factor in calculating crop water use, especially when the alfalfa roots could not effectively draw plant-available water from the deep soil. Almost the same growth period length and similar growth environments were observed in the two years, but the daily crop water use was higher in 2015 than in 2014 (3.4 mm d^{-1} in 2014 and 3.7 mm d^{-1} in 2015) because of more applied irrigation. The average daily water consumption increased with successive harvests across the two years, as Lamm et al. (2012) reported, with values of 2.9, 3.5, and 4.5 mm d^{-1}, respectively, for each cutting. The transpiration rates of alfalfa would be higher at high temperatures, which could be why the average daily crop water use was higher in the second and third cuttings. In addition, the average daily wind speed increased by 87%, to 0.9 m s^{-1} in the second cutting and 1.7 m s^{-1} in the third cutting. Alfalfa in the third cutting had the highest daily crop water use because the high temperatures and wind speeds accelerated evaporation from the soil surface. Although relatively high daily crop water use was obtained in the second cutting, the shortest growth time contributed to the lowest cumulative water consumption, while the third cutting had the greatest cumulative water consumption.

The total WUE of alfalfa increased significantly with decreased irrigation, with average values of 21.8, 26.8, and 29.8 kg ha^{-1} mm^{-1} for the 100%, 80%, and 60% ET irrigation levels, respectively. The WUE decreased dramatically with successive harvests, which was similar to the results reported by Undersander (1987). The WUE was significantly higher for the 100% ET irrigation level than for the other two irrigation levels in all three cuttings, except for the third cutting in 2015, which could be due to the small yield differences among the irrigation levels in the third cutting in 2015 (table 2). The average crop water use for the third cutting in the two years accounted for 38% of the total growing season water use, while the yield accounted for just 17% of the growing season total, which resulted in the lowest WUE for the third cutting. Additionally, while no significant differences in seasonal yield existed in the third cutting, crop water use decreased significantly with increased irrigation amount, with reductions of 72 mm in 2014 and 84 mm in 2015. Meanwhile, most of the precipitation for the entire growing period usually occurred in the third cutting. Thus, the third cutting has great potential for reducing the irrigation amount and improving WUE in semi-arid areas.

Effect of Irrigation Level on Quality

The RFV was significantly affected by irrigation level, while CP concentrations were almost unaffected by irrigation level (table 3). The CP concentration and RFV were higher for the 60% ET level than for the other two irrigation levels for all three cuttings, which indicates that water stress could improve the quality of alfalfa, as reported by Halim and Buxton (1989). The yield decreased with increased water stress, but the alfalfa quality increased because drought delayed maturation and increased the leaf-stem weight ratio (Peterson et al., 1992; Halim and Buxton, 1989). Although the CP concentrations were almost unaffected by irrigation level, the CP concentrations increased slightly with decreased irrigation. Alfalfa with a high leaf-stem weight ratio has higher CP concentrations and lower RFV. Thus, deficit irrigation at the 60% ET level achieved higher quality. The CP concentrations and RFV increased dramatically with successive harvests (table 3). Although all cuttings were harvested at the early flowering stage, the alfalfa maturity was slightly different for different cuttings. Additionally, the quality response to temperature was different in different seasons. Delaying harvest had a large negative impact on quality in spring growth because the interaction of increasing temperature and advancing maturity caused a rapid decline in forage quality with time. During late-summer regrowth, temperatures are not increasing with the advancing season, and advancing maturity often results in a slower decline in forage quality (Buxton, 1996).

The quality grades of alfalfa were not significantly affected by irrigation level, with first grade for all irrigation levels in the first cutting and prime grade for almost all irrigation levels in the second and third cuttings. The high quality grades obtained in this study were probably due to the suitable harvest time at the early flowering stage and the well-preserved samples. The CP concentration and RFV are the most important factors for evaluating alfalfa quality. Deficit irrigation at the 60% ET level could increase the CP concentration and RFV of alfalfa, as many studies have demonstrated, but the CP concentration and RFV did not improve the quality grade for all irrigation levels in this study, which illustrates that yield could be used as the most important factor for determining irrigation amounts in Inner Mongolia.

Differences in Yield and Quality between First Span, Second Span, and Overhang

Although the CU_H values were relatively similar among the first span, second span, and overhang, the CVs of annual yield for all irrigation levels ranged from 2% to 8%, while the CVs for actual irrigation amount ranged from 9% to 10% (table 4). Spatial variation in annual yield existed among the first span, second span, and overhang even though the overall CU_H (excluding the end gun) was 84%, which exceeded the acceptable criterion of 80% for center-pivot systems. This demonstrated that irrigation amount could be an important factor for determining annual alfalfa yield. The actual irrigation amount, annual yield, and crop water use were lower in the second span than in the first span and overhang but almost the same between the first span and overhang, which was similar to the pattern of water distribution uniformity, as shown in table 1. This demonstrated that the distributions of annual yield and quality were highly related to the water distribution of the system. In the first span, second span, and overhang, no significant differences in yield were observed between the 100% ET and 80% ET levels, but the 60% ET level caused a significant yield reduction. In addition, the trend that crop water use decreased as irrigation amount decreased also existed among the first span, second span, and overhang. The WUE was significantly higher for

