Field Crops Research 114 (2009) 58–65

Contents lists available at ScienceDirect

Field Crops Research

journal homepage: www.elsevier.com/locate/fcr

Productivity and water use of alfalfa and subsequent crops in the semiarid Loess Plateau with different stand ages of alfalfa and crop sequences

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ARTICLE INFO

Article history:
Received 1 December 2008
Received in revised form 4 July 2009
Accepted 8 July 2009

Keywords:
Alfalfa
Legume–crop rotation
Semiarid Loess Plateau
Water use
Yield

ABSTRACT

Alfalfa (*Medicago sativa* L.) plays an important role in crop–livestock mixed farming on marginal land in the semiarid Loess Plateau. However, the duration, yield performance and water use of long-term alfalfa stands and choice of appropriate subsequent crops are not clear. A 5-year field experiment was conducted at Zhonglianchuan, Gansu Province, China from 2001 to 2005. Productivity and water use were determined and compared between (1) three alfalfa stands that were 1–5 (A1–5), 6–10 (A6–10) and 11–15 (A11–15) years old during the trial; (2) alfalfa using conventional cultivation and a water-harvesting technique (RA1–5); and (3) conventional crop rotation (CK) and four 5-year crop sequence rotations sown after 10-year-old alfalfa had been ploughed, being millet–wheat–potato–pea–potato (MWLPL); millet–corn–corn–wheat–wheat (MCCWW); millet–potato–wheat–corn–corn (MLWCC) and millet–fallow–pea–potato–pea (MFPLP). Forage yield peaked in 7-year-old alfalfa (5740 kg ha^{-1}), but 9-year-old alfalfa had the maximum forage yield profit (4477 kg ha^{-1} y^{-1}) in terms of whole growing years. Soil water use efficiency (WUE_S in terms of forage yield and soil water use) of alfalfa increased dramatically up to the 11th year, and then leveled off from year 12 to 15. Forage yield and $WUE_{B/ET}$ (WUE in terms of aboveground biomass and evapotranspiration) of alfalfa were significantly higher using water harvesting compared with conventional cultivation, but were significantly lower than CK. Soil water content did not change in CK as stand age increased, but it decreased in conventional alfalfa stands. After 10 years of alfalfa, a fallow year was not necessary before planting annual crops as soil water was greatly restored after sowing subsequent annual crops. Yield of some crops in the four crop sequence rotations did not differ significantly from CK. MWLPL and MLWCC had more aboveground biomass than MCCWW and MFPLP but the choice of crop sequence needs to be further considered.

1. Introduction

The Loess Plateau lies in the North of China and is one of the most seriously affected soil erosion regions in the world (Chen et al., 2007). About 280,000 km^2 or 45% of the Loess Plateau is severely eroded (Tang, 1992). Each year, on average, nearly 1600 million Mg of topsoil are lost from the region through run-off and wind erosion, with associated losses of about 38 million Mg of nitrogen, phosphorus and potassium (Liu, 1999). Semiarid areas extend across almost 60% of the Plateau and include Yanbei of Shanxi province, north Shaanxi province, Xi-Hai-Gu of southern Ningxia province and Dingxi of Gansu province (Li, 1989). These regions are strongly controlled by a temperate continental monsoon climate characterized by cold winters, windy and dry springs, warm and rain-rich summers, and short, cool autumns. Annual rainfall, including snow, ranges between 250 and 550 mm, and mainly occurs from June to September. The major cultivated soil type is sandy loam of loess origin with loose structure and high risk of wind and water erosion (Chen et al., 1996).

Although soil erosion and land degradation have a biophysical root cause related to climatic, edaphic, topographic and geological features of the region, they are strongly tied to poor land-use management (Ren, 1992). Water resources for irrigation are not available in most of the region; rainfed farming is the most widespread land-use practice occupying nearly 80% of arable land (Shan and Chen, 1993). Since the beginning of the 20th century,

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0378-4290/$ – see front matter
doi:10.1016/j.fcr.2009.07.004

and particularly during the last several decades, the human population has increased significantly, leading to a rapid decline in the average arable land per capita in the region. As such, farmers have been forced to convert more and more marginal land into crop land and, at the same time, increase cultivation of steep erodible slopes in order to meet food requirements. Consequently, the scale and severity of soil erosion has increased and soil fertility has decreased; major factors affecting the sustainability of the agricultural system (Li and Xu, 2002).

In the last 10 years, advanced agricultural techniques such as application of chemical fertilizer, plastic film mulching and water harvesting have significantly increased unit grain yield in the semiarid Loess Plateau. More food is being produced on less land than ever before. Some low-productivity crop lands are available for non-grain crops (Li et al., 2003; He et al., 2007). Many studies have shown the benefit of crop–livestock mixed farming in this region, since it not only benefits farmers but also the environment (Shan and Chen, 1993; Li and Xu, 2002; Cheng and Mao, 2003). Government strongly promotes stockbreeding for its environmental effect, but there is no recommended plan. One difficulty is that productivity of fodder plants is limited.

