Available online at www.sciencedirect.com

ScienceDirect

Europ. J. Agronomy 28 (2008) 485–492

European Journal of Agronomy

www.elsevier.com/locate/eja

Switchgrass and milkvetch intercropping under 2:1 row-replacement in semiarid region, northwest China: Aboveground biomass and water use efficiency

B.C. Xu[a,b,*], F.M. Li[a,b], L. Shan[a]

[a] State Key Laboratory of Soil Erosion and Dryland Farming on Loess Plateau, Institute of Soil and Water Conservation, Chinese Academy of Sciences and Ministry of Water Resources, Northwest A & F University, Yangling, Shaanxi Province 712100, PR China

[b] MOE Key Laboratory of Arid and Grassland Ecology, School of Life Science, Lanzhou University, Lanzhou, Gansu Province 730000, PR China

Received 3 August 2007; received in revised form 9 November 2007; accepted 20 November 2007

Abstract

An experiment was conducted to investigate the aboveground biomass and water use characteristics of switchgrass (*Panicum virgatum*) and milkvetch (*Astragalus adsurgens* Pall.) in solecropping and 2:1 row-replacement intercropping in semiarid region on the Loess Plateau of China. Field experiments were conducted during the growing seasons from 2001 to 2005. The aboveground biomass production, considering the sum of dry litter and standing parts, was measured every year at the end of growth season. The aboveground biomass, soil water content dynamics, water use efficiency (WUE), actual yield loss (AYL), land equivalent ratio (LER) and aggressivity (A) were compared under sole and intercropping. Intercropping reduced the biomass production of the two component plants, compared with their respective pure stands. Milkvetch was the dominant species in the intercropping in 2001–2004, however its aggressivity to swichgrass decreased gradually as the growth years progressed, and in 2005 it became the dominant in the mixture. The equivalent biomass production under intercropping and whole WUE of mixture were significantly lower than their respective solecropping, although LER of the mixture was equal or bigger than 0. It is concluded that there was no advantage of growing switchgrass and milkvetch under 2:1 row-replacement in semiaird hilly-gully region of Loess Plateau if total biomass production is the primary purpose.

Keywords: Aboveground biomass; Actual yield loss (AYL); Aggressivity (A); Intercropping; Land equivalent ratio (LER); Milkvetch; Switchgrass

1. Introduction

Intercropping is the practice of growing two or multiple crops simultaneously in a given space, and it has been used widely to improve the match crop demands to available sunlight, water, nutrients and labour (Banik and Bagchi, 1993; Fuentes et al., 2003). In arid or semiarid regions, intercropping can improve the conservation of water and water use efficiency (Fortin et al., 1994). In intercropping systems involving a legume and a non-legume, part of the nitrogen fixed in the root nodule of the legume may become available to the non-legume component (Li et al., 2006). Therefore productivity normally is potentially enhanced by the inclusion of a legume in the cropping system (Maingi et al., 2001). Legumes, both pure stand and intercropped with cereals, have been advocated not only for yield augmentation but also for maintenance of soil health, particularly in degraded soil (Banik and Bagchi, 1993). Intercropping has long been used as one dryland farming practice in China, particularly in rain-fed areas (Shan and Chen, 1993; Tong, 1994; Zhang and Li, 2003), and mainly the crops such as maize and alfalfa (Chen et al., 2004), maize and soybean (Ma et al., 1994), wheat and bean (She et al., 2003) are intercropped, and also in some trees (Pei et al., 2000).

Milkvetch (*Astragalus adsurgens* Pall.) has been used in China as palatable forages and widely cultivated in diverse environments in arid and semiarid areas of northern China (Shan and Chen, 1993). Switchgrass (*Panicum virgatum*) is a native warm-season grass in the central and northern America, it can be used as forage and hay crop and for soil and water conservation (Sanderson et al., 1999; Xu et al., 2005;

* Corresponding author at: State Key Laboratory of Soil Erosion and Dryland Farming on Loess Plateau, Institute of Soil and Water Conservation, Chinese Academy of Sciences and Ministry of Water Resources, Northwest A & F University, Yangling, Shaanxi Province 712100, PR China. Fax: +86 29 87012210.

E-mail address: Bcxu@ms.iswc.ac.cn (B.C. Xu).

1161-0301/$ – see front matter © 2007 Elsevier B.V. All rights reserved.
doi:10.1016/j.eja.2007.11.011

Ichizen et al., 2005). As an introduced herbaceous grass, switchgrass has a good ecological and biological performance not only at the low but the hilly land in loess hilly-gully region (Li et al., 1999; Xu et al., 2005). Considerable research has been conducted in milkvetch and switchgrass for biomass production and water use characteristics in different regions under solecropping (Shan and Chen, 1993; Xu et al., 2005). However, little quantitative information on the aboveground biomass production and water use efficiency in milkvetch and switchgrass under intercropping has been reported. In semiarid loess area of China, there always exists the problems of sole grass variety and single cropping structure in artificial grasslands (Shan and Chen, 1993). Approaches towards the settlement of these problems include strengthening the research and selecting different species and cropping patterns appropriate to the environments. Therefore, the objective of this study was to investigate biomass production and water use of switchgrass and milkvetch under 2:1 row-replacement intercropping with respective solecropping, considering the changes with growth years. The results will be important for evaluating such intercropping pattern in semiarid region on the Loess Plateau of northwest China.