Table 3. Crude protein (CP) and relative feed value (RFV) of alfalfa with different irrigation levels in the second span in 2014 and 2015.[a]

		CP			RFV		
Year	Irrigation Level	1st Cutting	2nd Cutting	3rd Cutting	1st Cutting	2nd Cutting	3rd Cutting
2014	100% ET	19.0 a ±0.1	20.7 a ±0.2	22.5 a ±0.1	139.9 b ±3.6	144.0 b ±1.9	168.3 b ±4.5
	80% ET	18.9 a ±0.2	21.0 a ±0.3	23.0 a ±0.4	147.9 a ±3.4	152.1 ab ±6.3	176.1 a ±2.8
	60% ET	19.2 a ±0.2	21.6 a ±0.5	23.1 a ±0.2	148.8 a ±4.9	159.3 a ±10.0	180.3 a ±3.1
	Mean	19.0	21.1	22.9	145.5	153.7	174.9
	One-way ANOVA	NS (p = 0.16)	NS (p = 0.06)	NS (p = 0.07)	** (p = 0.00)	* (p = 0.04)	** (p = 0.01)
2015	100% ET	18.0 a ±0.7	20.7 a ±0.3	21.8 b ±0.5	145.9 a ±1.7	152.8 b ±2.6	167.4 b ±3.3
	80% ET	18.5 a ±0.1	20.8 a ±0.1	22.2 b ±0.1	148.3 a ±10.	155.0 ab ±1.4	175.7 a ±4.5
	60% ET	18.3 a ±0.4	21.0 a ±0.1	22.7 a ±0.2	148.0 a ±4.0	159.3 a ±2.8	177.7 a ±4.9
	Mean	18.3	20.8	22.3	147.4	155.7	173.6
	One-way ANOVA	NS (p = 0.35)	NS (p = 0.18)	* (p = 0.03)	NS (p = 0.25)	* (p = 0.03)	** (p = 0.01)

[a] Treatments with the same letter in the column are not significantly different at a probability level of $p < 0.05$. NS = not significant at a probability level of $p < 0.05$, * = significant at a probability level of $p < 0.05$, and ** = significant at a probability level of $p < 0.01$.

Table 4. Actual irrigation amount, annual alfalfa yield, crop water use, and WUE for the first span, second span, overhang, and end gun of the center-pivot system during the entire growing season in 2014 and 2015.[a]

Location	Year	Irrigation Level	Actual Irrigation Amount (mm)	Annual Alfalfa Yield (Mg ha^{-1})	Crop Water Use (mm)	WUE (kg ha^{-1} mm^{-1})
First span	2014	100% ET	487.3 a ±10.5	13.0 a ±0.5	592.4 a ±9.5	21.0 b ±0.2
		80% ET	400.5 b ±6.7	13.8 a ±0.8	526.5 b ±7.3	26.3 a ±1.0
		60% ET	330.3 c ±10.1	11.5 b ±0.4	443.2 c ±12.2	26.0 a ±0.7
		Mean	406.0	12.8	520.7	24.8
		One-way ANOVA	** (p = 0.00)	** (p = 0.00)	** (p = 0.00)	** (p = 0.00)
	2015	100% ET	539.3 a ±14.2	13.6 a ±0.5	621.3 a ±13.1	21.9 b ±1.2
		80% ET	423.2 b ±13.3	13.5 a ±0.4	506.2 b ±8.6	26.8 a ±0.4
		60% ET	306.9 c ±12.9	11.8 b ±0.3	438.2 c ±15.1	27.0 a ±0.8
		Mean	423.1	13.0	521.9	25.2
		One-way ANOVA	** (p = 0.00)	** (p = 0.00)	** (p = 0.00)	** (p = 0.00)
Second span	2014	100% ET	414.1 a ±9.7	12.4 a ±0.1	531.2 a ±7.4	23.4 b ±0.2
		80% ET	339.0 b ±10.1	12.1 a ±0.3	453.1 b ±12.5	26.7 a ±1.3
		60% ET	280.0 c ±10.1	10.4 b ±0.2	390.4 c ±10.3	26.7 a ±0.2
		Mean	344.4	11.6	458.2	25.6
		One-way ANOVA	** (p = 0.00)	** (p = 0.00)	** (p = 0.00)	** (p = 0.00)
	2015	100% ET	466.1 a ±10.4	12.7 a ±0.4	542.3 a ±10.0	23.4 c ±0.5
		80% ET	358.9 b ±11.3	12.2 ab ±0.5	445.3 b ±7.1	27.5 b ±0.9
		60% ET	262.0 c ±8.7	11.7 b ±0.4	346.1 c ±8.3	33.7 a ±1.8
		Mean	362.3	12.2	445	28.3
		One-way ANOVA	** (p = 0.00)	NS (p = 0.07)	** (p = 0.00)	** (p = 0.00)
Overhang	2014	100% ET	479.4 a ±11.2	13.22 a ±0.5	593.2 a ±8.2	21.1 b ±1.0
		80% ET	405.1 b ±7.6	12.92 a ±0.3	532.1 b ±11.3	24.3 b ±1.0
		60% ET	338.2 c ±9.1	12.18 b ±0.2	442.3 c ±5.1	27.6 a ±0.4
		Mean	407.6	12.8	522.6	24.7
		One-way ANOVA	** (p = 0.00)	** (p = 0.01)	** (p = 0.00)	** (p = 0.01)
	2015	100% ET	549.7 a ±7.4	13.7 a ±0.4	634.3 a ±11.3	21.6 b ±0.5
		80% ET	429.0 b ±9.6	14.0 a ±0.4	514.6 b ±11.9	27.2 a ±1.2
		60% ET	314.1 c ±10.1	12.1 b ±0.6	450.3 c ±13.1	26.7 a ±1.7
		Mean	430.9	13.3	533.1	25.2
		One-way ANOVA	** (p = 0.00)	** (p = 0.00)	** (p = 0.00)	** (p = 0.00)
End gun	2014	100% ET	554.4 a ±9.2	14.0 a ±0.7	679.1 a ±10.3	20.6 c ±1.0
		80% ET	446.9 b ±8.0	14.9 a ±0.4	579.7 b ±6.1	25.7 b ±0.8
		60% ET	372.2 c ±8.9	13.7 a ± 0.7	490.3 c ±7.3	27.9 a ±1.1
		Mean	457.8	14.2	583.0	24.8
		One-way ANOVA	** (p = 0.00)	NS (p = 0.11)	** (p = 0.00)	** (p = 0.00)
	2015	100% ET	630.1 a ±13.1	14.8 a ±0.4	708.2 a ±13.4	20.8 b ±0.3
		80% ET	474.3 b ±10.0	14.8 a ±0.4	584.3 b ±12.4	25.4 a ±0.9
		60% ET	351.2 c ±9.4	13.1 a ±0.3	486.2 c ±9.9	27.0 a ±1.0
		Mean	485.2	14.6	592.9	24.4
		One-way ANOVA	** (p = 0.00)	NS (p = 0.19)	** (p = 0.00)	** (p = 0.00)