Alfalfa (*Medicago sativa* L.) was widely planted and a dominant pasture until the 1960s in this region (Li, 2002). It has been reported that including alfalfa in a crop sequence improved subsequent crop yields and quality (Tan and Li, 1957; Hobbs, 1987; Caporali and Onnis, 1992; Geng et al., 1995). However, alfalfa almost disappeared in this region due to the application of chemical fertilizers. Local farmers preferred to use chemical fertilizers to rapidly increase crop production rather than legumes to improve soil fertility. Recently, alfalfa has regained its popularity with farmers in the region for crop–livestock mixed farming systems. Many studies on agronomic characteristics of alfalfa have been reported (Cheng et al., 2005; Geng et al., 1995; Hu et al., 2002); however, being perennial, alfalfa performs differently to annual crops. This study considered the following: (1) long-term performance of alfalfa, including forage yield, water use efficiency (WUE) and soil water content, using conventional cultivation; (2) the possibility of increasing forage yield using water-harvesting technology; and (3) performance of subsequent crops in terms of the whole cropping system. The objective of this study was to address these issues in a 5-year experiment comparing productivity and water use between (1) 1- to 15-year-old alfalfa stands, (2) alfalfa using conventional and water-harvesting methods, and (3) the local conventional crop rotation and different crop sequence rotations after alfalfa.

2. Materials and methods

2.1. Description of study site

The study was conducted from 2001 to 2005 at the Semiarid Ecosystem Research Station of Loess Plateau (36°02′N, 104°25′E, 2400 m above sea level), Lanzhou University which is located in Zhonglianchuan, in the northern mountainous region of Yuzhong County, Gansu, China. The area has a moderate semiarid climate, with an annual mean air temperature of 6.5 °C, maximum of 19.0 °C (July) and minimum of −8.0 °C (January). Long-term mean annual precipitation is 310 mm and long-term average annual free water evaporation is 1326 mm. The ratio of free evaporation to rainfall is 4.28 and approximately 56% of precipitation occurs between July and September. Rainfall data was collected every 10 days and rainfall totaled for each year of the experiment—wet years occurred in 2002 and 2005, a dry year in 2004, and normal rainfall in 2001 and 2003 (Fig. 2). The water table is more than 60 m deep, thus groundwater is unavailable for plant growth. The field site has a Rusty Dark loess soil (Chinese soil taxonomy) or Loess Orthic Entisol (FAO taxonomy) (sand 12.3%, silt 66.9%, clay 20.8%), with water content at field capacity of 22.9% (gravimetrically) and at permanent wilting point of 6.2%. The pH of surface soil (0–20 cm) was 8.1 (1:2.5 soil/water suspensions), with 8.1 g C, 38.7 mg N, and 3.9 mg P per kg soil; the soil chemical test was determined as described by Robertson et al. (1999).

2.2. Experimental design and field management

Three fields – Field I, Field II and Field III – were selected for the study which commenced in 2001. Previously Field I had been sown to spring wheat (2000), Field II to alfalfa for 5 years (1995–2000) and Field III to alfalfa for 10 years (1990–2000). There were nine treatments each with three replications, which are detailed below and in Fig. 1.

Field I was divided into three treatments: A1–5 which had 1- to 5-year-old alfalfa using conventional cultivation (in a flat field without mulch); RA1–5 had 1- to 5-year-old alfalfa using a water-harvesting technique—this treatment consisted of alternate 60-cm wide parallel ridges and furrows in the field, where ridges served as rainfall harvesting zones and furrows as planting zones; and CK had a conventional crop rotation (pea–wheat–pea–potato–pea).

Field II remained in alfalfa and had one treatment: A6–10, which consisted of 6- to 10-year-old alfalfa using conventional cultivation.

Field III was divided into five treatments: A11–15, which consisted of 11- to 15-year-old alfalfa using conventional cultivation; and the other four treatments had the existing 10-year-old alfalfa ploughed and one of the following crop rotations – MWLPL, MCCWW, MLWCC and MFPLP – where M is millet (*Setaria italica* Beauv), W is spring wheat (*Triticum aestivum* L.), L is potato (*Solanum tuberosum* L.), P is pea (*Pisum sativum* L.), C is corn (*Zea mays* L.) and F is fallow.

Planting date, seeding rate, depth of seeding and harvesting date for all crops grown in rotation are shown in Table 1. Crop sequences of different systems are shown in Table 2. According to