2. Materials and methods

2.1. Site description

Field experiments were conducted at the research farm of Ansai Research Station (ARS), Chinese Academy of Science (CAS), Shaanxi Province (36°51′30″N; 109°19′23″E; elev. 1068 m). It is located in the semiarid region of northwest China with mean annual rainfall of 540 mm. The average annual temperature is 8.8 °C, with extremes of −6.9 °C in January and 22.6 °C in July. The loessial soil is characterized as silt loam, highly calcareous in nature (pH 8.4), deep (50–80 m), low organic carbon (0.55%), low available N (50 mg kg^{-1}), low available P (1.7 mg kg^{-1}), and high in available K. Agriculture is rain-fed and the main crops are foxtail millet (*Setaria italica*), bean (*Glycine*) and potato (*Solanum tuberosum*). The cropping systems are annual spring or summer crop-winter fallow.

The long-term (1951–2000) average annual rainfall for the site is about 537.7 mm, while annual rainfall recorded during 2001, 2002, 2003, 2004 and 2005 was 515.2, 541.1, 577.8, 509.1 and 541.1 mm, respectively. In the area, rainfall of the growing season from April to October accounts for 85–95% of annual total, and July to September accounts for 60–80%, which is always considered the rainy season (Shan and Chen, 1993). During the experiment period, the growing season rainfall accounted for 93.0%, 94.2%, 89.3%, 97.2% and 99.2% of total annual rainfall from 2001 to 2005, and rainfall from July to September accounted for 68.2%, 40.88%, 59.5%, 72.9% and 69.2%, respectively (Fig. 1). For the period 1951–2000 rainfall contribution for the two periods averaged at 93.30% and 60.48%, respectively. The rainfall amount and pattern, during rainy seasons of 2002 and 2003 was lower than 50-year average, and in 2003 rainfall during growing season was higher than 50-year average.

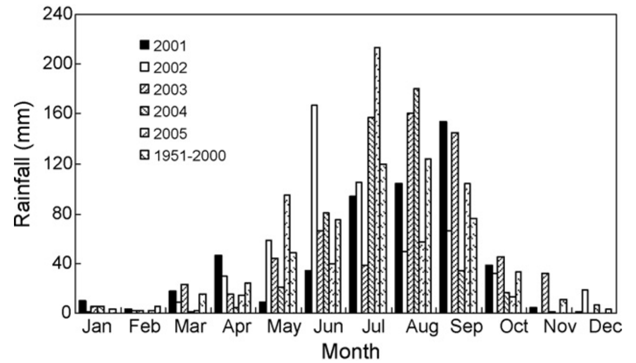

Fig. 1. Monthly rainfall distribution in each experimented year and 50-year (1951–2000) mean.

2.2. Field experimental design

The experimental field was on a lowland loess soil previously planted with apple trees (*Malus domestica*) between 1992 and 1997. Apple trees were cut down in October 1997 and the field was prepared for this experiment in late autumn of 2000. The experiments were conducted in five consecutive years from 2001 to 2005. The species used in the experiment included switchgras and milkvetch, and switchgrass is a perennials herbaceous grass while milvetch is a perennials legume. The varieties used were Alamo for switchgrass and super early vetch for milkvetch. The sowing was done in early May of 2001. The seeds of these species were obtained from the experimental fields of ARS in the autumn of 1999, and then were kept in dry places at laboratory in the dark under room temperature before use. All the seed germination rates were > 85% within 7 days using common tissue method at 25 °C.

Twelve experimental plots of 7 m × 6 m (three main treatments such as monoculture of switchgrass and milkvetch, respectively, and mixture and four replicates) were arrangement in a randomized complete block design with a 15 cm distance between the plots. The seeds of switchgrass and milkvetch were dot-sowed by hand, at the seed rate of 7.5 kg ha^{-1} for switchgrass and 15 kg ha^{-1} for milkvetch both under solecropping and intercropping, and the seeding methods were according to the recommendations for the two species (Shan and Chen, 1993; Li et al., 1999). Switchgrass and milkvetch were grown as monoculture and intercropped in 2:1 row ratio. Row spacing was 30 cm, and plant space within row was 15 cm (Fig. 2). The rows are parallel with the 6 m border side, so each plot contains 11 rows of milkvetch and 22 rows of switchgrass. Fertilizers N, P and K were applied prior to plow the plots at a rate of 60 kg N ha^{-1}, 45 kg P ha^{-1} and 45 kg K ha^{-1}. The field management such as wild grass removing and cultivation was conducted according to the methods used in farmland in the area. During the experimental period, there was no irrigation and any other form of water supplement.