[a] Treatments with the same letter in the column are not significantly different at a probability level of $p < 0.05$. NS = not significant at a probability level of $p < 0.05$ and ** = significant at a probability level of $p < 0.01$.

80% ET and 60% ET than for 100% ET in the first span, second span, and overhang, expect for the second span in 2015, which differed from the whole system.

The amount of irrigation water applied was less in the second span than in the first span and overhang. Compared with the first span and overhang, the second span generally had higher CP concentrations and RFV (table 5). This demonstrated that reduced irrigation might improve the quality of alfalfa. For all irrigation levels, the CVs for CP concentration and RFV were 1% to 5% and 1% to 7%, respectively, among the first span, second span, and overhang (table 5). The CP concentrations in the first span, second span, and overhang were almost unaffected by irrigation level, which was similar to the whole system. The RFV values for the second span and overhang were affected by irrigation level for all cuttings in 2014 and for the third cutting in 2015. The quality grade of alfalfa for the second span (prime grade) was higher than for the first span and overhang (first grade) in the first cutting. The quality grade for the 100% and 80% ET irrigation levels was also reduced to first grade in the first span and overhang in 2014.

Although the CVs for annual yield, CP concentration, and RFV of the whole system were low, the annual yield and quality of alfalfa for the end gun were different from the first span, second span, and overhang. For all irrigation levels, the CVs for annual yield, CP concentration, and RFV of the whole system were 5% to 12%, 2% to 8%, and 1% to 8%, respectively, while the CVs for actual irrigation amount ranged from 11% to 13%. The annual alfalfa yield for the end gun was higher than for the first span, second span, and overhang because of excess irrigation (table 4). The actual irrigation amount applied by the end gun was 1.2 times the average applied by the first span, second span, and overhang, which was less than the factor of 1.7 found in the water distribution test. The water distribution test was conducted in October 2013, when the water table in the well recovered after irrigation, and the system working pressure (414 kPa) was higher than in the alfalfa irrigation experiment

Table 5. Crude protein (CP) and relative feed value (RFV) of alfalfa with different irrigation levels for the first span, second span, overhang, and end gun of the center-pivot system during the entire growing season in 2014 and 2015.[a]