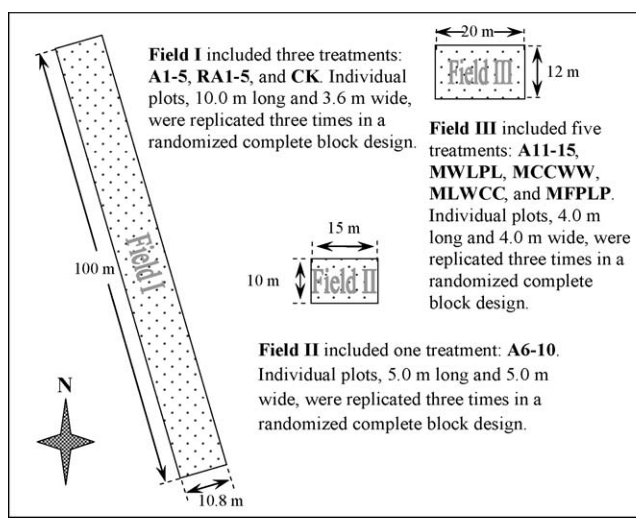

Fig. 1. Dimension, distribution and treatments of the experiment design. Previously Field I had been sown to spring wheat (2000), Field II to alfalfa for 5 years (1995–2000) and Field III to alfalfa for 10 years (1990–2000). A1–5, A6–10 and A11–15 denote alfalfa that was 1–5, 6–10, and 11–15 years old with conventional cultivation (in a flat field without mulch) from 2001 to 2005. RA1–5 denotes 1- to 5-year-old alfalfa using water-harvesting technique which consisted of alternate 60-cm wide parallel ridges and furrows in the field, where the ridges served as rainfall harvesting zones and the furrows as planting zones. CK denoted conventional crop sequence rotations (pea–wheat–pea–potato–pea from 2001 to 2005). MWLPL, MCCWW, MLWCC, and MFPLP denote four rotations after 10-year-old alfalfa was ploughed in Field III. M, W, L, P, C and F denote millet, spring wheat, potato, pea, corn and fallow, respectively.

Table 1
Planting date, seeding rate, depth of seeding and harvesting date for crops grown in the crop rotation treatments.

Crop	Planting date	Seeding rate (kg ha^{-1})	Depth of seeding (cm)	Harvesting date
Alfalfa[a]	Early–mid-April	22.5	2	Mid-July and mid-October
Corn	Late April–early May	22.5	4	Late September
Millet[a]	Late April	37.5	2	Late September
Pea	Mid April	135	4	Early August
Potato[b]	Late April–early May	1500 (fresh tuber)	10	Late September
Spring wheat	Late March–early April	165	3	Early August

[a] Harvested for forage.
[b] Harvested for tuber.

Table 2
Aboveground biomass (kg ha^{-1}) of crops in different systems from 2001 to 2005.

System	2001	2002	2003	2004	2005	Average*
A1–5	A 624.1	A 3389.8	A 4541.2	A 4657.1	A 5169.7	3676.4 d
RA1–5	A 763.8	A 4608.9	A 6631.2	A 6615.1	A 6932.3	5110.3 b
CK	P 4746.4	W 6380.6	P 4668.9	L 6828.7	P 4827.4	5586.0 a
MWLPL	M 4503.7	W 6830.6	L 5699.2	P 3674.2	L 5049.4	5151.4 b
MCCWW	M 4503.7	C 6745.1	C 5387.3	W 4265.2	W 4381.5	5056.6 c
MLWCC	M 4503.7	L 5957.5	W 5093.2	C 5534.7	C 4851.4	5188.1 b
MFPLP	M 4503.7	F	P 4365.6	L 7306.6	P 3715.4	4853.4 c

A1–5 denotes conventional alfalfa cultivation with 1- to 5-year-old stands; RA1–5 denotes ridge and furrow alfalfa system with 1- to 5-year-old stands; CK denotes conventional crop rotation; MWLPL, MCCWW, MLWCC and MFPLP denote different crop sequence rotations after ploughing 10-year-old alfalfa. M is millet (*Setaria italica* Beauv), W is wheat (*Triticum aestivum* L.), L is potato (*Solanum tuberosum* L.), P is pea (*Pisum sativum* L.), C is corn (*Zea mays* L.) and F is fallow. Values in year columns are preceded by a capital letter representing the crop grown in any given year and treatment.
* denotes annual average aboveground biomass from 2001 to 2005 in the given treatment; values in this column followed by the same lower case letter are not significantly different at $P < 0.05$.

local fertilizer application practices, farmyard manure at 15,000 kg ha^{-1} was applied annually to peas; chemical fertilizer with 90 kg N ha^{-1} and 13.1 kg P ha^{-1} was applied annually to spring wheat; farmyard manure at 30,000 kg ha^{-1} and chemical fertilizer with 150 kg N ha^{-1} and 33 kg P ha^{-1} was applied to potatoes in CK rotation. Bi-ammonium phosphate and urea with 34.5 kg N ha^{-1} and 8.0 kg P ha^{-1} was applied at time of sowing in A1–5 and RA1–5. All crops grew under rainfed conditions. A plastic covering film was used for corn, due to the high altitude often resulting in poor establishment of corn seedlings.

2.3. Sampling and measurements

2.3.1. Soil water content

Soil moisture (mm) was determined gravimetrically to a depth of 500 cm at 20 cm intervals at the beginning and end of each growing season using a soil auger (diameter 8 cm, height 20 cm). Three auger samples were taken per replicate plot.

2.3.2. Yield and aboveground biomass

Crop yield and aboveground biomass of all plots was measured by taking three quadrat cuts (1.2 m long × 1.2 m wide) at ground level per replicate plot. All samples of herbage, grain and tuber (Table 1) were oven-dried at 105 °C for 1 h and at 70 °C for a minimum of 72 h. In this study, crop yield refers to grain yield of spring wheat, corn, pea; tuber yield of potato; forage yield refers to hay yield of alfalfa and millet; aboveground biomass refers to total biomass removed from field by farmers. The forage yield of alfalfa and millet is the same as their aboveground biomass.

2.3.3. Maximum forage yield profit of alfalfa and annual average aboveground biomass

A1–5, A6–10 and A11–15 represented a 1- to 15-year-old alfalfa stand. Annual average alfalfa yield (AY) was calculated as follows:

$$\mathrm{AY}\,j(j = 1, 2, 3, \ldots, 15) = \frac{\sum_{i=1}^{j} \mathrm{yield}_i}{j} \quad (1)$$

where AY_j is average alfalfa yield in j-year, yield_i is alfalfa forage yield of given year; and j is the number of year (1–15 years). Maximum forage yield profit of alfalfa was the maximum value from AY_1 to AY_{15}.