2.3. Shoot sampling

Aboveground biomass samples were taken every year at the end of growth season and were determined by cutting the

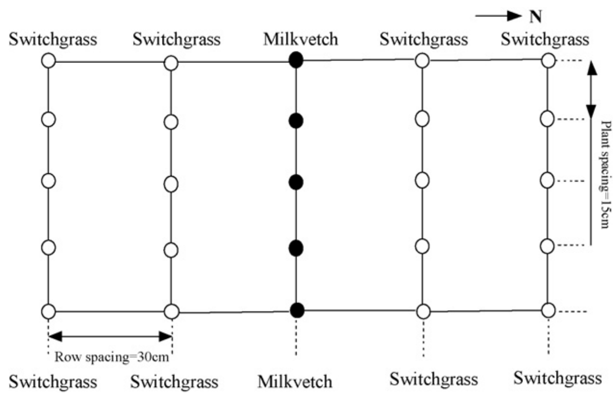

Fig. 2. Planting pattern of switchgrass and milkvetch in intercropping system.

plants with hand-held shears to ground level. For each treatment, the measurement was made on three sampling areas randomly chosen (three replications) from the four plots. The sampling areas were not used twice. To reduce the edge effect, the samples were taken about three rows from the plot border. Total aboveground biomass of each species either solecropped or intercropped was considered the sum of dry litter and standing parts. For solecropping, standing aboveground biomass parts were sampled from 50 cm section in each of three proximate rows. For intercropping, two sections of switchgrass and one section for milkvetch were chosen and harvested. The litter was collected after aboveground biomass sampled and separated into switchgrass and milkvetch for intercropping. Plant samples were dried in a forced draft oven at 65 °C for 24 h and weighed. The equivalent biomass production of switchgrass or milkvetch could be obtained according to the sample results and their respective occupying area under intercropping, and the actual biomass production of intercropping was calculated as: switchgrass equivalent biomass production under intercropping × 2/3 + milkvetch equivalent biomass production under intercropping × 1/3 (Table 1). All the experimental plots were harvested after sampling every year.

2.4. Soil water content

Soil water content measurements were made using soil core sampler and gravimetric method (Ø4 cm cores) before and after the growth season every year. The sampling site was at the center of two rows in solecropping, and for intercropping it was at the center of switchgrass and milkvetch rows. The soil water content (ω%) was determined from the analysis of soil gravimetric water content where soil sample was dried at 105 °C for 24 h, and which was calculated as follows:

$$\omega\,(\%) = \frac{(W_\mathrm{w} - W_\mathrm{d})}{W_\mathrm{d}} \times 100 \quad (1)$$

where W_w and W_d were the wet and dry weight mass of soil samples. Considering the initiation and development of grasslands (Shan and Chen, 1993), the soil water content was measured down to 3 m in 2001 and 2002 but extended to 5 m from 2003 to 2005. Soil bulk density (ρ) is 1.1 g cm^{-3} for 0–20 cm layer and 1.3 g cm^{-3} for below 20 cm, respectively (Shan and Chen, 1993; Yang and Shao, 2000). Soil water storage (W) at each measured time was calculated as: $W = 10 \times H$ (soil depth) (cm) $\times \rho$ (g cm^{-3}) $\times \omega$ (%). Evapo-transpiration (ET) was calculated as the total rainfall during the crop growing season plus the difference in soil water between two soil water content measurements (Li et al., 2003). We assumed that there were no runoff and subsurface drainage in the lowland farmland (Shan and Chen, 1993), so they are not considered in calculation of ET. Rainfall was recorded at a weather station about 100 m from the experimental fields. Water use efficiency (WUE) was defined as the amount of biomass produced per unit volume of water evapo-transpired (Fuentes et al., 2003).

2.5. Competition indices

There are a lot of indicators of productivity and species interaction widely used in intercropping research (Connolly et al., 2001b; Ghosh, 2004). Three competition indices were introduced for the intercropped system in this study. They were: actual yield loss, which is the sum of relative yields decrease per unit of sowing proportion (the sum refers to the specific crops); land equivalent ratio, which is the sum of the relative yields increase (the sum refers to the specific crops) and aggressivity, the difference in relative yield increase per unit of occupied area between the milkvetch and the grass.

Actual yield loss (AYL) is the proportionate yield loss or gain of intercrops in comparison to the respective sole crop, i.e.

Table 1
Yearly biomass production (g m^{-2}) of switchgrass and milkvetch in monocropping and intercropping*

Year	2001	2002	2003	2004	2005	Mean ± S.E.
Switchgrass (solecropped)	305.7 d (d)	1655.4 a (b)	1252.4 c (b)	1342.5 c (a)	1460.3 b (a)	1203.3 ± 18.6 (a)
Milkvetch (solecropped)	357.1 e (c)	1824 a (a)	1355.5 b (a)	1137.3 d (b)	1248.3 c (b)	1184.4 ± 8.1 (b)
Switchgrass + milkvetch (2:1)[a]	391.8 d (b)	743.4 c (d)	838.1 b (d)	1210 a (b)	874 b (c)	811.4 ± 11.2 (c)
Switchgrass (intercropped)[b]	273.7 e (e)	478 d (e)	743.4 c (e)	1311.6 a (a)	1140.2 b (c)	789.4 ± 0.7 (d)
Milkvetch (intercropped)[b]	628 c (a)	1274.1a (c)	1027.4 b (c)	1006.6 b (c)	341.7 d (d)	855.6 ± 41.2 (c)
Switchgass intercropped (%)	46.57	42.87	59.14	72.27	86.97	61.56
Milkvetch intercropped (%)	53.43	57.13	40.86	27.73	13.03	38.44