Location	Year	Irrigation Level	CP 1st Cutting	CP 2nd Cutting	CP 3rd Cutting	RFV 1st Cutting	RFV 2nd Cutting	RFV 3rd Cutting
First span	2014	100% ET	18.9 a ±0.4	20.4 a ±0.8	23.1 a ±0.6	138.5 a ±2.0	148.2 b ±2.4	168.1 a ±7.5
		80% ET	18.4 a ±0.7	21.0 a ±0.1	21.7 a ±0.2	141.5 a ±2.3	146.8 b ±3.3	168.9 a ±7.1
		60% ET	19.3 a ±0.3	21.9 a ±1.9	23.9 ±0.3	142.1 a ±3.2	154.8 a ±9.0	177.5 a ±5.1
		Mean	18.9	21.1	23.6	140.8	149.9	171.5
		One-way ANOVA	NS (p = 0.18)	NS (p = 0.32)	NS (p = 0.12)	NS (p = 0.22)	NS (p = 0.27)	NS (p = 0.24)
	2015	100% ET	17.9 a ±1.5	20.4 a ±0.6	22.1 a ±0.9	146.9 a ±4.4	151.5 a ±6.9	162.4 a ±2.9
		80% ET	19.3 a ±0.5	21.1 a ±0.4	22.9 a ±0.4	148.2 a ±0.7	155.4 a ±6.6	170.6 a ±9.2
		60% ET	18.4 a ±0.8	20.9 a ±0.7	23.2 a ±1.0	142.6 a ±5.8	163.9 a ±6.9	177.3 a ±5.7
		Mean	18.5	20.8	22.7	145.9	156.9	170.1
		One-way ANOVA	NS (p = 0.35)	NS (p = 0.30)	NS (p = 0.30)	NS (p = 0.30)	NS (p = 0.13)	NS (p = 0.09)
Second span	2014	100% ET	19.8 a ±0.5	21.2 a ±0.1	23.2 b ±0.4	149.9 b ±5.4	153.8 c ±0.9	171.8 b ±5.5
		80% ET	19.9 a ±1.0	21.7 a ±0.3	23.8 b ±0.3	161.0 a ±2.1	161.4 b ±2.8	185.5 a ±4.0
		60% ET	19.6 a ±0.2	22.6 a ±1.2	24.7 a ±0.5	163.1 a ±1.7	169.3 a ±5.3	188.8 a ±3.0
		Mean	19.8	21.8	23.9	158.0	161.5	182.0
		One-way ANOVA	NS (p = 0.84)	NS (p = 0.14)	** (p = 0.01)	** (p = 0.01)	** (p = 0.01)	** (p = 0.01)
	2015	100% ET	18.3 a ±0.9	21.2 a ±0.4	22.7 b ±0.6	152.4 a ±1.0	157.1 a ±2.4	171.1 b ±13.4
		80% ET	18.2 a ±0.2	21.8 a ±0.4	23.4 ab ±0.3	151.2 a ±4.7	156.0 a ±3.3	182.9 a ±8.5
		60% ET	18.3 a ±0.4	21.3 a ±0.5	24.2 a ±0.2	156.9 a ±5.5	155.2 a ±4.5	187.4 a ±6.9
		Mean	18.3	21.4	23.4	153.5	156.1	180.4
		One-way ANOVA	NS (p = 0.98)	NS (p = 0.28)	NS (p = 0.12)	NS (p = 0.30)	NS (p = 0.95)	** (p = 0.01)
Overhang	2014	100% ET	19.1 a ±0.3	20.79 a ±0.47	22.9 a ±0.8	136.4 b ±0.4	138.2 b ±2.3	160.59 b ±3.1
		80% ET	19.1 a ±0.5	20.69 a ±0.53	22.6 a ±0.7	148.1 a ±2.5	150.4 a ±4.1	180.08 a ±1.8
		60% ET	19.4 a ±0.2	21.22 a ±0.80	23.0 ±0.5	146.1 a ±1.6	152.8 a ±6.7	183.31 a ±1.1
		Mean	19.2	20.9	22.9	143.5	147.1	174.7
		One-way ANOVA	NS (p = 0.50)	NS (p = 0.56)	NS (p = 0.67)	** (p = 0.01)	* (p = 0.02)	** (p = 0.00)
	2015	100% ET	17.7 a ±0.5	20.8 a ±0.5	21.6 a ±0.6	144.7 a ±5.1	152.9 a ±14.44	165.3 b ±2.52
		80% ET	18.6 a ±0.6	21.0 a ±0.7	22.1 a ±0.4	152.8 a ±3.7	156.9 a ±5.5	173.9 ab ±11.06
		60% ET	17.7 a ±0.3	20.8 a ±0.4	22.4 a ±0.4	149.8 a ±6.1	169.2 a ±5.0	182.9 a ±1.8
		Mean	18.0	20.9	22.1	149.8	159.7	174.0
		One-way ANOVA	NS (p = 0.08)	NS (p = 0.85)	NS (p = 0.12)	NS (p = 0.22)	NS (p = 0.17)	* (p = 0.05)
End gun	2014	100% ET	18.3 a ±0.3	20.5 a ±0.3	20.7 a ±1.1	134.8 b ±6.3	135.6 a ±0.4	172.6 a ±3.8
		80% ET	18.0 a ±0.5	20.5 a ±0.6	21.8 a ±0.8	140.9 a ±2.0	146.5 a ±8.1	169.7 a ±2.7
		60% ET	18.5 a ±0.2	20.7 a ±0.8	20.8 a ±0.5	143.7 a ±7.8	146.5 a ±5.2	171.7 a ±10.3
		Mean	18.3	20.5	21.1	139.78	142.9	171.3
		One-way ANOVA	NS (p = 0.70)	NS (p = 0.94)	NS (p = 0.25)	NS (p = 0.37)	NS (p = 0.09)	NS (p = 0.86)
	2015	100% ET	18.0 a ±1.4	20.3 c ±0.3	20.9 a ±0.4	139.7 a ±2.4	150.9 a ±1.9	170.8 a ±2.1
		80% ET	18.0 a ±0.9	19.4 b ±0.2	20.5 a ±0.7	140.9 a ±4.3	151.6 a ±3.3	168.7 a ±3.8
		60% ET	18.9 a ±1.2	21.9 a ±0.2	21.0 a ±0.3	142.6 a ±3.3	149.1 a ±3.2	170.1 a ±1.6
		Mean	18.3	20.2	20.8	141.1	150.5	167.0
		One-way ANOVA	NS (p = 0.18)	** (p = 0.00)	NS (p = 0.45)	NS (p = 0.61)	NS (p = 0.57)	NS (p = 0.64)