Annual average aboveground biomass was expressed as total aboveground biomass over 5 years divided by 5 in all treatments.

2.3.4. Water use efficiency

Water use efficiency in terms of yield and evapotranspiration (ET) ($\mathrm{WUE}_{Y/ET}$) was calculated as follows:

$$\mathrm{WUE}_{Y/ET} = \frac{\mathrm{yield}}{\mathrm{ET}} \quad (2)$$

where yield is grain yield (spring wheat, corn and pea), tuber yield (potato) or forage yield (alfalfa and millet), ET is evapotranspiration in crop growing season, which was roughly calculated as rainfall during growing season plus difference in soil water content (0–500 cm) between the beginning and end of the growing season, because there was no irrigation and infiltration is very limited in this area.

Water use efficiency in terms of biomass and ET ($\mathrm{WUE}_{B/ET}$) was calculated as follows:

$$\mathrm{WUE}_{B/ET} = \frac{\mathrm{biomass}}{\mathrm{ET}} \quad (3)$$

where biomass is aboveground biomass, ET as per Formula (2).

Water use efficiency of total biomass (WUE_T) of various treatments was calculated as follows:

$$\mathrm{WUE}_T = \frac{\mathrm{biomass}_T}{\mathrm{ET}_T} \quad (4)$$

where $\mathrm{biomass}_T$ is total aboveground biomass of the crop over 5 years, ET_T is total evapotranspiration over 5 years, which was calculated as rainfall plus difference in soil water content (0–500 cm) between the beginning and end of the trial.

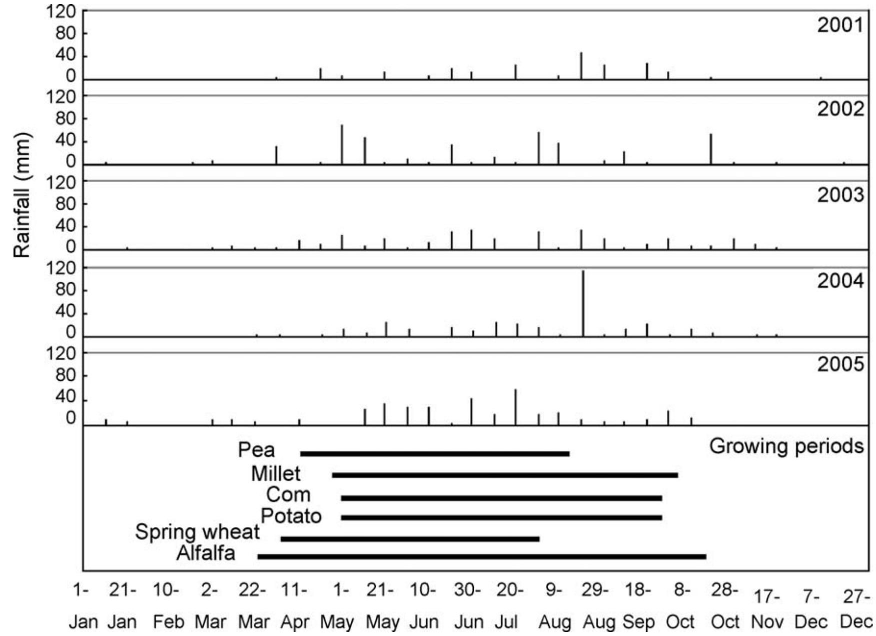

Fig. 2. Distribution of rainfall at the study site every 10 days during the 5-year experiment (2001–2005) and growing periods of the plants.

2.3.5. Soil water use efficiency

To calculate the efficiency of soil water use in conventional alfalfa stands, soil water consumption (SWC) was measured gravimetrically to 500 cm at 20 cm intervals at the beginning and end of each growing season (from mid-July to mid-October). Soil water use efficiency (WUE_S) was calculated as follows:

$$WUE_S = \frac{\text{yield}}{\text{SWC}} \qquad (5)$$

where yield is as per Formula (1).

2.4. Statistical methods

Statistical analysis was performed using ANOVA (SAS Institute, 1989). Multiple comparisons were conducted with least significant difference (LSD) at the 0.05 probability level. Mean values are reported in tables and figures.

3. Results

3.1. Rainfall and growing periods of crops

Most rainfall occurred between July and September (Fig. 2). The highest rainfall occurred in 2002 (381 mm) and 2005 (378 mm) while 2004 had the lowest rainfall (202 mm). Rainfall in 2001 and 2003 was normal with 287 and 325 mm, respectively (Fig. 2). Alfalfa had the longest growing period of ~200 days followed by millet (~165 days), corn (~155 days), potato (~155 days), pea (~130 days) and spring wheat (~125 days) (Fig. 2). Rainfall in the alfalfa growing period accounted for approximately 90% of total annual rainfall. Corresponding values for millet, corn, and potato were about 80%; and spring wheat and pea were about 57% (Fig. 2).

3.2. Aboveground biomass and crop yield

Forage yield of 1- to 15-year-old alfalfa stands is illustrated in Fig. 3. In the first 6 years, forage yield increased with increasing stand age, peaking in the 7th year, followed by a fluctuating decrease over the next 8 years (Fig. 3). Maximum forage yield profit of alfalfa occurred in the 9th year.