* Values within a row followed by different letters are significantly different ($P < 0.05$), and values within a column with different small letters in bracket are also significantly different ($P < 0.05$). S.E. means standard error of mean.
[a] Biomass production of switchgrass and milkvetch under intercropping.
[b] Equivalent aboveground biomass production under intercropping.

it takes into account the actual sown proportion of the component crops with its pure stand (Banik et al., 2000), which was calculated as follows:

$$\mathrm{AYL} = (\mathrm{AYL_a} + \mathrm{AYL_b}) = \left\{\left[\frac{(Y_{ab}/Z_{ab})}{(Y_{aa}/Z_{aa})}\right] - 1\right\} + \left\{\left[\frac{(Y_{ba}/Z_{ba})}{(Y_{bb}/Z_{bb})}\right] - 1\right\} \quad (2)$$

where Y is the biomass production per unit area and Z is the sown proportion, subscripts aa and bb refer to pure stands (sole crops) of species A (milkvetch) and B (switchgrass), and ab and ba refer to intercrops. Partial actual yield loss $\mathrm{AYL_a}$ and $\mathrm{AYL_b}$ represent the relative decrease of yield per sowing proportion in mixture of species milkvetch and switchgrass compared to corresponding yield in monoculture. A measure of competition is to add these values for respective crop, and therefore AYL is the sum of $\mathrm{AYL_a}$ and $\mathrm{AYL_b}$. The sign (positive or negative) of the AYL score gives a quantitative assessment of advantage/disadvantage accrued under any intercrop situation when the main objective is to compare yield on a per plant basis (Banik et al., 2000). Z_{ab} and Z_{ba} represent the sowing proportion of milkvetch and switchgrass in mixture, and which is 1/3 and 2/3, respectively. Z_{aa} and Z_{bb} represent the sowing proportion of milkvetch and switchgrass in monoculture, and the value of each is 1.0.

The land equivalent ratio (LER) gives an accurate assessment of the greater biological efficiency of the intercropping situation and was calculated as follows (Willey, 1979):

$$\mathrm{LER} = (\mathrm{LER_a} + \mathrm{LER_b}) = \left\{\left(\frac{Y_{ab}}{Y_{aa}}\right) + \left(\frac{Y_{ba}}{Y_{bb}}\right)\right\} \quad (3)$$

in which $\mathrm{LER_a}$ and $\mathrm{LER_b}$ are the partial LER of milkvetch and switchgrass, respectively. The land equivalent ratio (LER) is defined as the relative land area growing sole crops that is required to produce the yields achieved when growing intercrops (Hauggaard-Nielsen et al., 2006). Y_{aa} and Y_{bb} denote yields of milkvetch and switchgrass in sole culture and Y_{ab} and Y_{ba} are the corresponding yields in mixture. LER values greater than 1.0 are considered advantageous of mixture as a whole on biomass production compared to the monoculture.

Aggressivity (A) is another index that represents a simple measure of how much the relative yield increase in 'a' crop is greater than that of 'b' crop in an intercropping system (Ghosh, 2004). It measures the interspecies competition in intercropping by relating the yield changes of the two component crops (Willey and Rao, 1980). In this paper, we employed the aggressivity concept to evaluate the difference between the extent to which intercropped species 'a' (milkvetch) and 'b' (switchgrass) vary from their respective monocropping aboveground biomass:

$$A_{ab} = \frac{Y_{ab}}{Y_{aa} \times Z_{ab}} - \frac{Y_{ba}}{Y_{bb} \times Z_{ba}} \quad (4)$$

in which the meanings of the variables (e.g. Y_{ab}, Y_{ba}, Y_{aa}, Y_{bb}, Z_{ab} and Z_{ba}) are same as defined in Eqs. (2) and (3). A_{ab} is regarded the difference between the relative change of yield of milkvetch in mixture and the corresponding value for switchgrass. The yield is expressed per unit of occupied area so the yield refers to the resource base in some sense, for instance the amount of received solar radiation and the soil nutrients and water. If $A_{ab} = 0$, both species are equally competitive, and if A_{ab} is positive then milkvetch is the dominant species, while A_{ab} is negative means milkvetch is the dominated species in intercropping (Li et al., 2001).

2.6. Statistical analysis

The data obtained were analyzed by standard ANOVA using SPSS 11.0. The paired-samples t-test was used for comparison between years or treatments ($P = 0.05$). Mean values were reported along with their standard errors.

3. Results

3.1. Aboveground biomass

Although the litter was measured carefully during the experiment, it only accounted for not more than 5% of the total aboveground biomass production, and there were no significant difference between solecropping and intercropping calculated as equivalent biomass production, thereby it was not explained here separately. There were no common trends in aboveground biomass production with the growth year for milkvetch and switchgrass under sole or intercropping, but the biomass for each treatment was the lowest in 2001 (Table 1). Sole switchgrass or milkvetch had the highest biomass production in 2002, while it was 2004 for intercropping. Except the establishment year of 2001, the biomass contribution of switchgrass to intercropped stands increased gradually from 42.87% in 2002 to 86.97% in 2005, while milkvetch decreased from 57.13% to 13.03% (Table 1). Under solecropping milkvetch aboveground biomass production was significantly higher than switchgrass in the 2001–2003, but reversely in the later 2 years. The biomass production in a descending order for the 5-year mean was sole switchgras, sole milkvetch and switchgrass and milkvetch intercropped in 2:1 row-replacement.