[a] Treatments with the same letter in the column are not significantly different at a probability level of $p < 0.05$. NS = not significant at a probability level of $p < 0.05$, * = significant at a probability level of $p < 0.05$, and ** = significant at a probability level of $p < 0.01$.

(207 kPa). Consequently, the flow rate of the end gun in the water distribution test was greater. Compared with the average value for the first span, second span, and overhang, the increased irrigation with the end gun could not obtain the same increase in yield, especially for the 100% ET irrigation level, which only increased by 9% and 10% while the crop water use increased by 19% and 18% in 2014 and 2015, respectively. That is why the WUE for 100% ET declined with the end gun. The WUE for the 80% and 60% ET irrigation levels with the end gun did not decline because of the relatively high increase in annual yield. The irrigation amounts for the 60% ET level with the end gun were lower than the mean values of the first span, second span, and overhang for the 80% and 100% ET levels, but the 60% ET level with the end gun had a higher annual yield. This is probably because the large droplet size and high droplet kinetic energy of the end gun decreased the amount of canopy-intercepted water, which can account for 11% to 15% of the total seasonal water applied in a sprinkler system (Montazar and Sadeghi, 2008), and more water reached the soil.

Compared to the second span, the average actual irrigation amounts with the end gun for the 100% and 80% ET levels increased by 35% and 32%, respectively, while the annual yield only increased by 15% and 22%, which resulted in a decline of total WUE. The actual irrigation amounts with the end gun for the 100% and 80% ET levels were higher than the design value (414 mm and 466 mm in 2014 and 2015) during the entire growing season, which meant that the 100% ET and 80% ET plots were over-irrigated with the end gun. In this study, the design irrigation amounts were implemented with the second span because of the highest uniformity and reasonable water distribution uniformity. The over-irrigation caused by the end gun caused the alfalfa yield to increase rather than decline, which differs from the findings of Donovan and Meek (1983). This result could be due to the well-drained soils that reduced the possibility of waterlogging, as excess water was removed before the threshold for alfalfa (Williamson and Kriz, 1970).

The end gun produced lower CP concentrations and RFV due to larger irrigation amounts in all three cuttings (table 5), which also shows that appropriate water stress might improve the quality of alfalfa. The CP concentrations and RFV with the end gun were largely unaffected by irrigation level, which might be because the 60% ET alfalfa was not water-stressed with the end gun. The quality of the first and second cuttings was first grade, and the quality of the third cutting was prime grade. Annual yield, CP concentration, and RFV with the end gun were unaffected by irrigation level, while WUE increased significantly with decreased irrigation. These results differed from the results for the whole system and could be due to the excess applied water, which eliminated the yield gap caused by deficit irrigation at the 60% ET level. Overall, the over-irrigation caused by the end gun contributed to an increased annual yield but decreased alfalfa quality and WUE during the entire growing season.

Short-length center-pivot systems, which are widely used in Inner Mongolia, often have a low water application uniformity. In this study, spatial variation in annual yield and RFV existed among the first span, second span, overhang, and end gun of the center-pivot system, with variations of 7%, 11%, and 8% for the 100%, 80%, and 60% ET irrigation levels, respectively. The spatial variation was mainly caused by the relatively non-uniform water distribution of the system (CU_H = 64%).

Yield Response to Irrigation Amount in Individual Harvests

Quadratic regressions between alfalfa yield and irrigation amount for each cutting were fitted to the data, indicating that moderate water stress could obtain the maximum yield. The relationships between yield and total actual water applied (actual irrigation amount plus effective precipitation) were parabolic, using the data from average alfalfa yield and average actual irrigation amount for each cutting in the two years (fig. 5). Different relationships between yield (*Y*) and irrigation amount (*I*) existed among the three cuttings because of different growing conditions (Myer et al., 1991). The relationships were:

$$Y_{1st\ cutting} = -0.29(I^2) + 88.38(I) + 799.5 \qquad R^2 = 0.63 \tag{6}$$

$$Y_{2nd\ cutting} = -0.10(I^2) + 39.98(I) + 185.51 \qquad R^2 = 0.49 \tag{7}$$

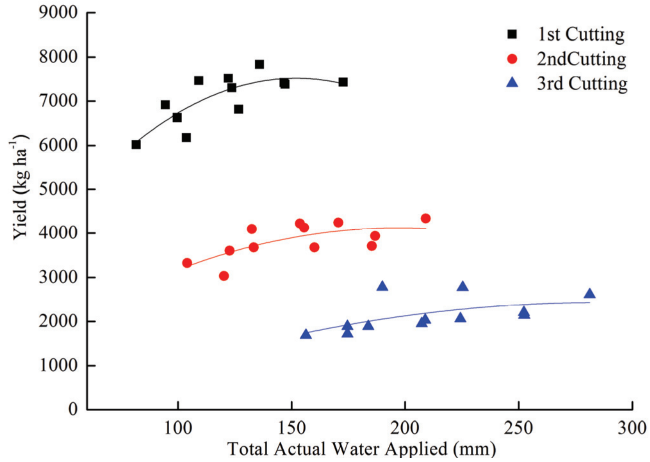

Figure 5. Relationships between alfalfa yield and total actual water applied for different harvests in the two growing seasons.

$$Y_{3rd\ cutting} = -0.04(I^2) + 23.34(I) - 919.31 \qquad R^2 = 0.33 \tag{8}$$

As shown in figure 5, in the first and second cuttings, yield first increased with increasing irrigation and then decreased with increasing irrigation after obtaining the maximum yield at the appropriate irrigation amount. The third cutting had a relatively low increase in yield as irrigation increased because of the weak ability to regrow and poor growing conditions, which resulted in lower WUE than for the other two cuttings. The proportions of seasonal actual water applied for the three harvests were approximately 25%, 32%, and 43%, with proportions of 54%, 30%, and 16% to annual yield, respectively, which illustrates that the seasonal yields of the first and second cuttings had a great contribution to annual yield, and the third cutting had a great potential to save water in semi-arid Inner Mongolia. Therefore, the 80% ET irrigation level is recommended for the first and second cuttings for relatively high yield and WUE, and the 60% ET irrigation level should be used for the third cutting to save water.

Conclusions

No significant differences existed in alfalfa yield between the 100% and 80% ET levels, but the 60% ET level caused a significant yield reduction. Seasonal yield decreased with successive harvests, with different parabolic relationships between yield and irrigation amount for each harvest. The seasonal yield of the first and second cuttings had a greater contribution to annual yield. The 80% ET irrigation level for the first and second cuttings and the 60% ET irrigation level for the third cutting are recommended due to the serious water shortages in Inner Mongolia. Alfalfa quality grade was unaffected by irrigation level, even though deficit irrigation significantly increased RFV, illustrating that yield can be considered the most important factor for determining irrigation amounts in Inner Mongolia. Distributions of annual yield and quality were highly related to the water distribution of the center-pivot irrigation system. Over-irrigation caused by the end gun decreased the quality and WUE of alfalfa in all three cuttings, even though it slightly increased the annual yield. Selecting a proper end gun for a center-pivot irrigation system is important to ensure uniform application of irrigation water across the field.

Acknowledgements

This study was financially supported by the National Natural Science Foundation of China (Grant Nos. 51679238 and 51621061) and the Opening Fund of the State Key Laboratory of Soil-Plant-Machinery System Technology (2014-SKL-09).

References

Allen, R. G., Pereira, L. S., Raes, D., & Smith, M. (1998). Crop evapotranspiration: Guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper No. 56. Rome, Italy: United Nations FAO.

ASAE. (1996). S436.1: Test procedure for determining the uniformity of water distribution of center pivot and lateral move irrigation machines equipped with spray or sprinkler nozzles. St. Joseph, MI: ASAE.

Barta, A. L., & Sulc, R. M. (2002). Interaction between waterlogging injury and irradiance level in alfalfa. *Crop Sci., 42*(5), 1529-1534. https://doi.org/10.2135/cropsci2002.1529

Brown, P. W., & Tanner, C. B. (1983). Alfalfa stem and leaf growth during water stress. *Agron. J., 75*(5), 799-805. https://doi.org/10.2134/agronj1983.00021962007500050017x

Buxton, D. R. (1996). Quality-related characteristics of forages as influenced by plant environment and agronomic factors. *Animal Feed Sci. Tech., 59*(1), 37-49. http://dx.doi.org/10.1016/0377-8401(95)00885-3

Carter, P. R., & Sheaffer, C. C. (1983). Alfalfa response to soil water deficits: I. Growth, forage quality, yield, water use, and water use efficiency. *Crop Sci., 23*(4), 669-675. https://doi.org/10.2135/cropsci1983.0011183X002300040016x

China. (2015). *China statistical yearbook* [in Chinese]. Beijing, China: China Statistics Press.

Donovan, T. J., & Meek, B. D. (1983). Alfalfa responses to irrigation treatment and environment. *Agron. J., 75*(3), 461-464. https://doi.org/10.2134/agronj1983.00021962007500030011x

Guo, Y., & Xu, Z. (1997). Crop water requirement and irrigation amount [in Chinese]. In Y. Guo (Ed.), *Irrigation and drainage engineering* (3rd ed., p. 41). Beijing, China: China Water and Power Press.