Annual average aboveground biomass of alfalfa was significantly lower in A1–5 than in CK, MWLPL, MCCWW and MLWCC ($P < 0.05$) (Table 2). Although aboveground biomass of alfalfa in RA1–5 was more than A1–5, it was still significantly lower than CK ($P < 0.05$). Annual average aboveground biomass in MFPLP was the lowest of the four rotations after 10-year-old alfalfa ploughed. There was no significant difference in the annual average aboveground biomass between MWLPL and MLWCC (Table 2).

Yield of spring wheat in MWLPL was not significantly different from CK in 2002. This was also the case for peas between MFPLP and CK in 2003 and 2005. No significant difference for potato yield was observed between CK and MFPLP in 2004. Yields of spring wheat in MWLPL in 2002 and MLWCC in 2003 were significantly higher than that of MCCWW in 2004 and 2005. Yield of pea in MFPLP in 2005 was significantly higher than in 2003 and in MWLPL in 2004. Yield of corn in MCCWW in 2002 was significantly higher

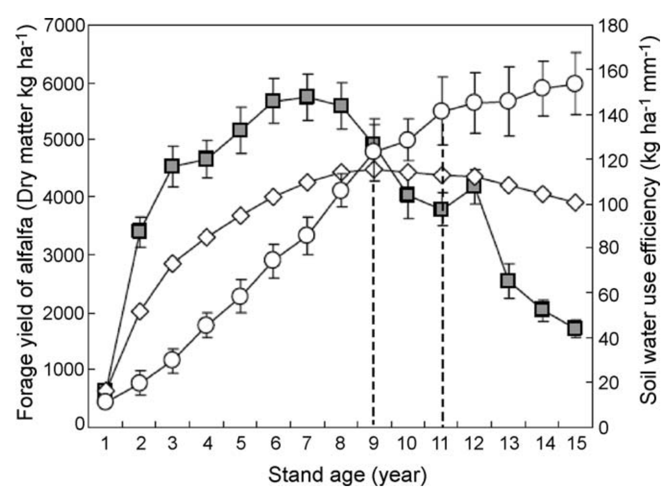

Fig. 3. Forage yield (■), annual average alfalfa yield (AY) (□) (calculated from Formula (1)) and annual soil water use efficiency (○) of 1- to 15-year-old alfalfa stand using conventional alfalfa cultivation: A1–5 (1- to 5-year-old stand), A6–10 (6- to 10-year-old stand) and A11–15 (11- to 15-year-old stand) together represented the 1- to 15-year-old alfalfa stand. The two vertical broken lines represent average yield for the 9-year-old stand and soil water use efficiency for the 11-year-old stand.

Table 3
Crop yield (kg ha^{-1}) and water use efficiency ($WUE_{Y/ET}$, kg ha^{-1} mm^{-1}) of crops in different crop treatment systems from 2001 to 2005.

Crop	Year	Treatments	Yield	$WUE_{Y/ET}$
Wheat	2002	CK	2937.2 a	10.8 b
	2002	MWLPL	2935.3 aA	12.5 aA
	2003	MLWCC	2037.3 B	11.0 AB
	2004	MCCWW	1791.5 C	10.7 B
	2005	MCCWW	1728.4 C	10.2 B
Pea	2003	CK	1425.0 b	6.9 b
	2003	MFPLP	1524.0 bB	8.4 aA
	2004	MWLPL	1273.4 C	7.3 B
	2005	CK	1648.2 a	7.3 b
	2005	MFPLP	1614.7 aA	8.2 aA
Corn	2002	MCCWW	3372.8 A	11.2 A
	2003	MCCWW	2586.6 B	12.1 A
	2004	MLWCC	2657.4 B	10.6 A
	2005	MLWCC	2586.4 B	11.8 A
Potato	2002	MLWCC	3574.5 A	13.8 B
	2003	MWLPL	3191.3 B	16.5 A
	2004	MFPLP	3603.3 aA	16.4 aA
	2004	CK	3498.3 a	13.9 b
	2005	MWLPL	3048.4 B	14.4 B

Values within a column followed by the same lower-case letter – means the yield of a certain crop does not differ significantly ($P < 0.05$) between in rotations treatments (MWLPL, MCCWW, MLWCC and MFPLP) and in CK in 1 year; by the same upper-case letter – means the yield of a certain crop between different rotations not differ significantly at $P < 0.05$ for one crop between years in the rotations. CK denotes conventional crop system. M is millet (*Setaria italica* Beauv), W is wheat (*Triticum aestivum* L.), L is potato (*Solanum tuberosum* L.), P is pea (*Pisum sativum* L.), C is corn (*Zea mays* L.) and F is fallow.

Table 4
Annual average aboveground biomass, $WUE_{B/ET}$ (in terms of aboveground biomass and evapotranspiration) of crops in different treatments from 2001 to 2005.

Plants	Annual aboveground biomass (kg ha^{-1})	$WUE_{B/ET}$ (kg ha^{-1} mm^{-1})
Wheat	5390.2 b	24.4 b
Pea	4333.0 c	21.3 c
Potato	6168.3 a	28.0 a
Corn	5629.6 b	23.0 b
Millet	4503.7 c	19.9 c
Alfalfa	4393.3 c	14.8 d

Values in the same column followed by the same letter are not significantly different at $P < 0.05$.

than in other treatments. The tuber yields of potato in MLWCC in 2002 and MFPLP in 2004 were significantly higher than that of MWLPL in 2003 and 2005 (Table 3).