The equivalent biomass production of milkvetch and switchgrass under intercropping was estimated according to their occupied areas. Results showed that the equivalent biomass of milkvetch was significantly higher than solecropping only in 2001, but in the other 4 years solecropping was significantly higher than under intercropping ($P < 0.05$). Except in 2004 there was no significant difference in equivalent biomass of switchgrass between intercropping and solecropping, the later was significantly higher that the former in the other 4 years. The equivalent biomass production of milkvetch was significantly higher than that of switchgrass during 2001–2003 and reversely in 2004 and 2005, which was same as in monoculture. The production stability of milkvetch under solecropping was higher than under intercropping, but switchgrass was more stable under intercropping (Table 1).

3.2. Soil water content

The yearly changes of mean soil water content in the three grasslands were similar before the end of growth season in

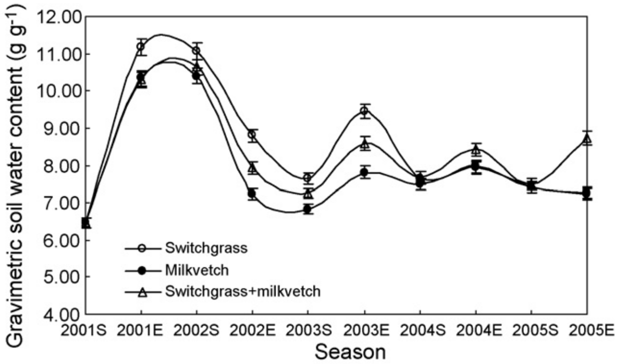

Fig. 3. Yearly soil gravimetric moisture content dynamics of each field in 2001–2005 (the capital letter S and E in abscissa referenced to the start and end of growth seasons in each year).

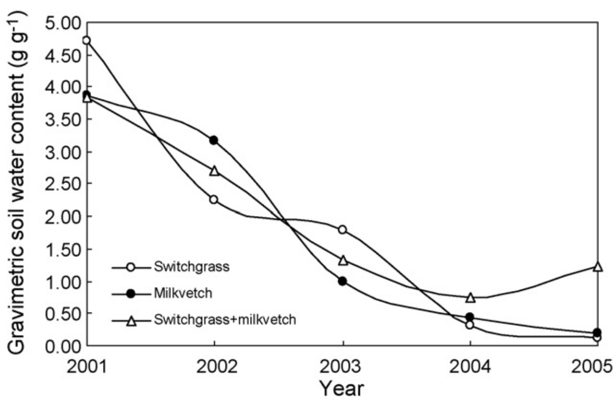

Fig. 4. Yearly soil gravimetric moisture content fluctuation extent dynamics of each field in 2001–2005.

2005 (Fig. 3). The ranking of 5-year averaged soil water content was sole switchgrass (8.49%) > switchgrass and milkvetch intercropped (8.35%) > sole milkvetch (7.91%). Before the growing season started in 2004, the mean soil water content of sole switchgrass was the highest of the three ($P < 0.05$), but there were no significant differences between sole milkvetch and the mixture. From the start of 2004 to the middle growing season of 2005, there were no significant differences among the three treatments. At the end of growing season in 2005, the intercropping field (8.73%) had significantly higher soil water content than switchgrass (7.27%) or milkvetch (7.23%) in solecropping, and there was no significant difference between sole switchgrass and sole milkvetch. The annual variation of soil water content decreased gradually from 2001 to 2005 except in 2005 for the mixture (Fig. 4)

Table 3
Indices of competition and productivity of milkvetch (crop a) and switchgrass (crop b) based on yearly aboveground biomass*

Year	2001	2002	2003	2004	2005	Mean ± S.E.
AYL_a	+4.28 a	+1.09 c	+1.27 c	+1.66 b	−0.18 d	1.62 ± 0.10
AYL_b	+0.34 b	−0.57 e	−0.11 d	+0.47 a	+0.17 c	0.06 ± 0.01
AYL	+4.62 a	+0.53 d	+1.17 c	+2.12 b	−0.01 d	1.67 ± 0.10
LER	+2.65 a	+0.99 e	+1.35 c	+1.86 b	+1.05 d	1.58 ± 0.03
A_{ab}	+3.93 a	+1.66 b	+1.38 bc	+1.19 c	−0.35 d	1.56 ± 0.11

* Values within a row followed by different letters are significantly different ($P < 0.05$). S.E. means standard error of mean.

3.3. Water use efficiency

In 2001 water use efficiency (WUE) was the lowest for all the three stands, and the mixture had the highest ($P < 0.05$), but there was no significant difference between sole milkvetch and sole switchgrass (Table 2). The ranking of 5-year mean WUE was sole switchgrass > sole milkvetch > switchgrass and milkvetch intercropped ($P < 0.05$). There was no obvious trend in WUE for switchgrass or milkvetch under solecropping as growing season changed over years, but the WUE of intercropped increased gradually since 2002 (Table 2).