Halim, R. A., Buxton, D. R., Hattendorf, M. J., & Carlson, R. E. (1989). Water-stress effects on alfalfa forage quality after adjustment for maturity differences. *Agron. J., 81*(2), 189-194. https://doi.org/10.2134/agronj1989.00021962008100020010x

Hanson, B., Putnam, D., & Snyder, R. (2007). Deficit irrigation of alfalfa as a strategy for providing water for water-short areas. *Agric. Water Mgmt., 93*(1), 73-80. http://dx.doi.org/10.1016/j.agwat.2007.06.009

Hu, Q., Pan, X., Shao, C., Zhang, D., & Yang, N. (2013). Distribution of precipitation in Inner Mongolia and its impact on potato irrigation amount [in Chinese]. *Chinese J. Agrometeorol., 34*(4), 419-424. http://dx.doi.org/10.3969/j.issn.1000-6362.2013.04.007

Huo, Z., Shi, H., Chen, Y., Wei, Z., & Qu, Z. (2004). Spatio-temporal variation and dependence analysis of ET_o in north arid and cold region [in Chinese]. *Trans. CSAE, 20*(6), 60-63. http://dx.doi.org/10.3321/j.issn:1002-6819.2004.06.014

Ismail, S. M., & Almarshadi, M. H. (2013). Maximizing productivity and water use efficiency of alfalfa under precise subsurface drip irrigation in arid regions. *Irrig. Drain., 62*(1), 57-66. https://doi.org/10.1002/ird.1705

ISO. (2009). 11545: Agricultural irrigation equipment - Center-pivot and moving lateral irrigation machines with sprayer or sprinkler nozzles - Determination of uniformity of water distribution. Geneva, Switzerland: ISO.

James, L. G. (1988). *Principles of farm irrigation systems design.* New York, NY: John Wiley & Sons.

King, B. A., & Bjorneberg, D. L. (2009). Potential runoff and erosion comparison of four center pivot sprinklers. ASABE Paper No. 095942. St. Joseph, MI: ASABE.

Kresović, B., Tapanarova, A., Tomić, Z., Životić, L., Vujović, D., Sredojević, Z., & Gajić, B. (2016). Grain yield and water use efficiency of maize as influenced by different irrigation regimes through sprinkler irrigation under temperate climate. *Agric. Water Mgmt., 169*, 34-43. http://dx.doi.org/10.1016/j.agwat.2016.01.023

Krogman, K. K., & Hobbs, E. H. (1965). Evapotranspiration by irrigated alfalfa as related to season and growth stage. *Canadian J. Plant. Sci., 45*(4), 309-313. https://doi.org/10.4141/cjps65-063

Lamb, J. F., Jung, H.-J. G., & Riday, H. (2014). Growth environment, harvest management, and germplasm impacts on potential ethanol and crude protein yield in alfalfa. *Biomass Bioenergy, 63*, 114-125. http://dx.doi.org/10.1016/j.biombioe.2014.02.006

Lamm, F. R., Harmoney, K. R., Aboukheira, A. A., & Johnson, S. K. (2012). Alfalfa production with subsurface drip irrigation in the Central Great Plains. *Trans. ASABE, 55*(4), 1203-1212. https://doi.org/10.13031/2013.42258

Li, J., Rao, M., & Zhang, J. (2003). Water requirements of drip-irrigated maize in arid regions [in Chinese]. *Water Saving Irrig., 22*(1), 16-21. http://dx.doi.org/10.3969/j.issn.1672-3317.2003.01.005

Li, L., Li, G., Qiao, X., & Jin, L. (2015). Assessment of influence of off-design conditions on uniformity of sprinkler irrigation of center-pivot irrigation system [in Chinese]. *Trans. CSAM, 46*(12), 62-67. http://dx.doi.org/10.6041/j.issn.1000-1298.2015.12.009

Li, L., Zhang, X., Qiao, X., & Liu, G. (2016). Analysis of the decrease of center pivot sprinkling system uniformity and its impact on maize yield. *Intl. J. Agric. Biol. Eng., 9*(5), 108-119. http://dx.doi.org/10.3965/j.ijabe.20160904.1129

Lindenmayer, B., Hansen, N., Crookston, M., Brummer, J., & Jha, A. (2008). Strategies for reducing alfalfa consumptive water use. *Proc. Hydrology Days 2008* (pp. 52-61). Fort Collins, CO: Colorado State University.

Lindenmayer, R. B., Hansen, N. C., Brummer, J., & Pritchett, J. G. (2011). Deficit irrigation of alfalfa for water savings in the Great Plains and Intermountain West: A review and analysis of the literature. *Agron. J., 103*(1), 45-50. https://doi.org/10.2134/agronj2010.0224

Liu, Z., Duan, A., Xiao, J., & Liu, Z. (2007). Research progress on calculation methods of effective rainfall in growing period on dry crop [in Chinese]. *Water Saving Irrig., 26*(3), 27-34.