The order of annual average aboveground biomass (kg ha^{-1}) was potato (6168.3) > corn (5629.6) > spring wheat (5390.2) > millet (4503.7) > alfalfa (4393.3) > pea (4333.0) (Table 4).

3.3. Soil water content

Soil moisture in the upper 500 cm layer in alfalfa using conventional cultivation (1- to 15-year-old alfalfa) decreased as stand age increased, except for topsoil moisture that was strongly affected by precipitation (Fig. 4). Soil moisture decreased rapidly after 3 years of conventional alfalfa cultivation. Moreover, soil water content below 140 cm was lower than permanent wilting coefficient (PWC, 6.2%) after 5 years of conventional alfalfa cultivation.

Soil water storage from 0 to 500 cm recognized as a function of stand age (from 1 to 15 years) in conventional alfalfa cultivation is shown in Fig. 5. Before sowing alfalfa, approximately 700 mm water was stored; however, after 3 years, soil water storage decreased to approximately 400 mm, and from the 3rd to 15th year, slowly decreased to 100 mm.

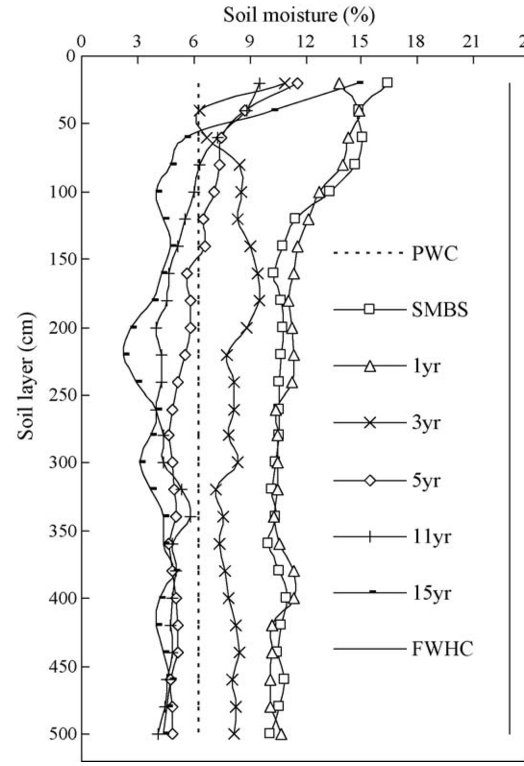

Fig. 4. Profile of soil moisture in the 0–500 cm layer at 20 cm intervals in the conventional alfalfa cultivation system with different stand ages. SMBS denotes Soil Moisture Before Alfalfa Sowing; 1 yr denotes 1-year-old stand, 3 yr denotes 3-year-old stand, and so on. PWC denotes permanent wilting coefficient (6.2%); and FWHC denotes field water holding capacity (maximum capillary held water, 22.9%).

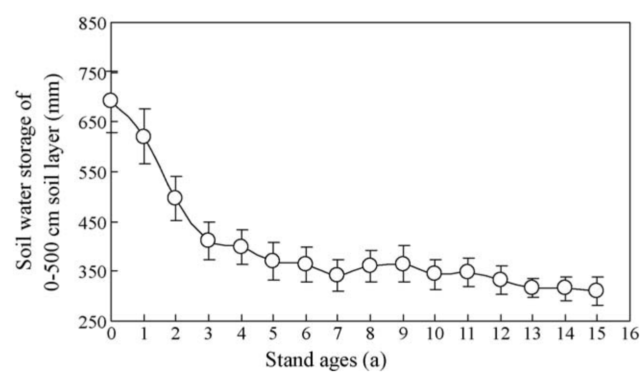

Fig. 5. Soil water storage in 0–500 cm soil layer as a function of stand age in the conventional alfalfa cultivation system.

The soil moisture profile in the upper 500 cm layer at 20 cm intervals in different crop systems at the beginning and end of the experiment is shown in Fig. 6. Soil moisture remained balanced in the CK system after five seasons; in the top 150 cm it decreased with increasing soil depth, but remained the same (10–11%) below 150 cm.

3.4. Water use efficiency

$WUE_{Y/ET}$ for spring wheat in 2002, peas in 2003 and 2005, and potatoes in 2004 was significantly lower in CK than in the rotations ($P < 0.05$) (Table 3). The order of $WUE_{B/ET}$ (kg ha^{-1} mm^{-1}) was potato (28.0) > spring wheat (24.4) > corn (23.0) > pea (21.3) > millet (19.9) > alfalfa (14.8) (Table 4). WUE_T was significantly lower in conventional alfalfa stands than other treatments during the 5-year experiment ($P < 0.05$) (Table 5). WUE_S in conventional alfalfa stands increased dramatically as stand age