3.4. Competition index

The partial AYL_a of milkvetch in 2001–2004 gave positive values, indicating yield gain, while the partial AYL_b of switchgrass was negative in 2002 and 2003, showing yield loss (Table 3). The higher value of AYL_a than AYL_b in the first 4 consecutive years (2001–2004) was consistent with the positive Aab. This revealed that milkvetch was the dominant species whereas switchgrass was the dominated species before 2004. LER in each year except 2002 (0.99) was significantly higher than 0. The aggressivity of milkvetch (crop 'a') to switchgrass (crop 'b') (Aab) decreased gradually as the growth year postponed and in 2005 it changed into negative value, which showed that switchgrass had become the dominant (Table 3).

4. Discussion

Primary production is affected by many factors, and fluctuations in weather parameters especially rainfall distribution affected the biomass production over years in semiarid regions (Briggs and Knapp, 1995; O'Connor et al., 2001; Haddad et al., 2002). After statistically analyzing the relationship between yearly biomass production and soil water storage volume as well

Table 2
Yearly water use efficiency ($g\,m^{-2}\,mm^{-1}$) of switchgrass and milkvetch in solecropping and intercropping*

Year	2001	2002	2003	2004	2005	Mean ± S.E.
Sole switchgrass	1.12 c (b)	2.76 ab (a)	2.89 a (a)	2.60b (a)	2.67b (a)	2.41 ± 0.07 (a)
Sole milkvetch	1.17 d (b)	2.87 a (a)	2.80 a (b)	2.19 c (b)	2.58 b (a)	2.32 ± 0.05 (b)
Switchgrass + milkvetch (2:1)	1.28 c (a)	1.21 c (b)	1.81 b (c)	1.98 ab (c)	2.06 a (b)	1.67 ± 0.04 (c)

*Values within a row followed by different letters are significantly different ($P < 0.05$), and values within a column with different small letters in bracket are also significantly different ($P < 0.05$). S.E. means standard error of mean.

as its change, monthly rainfall and water consumption, we found that biomass production of milkvetch was significantly correlated with whole rainfall of April–June in the region (Xu et al., 2006a,b), which may explain the highest biomass production of sole milkvetch in 2002 because the biggest rainfall month was June in that year, and which was 166.6 mm accounting for 30.8% of the yearly precipitation (Table 1; Fig. 1). The biomass production of switchgrass was also correlated with yearly and seasonal rainfall, and the water supplement in June was very important because its jointing growth stage was in that month (Li et al., 1999). Higher biomass production of sole milkvetch or switchgrass relative to intercropping may be due to the homogeneous environment under monocropping (Table 1) (Banik and Bagchi, 1993). The lower equivalent biomass of milkvetch and switchgrass when intercropped compared to respective monocrop was due to lower total productivity because there was competition in the intercropping (Table 1) (Banik et al., 2006; Thorsted et al., 2006).

Competition is one of the factors that have significant impacts on yield of mixture compared with component pure stands (Connolly et al., 2001a). Competition between plants usually includes competition for soil water, available nutrients and solar radiation (Thorsted et al., 2006; Jahansooz et al., 2007). Several indices such as land equivalent ratio (LER), relative crowding coefficient (k), competitive ratio (CR), aggressivity (A), equivalent yield (EY), actual yield loss (AYL) and intercropping advantage (IA) have been developed to describe competition and economic advantage in intercropping (Willey, 1979; Banik and Bagchi, 1993; Connolly et al., 2001a; Ghosh, 2004; Agegnehu et al., 2006). Of which LER indicates the efficiency of intercropping for using the resources of the environment compared with monocropping (Banik and Bagchi, 1993). Higher LER under intercropping indicated biomass production advantage over monocropping due to better land utilization (Table 3) (Banik et al., 2006). Actual yield loess values can give more precise information than the other indices on the inter- and intra-specific competition of the component crops and the behaviour of each species involved in the intercropping systems (Banik et al., 2000). Positive or negative values of AYL indicate an advantage or disadvantage in intercrops when the main objective is to compare yield on each plant basis (Thorsted et al., 2006). During 2001–2004, partial AYL of milkvetch (AYL_a) had positive values in the mixture indicated a yield advantage, probably because of the positive effect of switchgrass on milkvetch when grown in association (Banik et al., 2000), and it also revealed that milkvetch was the dominant in the mixture because its partial AYL was greater than that of switchgrass (AYL_b). The results of aggressivity conformed to those of LER and AYL (Table 3).