Meng, Z., Gao, Y., Yu, Y., & Ren, X.-m. (2013). Crisis of water resources on the Ulan Buh Desert Oases, Inner Mongolia, China: A case study of Dengkou County. *J. Integrative Agric., 12*(8), 1409-1413. http://dx.doi.org/10.1016/S2095-3119(13)60545-6

Montazar, A. (2010). Predicting alfalfa hay production as related to water distribution functions. *Irrig. Drain., 59*(2), 189-202. https://doi.org/10.1002/ird.450

Montazar, A., & Sadeghi, M. (2008). Effects of applied water and sprinkler irrigation uniformity on alfalfa growth and hay yield. *Agric. Water Mgmt., 95*(11), 1279-1287. http://dx.doi.org/10.1016/j.agwat.2008.05.005

Mouradi, M., Farissi, M., Bouizgaren, A., Makoudi, B., Kabbadj, A., Very, A.-A., ... Ghoulam, C. (2016). Effects of water deficit on growth, nodulation, and physiological and biochemical processes in *Medicago sativa*-rhizobia symbiotic association. *Arid Land Res. Mgmt., 30*(2), 193-208. http://dx.doi.org/10.1080/15324982.2015.1073194

Myer, G. L., Miller, W. W., Narayanan, R., Jensen, E. H., & Zheng, Y.-B. (1991). Water management of alfalfa through individual harvest production functions. *J. Prod. Agric., 4*(4), 505-508. https://doi.org/10.2134/jpa1991.0505

Pair, C. H. (1968). Water distribution under sprinkler irrigation. *Trans. ASAE, 11*(5), 648-651. https://doi.org/10.13031/2013.39488

Pembleton, K. G., Rawnsley, R. P., Donaghy, D. J., & Volenec, J. J. (2009). Water deficit alters canopy structure but not photosynthesis during the regrowth of alfalfa. *Crop Sci., 49*(2), 722-731. https://doi.org/10.2135/cropsci2008.08.0456

Peterson, P. R., Sheaffer, C. C., & Hall, M. H. (1992). Drought effects on perennial forage legume yield and quality. *Agron. J., 84*(5), 774-779. https://doi.org/10.2134/agronj1992.00021962008400050003x

Rohweder, D. A., Barnes, R. F., & Jorgensen, N. (1978). Proposed hay grading standards based on laboratory analyses for evaluating quality. *J. Animal Sci., 47*(3), 747-759. https://doi.org/10.2527/jas1978.473747x

Sadeghi, S.-H., & Peters, T. (2013). Adjusted friction correction factors for center-pivots with an end gun. *Irrig. Sci., 31*(3), 351-358. https://doi.org/10.1007/s00271-011-0307-z

Schneekloth, J. P., & Andales, A. A. (2009). Seasonal water needs and opportunities for limited irrigation for Colorado crops. Fort Collins, CO: Colorado State University Extension. Retrieved from http://extension.colostate.edu

Shenk, J. S., & Westerhaus, M. O. (1991). Population definition, sample selection, and calibration procedures for near-infrared reflectance spectroscopy. *Crop Sci., 31*(2), 469-474. https://doi.org/10.2135/cropsci1991.0011183X003100020049x

Tovey, R. (1964). Alfalfa growth as influenced by static and fluctuating water tables. *Trans. ASAE, 7*(3), 310-312. https://doi.org/10.13031/2013.40766

Undersander, D. J. (1987). Alfalfa (*Medicago sativa* L.) growth response to water and temperature. *Irrig. Sci., 8*(1), 23-33. https://doi.org/10.1007/bf00256813

Valin, M. I., Cameira, M. R., Teodoro, P. R., & Pereira, L. S. (2012). DEPIVOT: A model for center-pivot design and evaluation. *Comput. Electron. Agric., 87*, 159-170. http://dx.doi.org/10.1016/j.compag.2012.06.004

Von Bernuth, R. D. (1983). Nozzling considerations for center pivots with end guns. *Trans. ASAE, 26*(2), 419-422. https://doi.org/10.13031/2013.33950

Warrick, A. W., & Gardner, W. R. (1983). Crop yield as affected by spatial variations of soil and irrigation. *Water Resour. Res., 19*(1), 181-186. https://doi.org/10.1029/WR019i001p00181

Williamson, R. E., & Kriz, G. J. (1970). Response of agricultural crops to flooding, depth of water table, and soil gaseous composition. *Trans. ASAE, 13*(2), 216-220. https://doi.org/10.13031/2013.38573

Yan, H., Zhu, Y., Bai, G., & Yu, P. (2009). Discussion on application of large-sized sprinkler irrigation machines in Inner Mongolia autonomous region [in Chinese]. *Water Saving Irrig.,* 1, 19-21.

Zhang, D. (2007). Research on what affects the CP content of *Medicago Sativa* [in Chinese]. *J. Animal Sci. Vet. Med., 26*(5), 4-7. http://dx.doi.org/10.3969/j.issn.1004-6704.2007.05.002