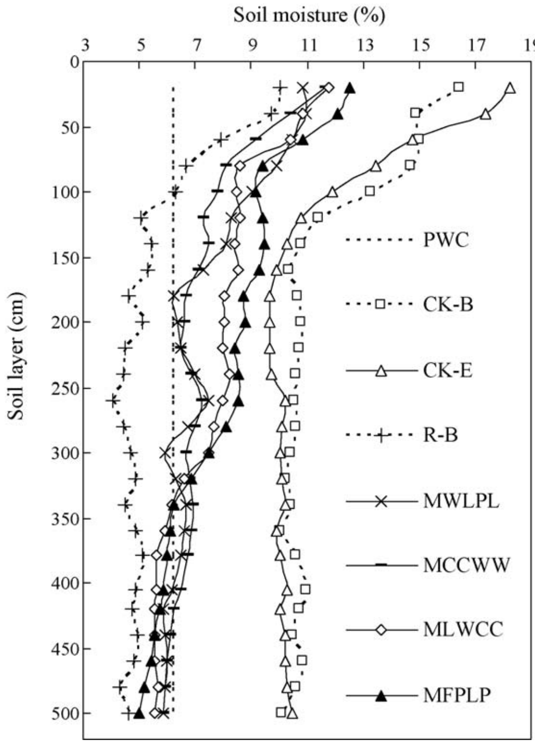

Fig. 6. Profile of soil moisture in the 0–500 cm layer at 20 cm intervals in different crop rotation systems at the beginning and end of the experiment. PWC denotes permanent wilting coefficient (6.2%); R-B denotes soil moisture at beginning of the experiment in rotation system after ploughed alfalfa (R); CK-B denotes soil moisture at beginning of the experiment in conventional crop system; CK-E denotes soil moisture at end of the experiment in conventional crop system; MWLPL, MCCWW, MLWCC and MFPLP denote soil moisture in different crop sequences of RS at end of the experiment.

Table 5
Yearly biomass water use efficiency ($WUE_{B/ET}$, kg ha^{-1} mm^{-1}) and total biomass water use efficiency (WUE_T, kg ha^{-1} mm^{-1}) of plants in systems with different treatments from 2001 to 2005.

Systems	2001	2002	2003	2004	2005	WUE_T
A1–5	A 2.9	A 8.1	A 12.2	A 22	A 17.4	8.8 e
A6–10	A 19.9	A 20.8	A 18.9	A 21.8	A 16.5	11.3 d
A11–15	A 14.5	A 10.2	A 9.2	A 8.6	A 7.3	8.0 e
RA1–5	A 3.6	A 11.3	A 17.0	A 30.6	A 23.5	12.1 c
CK	P 20.1	W 23.5	P 21.0	L 28.1	P 19.4	15.4 b
MWLPL	M 19.9	W 29.1	L 29.5	P 20.4	L 27.5	16.2 a
MCCWW	M 19.9	C 22.5	C 25.6	W 26.4	W 14.4	15.2 b
MLWCC	M 19.9	L 23.0	W 28.6	C 22.1	C 21.6	16.0 a
MFPLP	M 19.9	F	P 24.4	L 32.1	P 22.3	11.9 c

A1–5, A6–10 and A11–15 denote conventional alfalfa cultivation system with 1- to 5-, 6- to 10- and 11- to 15-year-old stands, respectively; RA1–5 denotes ridge and furrow alfalfa system with 1- to 5-year-old stands; CK denotes conventional crop rotation; MWLPL, MCCWW, MLWCC and MFPLP denote different crop sequence rotations after ploughing 10-year-old alfalfa. M is millet (*Setaria italica* Beauv), W is wheat (*Triticum aestivum* L.), L is potato (*Solanum tuberosum* L.), P is pea (*Pisum sativum* L.), C is corn (*Zea mays* L.) and F is fallow. Values in WUE_T (in terms of the total ET and total aboveground biomass during the trial in one treatment) column followed by same letter are not significantly different at $P < 0.05$.

increased up to the 11th year, but leveled off from the 12th to 15th year (Fig. 3).

4. Discussion

4.1. Forage yield and stand duration of alfalfa

Alfalfa has a much higher water requirement than other crops (Saeed and Ei-Nadi, 1997; Blad and Rosenberg, 1976) and is able to take up water from deep in the soil (Wan et al., 2008). An Australian study found that soil profiles under lucerne-based perennial pastures (also containing annual medic and Wimmera ryegrass) remained consistently drier throughout the year compared with continuous annual cropping (McCallum et al., 2001). Alfalfa is often planted perennially in the Loess Plateau, which leads to the desiccation of the deep soil layer (Yang et al., 2006). Therefore, the long alfalfa stand duration may deplete available soil water, which would negatively impact production of subsequent crops (Li, 2002). However, alfalfa's profit strongly depends on its stand duration considering seed cost and forage yield dynamic. The shorter alfalfa stand duration is unlikely to be profitable for farmers. Therefore, the question is how to balance soil water use and profit to determine the optimal duration of an alfalfa stand.

In the past, local farmers decided the life of an alfalfa stand and the subsequent crop sequence based on their needs at the time, which sometimes required supplementing soil water resulting in less profit. Researchers have differing opinions on the optimal duration of an alfalfa stand in the semiarid Loess Plateau region. For example, Du and Qu (1994) found that stand ages of the perennial legumes, alfalfa and erect milk vetch (*Astragalus adsurgens* Pall), should be less than 3 years where rainfall was ~300 mm, since forage yield decreased significantly after the 3rd year. Zhang et al. (2004) reported that alfalfa should be ploughed for 4–5 years to obtain high forage yields in the Plateau where rainfall was 502 mm. Other studies suggested 6- to 8-year-old alfalfa stands on 400 mm of rainfall (Du et al., 1999b) and 10-year-old stands on 445 mm of rainfall in the Plateau (Cheng et al., 2005). Our results suggested that the appropriate stand age of alfalfa should be ~9 years considering the maximum average yield, even though forage yield peaked in the 7th year (Fig. 3). Considering water use efficiency alone, the optimal duration of an alfalfa stand should be more than 11 years because high WUE_S occurred from 11 to 15 years (Fig. 3).