Greater competitive ability of milkvetch to exploit resources especially soil water has been reported (Shan and Chen, 1993; Xu et al., 2006a,b). While our results demonstrated that switchgrass had the potential to substitute milkvetch under 2:1 row-replacement intercropping (Table 3). Knee and Thomas (2002) has reported that switchgrass had higher competitiveness than some tallgrass prairie species such as *Echinacea purpurea* and *Ratibida pinnata*, and its higher competitiveness came from its high photosynthetic rates in relation to canopy light interception. After comparing the diurnal changes of photosynthesis characteristics of switchgrass with native herbaceous grass Old world bluestems (*Bothriochia ischaemum*) during dry seasons in the same researched region, we found that switchgrass had relative higher photosynthetic rate, lower transpiration rate and higher water use efficiency (Xu et al., 2003). Besides high water use and radiation capture abilities, competitiveness of a given species also depends on the phenology and/or morphology development. Jahansooz et al. (2007) reported that because of the slow growth rate and small canopy of chickpea, the chickpea/wheat intercropping system is of no advantageous in biomass or grain yield in South Australia. During our research period, milkvetch normally sprouted about half a month later than switchgrass, and it started growing fast in June, and then switchgrass plant height was about 60 cm with the coverage 75%. These can have a significant impact on the growth rate of milkvetch in mixtures, and thus affected its canopy development and radiation capture.

Because the annual rainfall is relatively low and highly variable and the monthly distribution is very unreliable in which case the water stored in the soils is of great importance to increase and stabilize crop yields in the research region (Shan and Chen, 1993). The fluctuation extent of soil water content decreased gradually as the growing season progressed with years (Figs. 3 and 4), which showed that the soil water content became more stable in the measured soil layers. This phenomenon may be partly due to the main soil water use layer of plants moved downward as the competition between intercropped species increased (Brooker, 2006).

WUE may vary in space and time, and is influenced by plants, soil conditions, agricultural practices and atmospheric factors (Fuentes et al., 2003). In general, highest WUE occurred with highest biomass in water-limited environments, but was plant-specific. Sole switchgrass and sole milkvetch had significantly higher biomass and WUE than the mixture (Tables 1 and 2). This may be due to the higher biomass but not excessive ET. In 2004, there was no significant difference between the biomass productions of sole milkvetch and the mixture, but the WUE of sole milkvetch was significantly higher (Tables 1 and 2). While in 2005 the biomass of mixture was significantly lower than that in 2004, but the WUE of it was significantly higher (Tables 1 and 2), the reasons for these were that the actual layer of soil water usage was deeper than the calculated soil layers, and which would induce the overestimation of WUE (Fuentes et al., 2003). This was corresponding to soil water yearly change (Fig. 4).

Competition for soil resources including soil water and nutritions plays a key role in the outcome of intercropping systems. In cereal–legume intercrops, competition for soil nitrogen during the vegetative phase greatly influences the final performance of the intercropped species (Li et al., 2001). The dominance of cereals over legumes is often attributed to their faster growing and better rooting system (Maingi et al., 2001; Li et al., 2006). The differences found between the sole and the mixture in this study can be attributed to the aggressivity of switchgrass and also to other factors such as morphology, physiology and the different requirements for nutrients. The tall-growing switchgrass intercropped with milkvetch and its high proportion (at least 67%)

in the mixture can affect nitrogen fixation of milkvetch due to shading by the switchgrass. This can result in poor growth and competitive ability of milkvetch in this mixture. However, to find out the real causes especially crop morphology and physiology background for the differences between the soles and mixture need further studies.

5. Conclusions

In semiarid hilly-gully region of China, to find sustainable and rational cropping patterns of various grass species is among the cardinal goals of research and extension systems (Shan and Chen, 1993). In this study, milkvetch was the dominant species in the intercropping in 2001–2004, while its aggressivity to swichgrass decreased gradually and in 2005 it was the dominant species in the mixture. Although the advantages of the intercropping systems found in this study can be attributed to the better utilization of growth resources (LER $\geq$ 1.0), the mixed culture as a whole exhibited lower aboveground biomass and water use efficiency (WUE). Hence, growing these two species in 2:1 row-replacement mixture is of no advantage if total biomass production is the primary purpose.

Acknowledgements

We are particularly grateful to Dr. Qingwu Xue from Montana State University (USA) for his valuable comments and suggestions to improve earlier versions of this manuscript. This work was funded by the "Talent Training Project in West China" Programs of the CAS (No. 2006YB01). Mr. Jun Jiang is most sincerely thanked for his assistance in the field measurements.

References

Agegnehu, G., Ghizaw, A., Sinebo, W., 2006. Yield performance and land-use efficiency of barley and faba bean mixed cropping in Ethiopian highlands. Eur. J. Agron. 25, 202–207.

Banik, P., Bagchi, D.K., 1993. Effect of legumes as sole and intercrop on residual soil fertility and succeeding crop in upland situation. Ind. Agric. 37, 69–75.

Banik, P., Sasmal, T., Ghosal, P.K., Bagchi, D.K., 2000. Evaluation of mustard (*Brassica competris* Var. Toria) and legume intercropping under 1:1 and 2:1 row-replacement series system. J. Agron. Crop Sci. 185, 9–14.

Banik, P., Midya, A., Sarkar, B.K., Ghose, S.S., 2006. Wheat and chickpea intercropping systems in an additive series experiment: advantages and weed smothering. Eur. J. Agron. 24, 325–332.

Briggs, J.M., Knapp, A.K., 1995. Interannual variability in primary production in tall prairie: climate, soil moisture, topographic position, and fire as determinants of aboveground biomass. Am. J. Bot. 82, 1024–1030.