4.2. Water-harvesting technique for alfalfa cultivation

The water-harvesting technique (RA1–5) had benefits for planting alfalfa in the semiarid loess region, although it required extra labor and investment in mulching films. It significantly increased forage yield and WUE_T in the first 5 years compared with conventional cultivation (CK) (Jia et al., 2006), but aboveground biomass and WUE_T of alfalfa were still significantly lower in RA1–5 than in CK. Nevertheless, stand duration of alfalfa in the water-harvesting system remains to be determined.

4.3. Water use efficiency of alfalfa

Considering the limitation of rainfall in the semiarid Loess Plateau of northwest China, water use efficiencies are extremely important for productivity of arable land. Alfalfa requires more water than other crops (Blad and Rosenberg, 1976). In our study, WUE_T of alfalfa was lower in both conventional cultivation and the water-harvesting system than in the conventional crop rotation (Table 4). From an economic perspective, alfalfa is still an ideal forage for using water resources in semiarid areas compared with spring wheat, pea, potato and corn, because of its importance for animal husbandry in crop–livestock mixed farming. The cover time of alfalfa was longer than other crops (Fig. 2), which may effectively reduce wind erosion in spring and autumn in this region (Hu et al., 2002). Moreover, while total biomass of alfalfa was the same as wheat, total nitrogen was 2–3 times higher (Shen et al., 2004).

4.4. Soil water content profile

While soil water under conventional cultivation was kept in balance, it dramatically decreased as stand age of alfalfa increased (Fig. 5). Alfalfa may negatively affect growth of subsequent crops due to water consumption in the deep soil layer (Du et al., 1999a; Li, 2002; Liu et al., 2000). Therefore, restoring soil moisture and soil water condition after long-term alfalfa stands was recommended (Ridley et al., 2001; Li and Shao, 2001; Yang and Shao, 2000). On the north edge of the Loess Plateau where annual rainfall is 440 mm, 25% of soil moisture could be restored during the first winter fallow after 10 years of alfalfa cultivation. It took 4 or 5 years to restore water condition in the top 500 cm of soil after 8 years of alfalfa using different models to predict (Du et al., 1999a). In this study, soil water content gradually increased during crop growth in crop sequence rotations after alfalfa was ploughed. The degree of soil water recovery in these rotations (MWLPL, MCCWW, MLWCC and MFPLP) was derived from soil water comparisons with the conventional crop rotation (CK). Rotation MFPLP, which had 1 year of fallow, had the best capacity to restore soil water. But WUE_T was significantly lower than the other rotations. In addition, fallow appeared to enhance erosion of water and wind in the semiarid Loess Plateau. Planting annual crops immediately after alfalfa was ploughed did not significantly affect soil water restoration in following years (Wang et al., 2003). Therefore, planting annual crops after alfalfa is feasible to restore soil water content, but longer recovery time is required to obtain better soil moisture.

4.5. Crop sequence after alfalfa

Crop yield and water use efficiency are two important criteria for determining which cropping system to use in the Loess Plateau. Biomass productivity is also crucial due to the lack of water resources and low living standards. Farmers not only need grain for their food, but they also need crop straw to feed animals, improve soil quality, for household fuel and even for construction materials. Furthermore, the contribution of biological N_2 fixation to the N economy of these different systems has been strongly linked with biomass production by legume components of pastures in the cropping sequence (McCallum et al., 2000). Total aboveground biomass was higher in MWLPL and MLWCC than MCCWW and MFPLP, and WUE_T was higher in these two systems than in the CK system. A number of factors need to be considered when choosing the subsequent crop rotation, such as economic benefit, lifestyle, labor, custom and so on; if biomass productivity and water use efficiency were the only factors considered, the best subsequent crop rotations in the Loess Plateau after 10 years of alfalfa would be millet–wheat–potato–pea–potato or millet–corn–corn–wheat–wheat.

5. Conclusion

The results of this study led to the following conclusions: (1) average alfalfa yield peaked in the 9th year in terms of whole growth; alfalfa more than 11 years old had higher soil water use efficiency than younger alfalfa; (2) both forage yield and water use efficiency of alfalfa using the water-harvesting technique were higher than local conventional methods; (3) 1 year of fallow was not necessary after ploughing a 10-year alfalfa stand in order to plant annual crops; (4) yield of certain crops in subsequent crop sequence rotations was not significantly different from yield in CK; (5) after 10-year-old alfalfa was ploughed, soil water content gradually increased when subsequent annual crops served as a ground cover; (6) although MWLPL and MLWCC benefited more in relation to aboveground biomass than MCCWW and MFPLP, further consideration of the subsequent crop rotation is needed.

Acknowledgements

This study was supported by '973' program (2007CB106804), NSFC (3070014), Education Ministry of China RFDP & SRFDP (20060730027, 20070730049) and Crawford Fund Training Award (07/08-12/08).

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