Brooker, R.W., 2006. Plant–plant interactions and environmental change. New Phytol. 171, 271–284.

Chen, Y.X., Zhou, D.W., Zhang, Y.F., 2004. Yield and photosynthesis of intercropped maize and alfalfa. Acta Agrestia Sin. 12 (2), 107–112 (in Chinese with English abstract).

Connolly, J., Wayne, P., Bazzaz, F.A., 2001a. Interspecific competition in plants: how well do current methods answer fundamental questions? Am. Nat. 157, 107–125.

Connolly, J., Goma, H.C., Rahim, K., 2001b. The information content of indicators in intercropping research. Agric. Ecosyst. Environ. 87, 191–207.

Fortin, M.C., Culley, J., Edwards, M., 1994. Soil water, plant growth, and yield of strip-intercropped corn. J. Prod. Agric. 7, 63–69.

Fuentes, J.P., Flury, M., Huggins, D.R., Bezdicek, D.F., 2003. Soil water and nitrogen dynamics in dryland cropping systems of Washington State, USA. Soil Till. Res. 71, 33–47.

Ghosh, P.K., 2004. Growth, yield, competition and economics of groundnut/cereal fodder intercropping systems in the semi-arid tropics of India. Field Crop Res. 88, 227–237.

Haddad, N.M., Tilman, D., Knops, J.M.H., 2002. Long-term oscillation in grassland productivity induced by drought. Ecol. Lett. 5, 110–120.

Hauggaard-Nielsen, H., Andersen, M.K., Jørnsgaard, B., Jensen, E.S., 2006. Density and relative frequency effects on competitive interactions and resource use in pea–barley intercrops. Field Crop Res. 95, 256–267.

Ichizen, N., Takahashi, H., Nishio, T., Liu, G.B., Li, D.Q., Huang, J., 2005. Impacts of switchgrass (*Panicum virgatum* L.) planting on soil erosion in the hills of the Loess Plateau in China. Weed Biol. Manage. 5, 31–34.

Jahansooz, M.R., Yunusa, I.A.M., Coventry, D.R., Palmer, A.R., Eamus, D., 2007. Radiation- and water-use associated with growth and yields of wheat and chickpea in sole and mixed crops. Eur. J. Agron. 26, 275–282.

Knee, M., Thomas, L.C., 2002. Light utilization and competition between *Echinacae purpurea*, *Panicum virgatum* and *Ratibida pinnata* under greenhouse and field conditions. Ecol. Res. 17, 591–599.

Li, D.Q., Liu, G.B., Huang, J., Jiang, J., 1999. Study on introduction and bio-ecological characters of *Panicum virgatum* in Ansai loess hilly region. J. Soil Erosion Soil Water Conserv. 5 (Special), 125–128 (in Chinese with English abstract).

Li, L., Sun, J.H., Zhang, F.S., Li, X.L., Yang, S.C., Rengel, Z., 2001. Wheat/maize or wheat/soybean strip intercropping. I. Yield advantage an interspecific interactions on nutrients. Field Crop Res. 71, 123–137.

Li, F.M., Guo, A.H., Wei, H., 2003. Effects of clear plastic film mulch on yield of spring wheat. Field Crop Res. 63, 79–86.

Li, L., Sun, J.H., Zhang, F.S., Guo, T.W., Bao, X.G., Smith, F.A., Smith, S.E., 2006. Root distribution and interactions between intercropped species. Oecologia 147, 280–290.

Ma, J., Ma, S.Y., Cheng, Y.S., Mao, J.C., Bai, S.B., 1994. An analysis of effect of intercropping of maize with soybean. Acta Univ. Agric. Boreali-occidentalis 22 (4), 80–84 (in Chinese with English abstract).

Maingi, J.M., Shisanya, C.A., Gitonga, N.M., 2001. Berthold Hornetz nitrogen fixation by common bean (*Phaseolus vulgaris* L.) in pure and mixed stands in semi-arid south-east Kenya. Eur. J. Agron. 14, 1–12.

O'Connor, T.G., Haines, L.M., Snyman, H.A., 2001. Influence of precipitation and species composition on phytomass of a semi-arid African grassland. J. Ecol. 89, 850–860.

Pei, B.H., Yuan, Y.X., Jia, Y.B., Wang, W.Q., Josef, E., 2000. A study on light utilization of poplar-crop intercropping system. Scientia Silvae Sin. 36 (3), 13–18 (in Chinese with English abstract).

Sanderson, M.A., Read, J.C., Read, R.L., 1999. Harvest management of switchgrass for biomass feedback and forage productions. Agron. J. 91, 5–10.

Shan, L., Chen, G.L., 1993. Theory and Practice of Dryland Farming on the Loess Plateau. Chinese Science Press, Beijing, pp. 256–280 (in Chinese).

She, L.N., Zheng, Y., Zhu, Y.Y., 2003. Nitrogen uptake and utilization in wheat and broad bean intercropping. J. Yunnan Agric. Univ. 18 (3), 256–258, 269 (in Chinese with English abstract).

Thorsted, M.D., Weiner, J., Olesen, J.E., 2006. Above- and below-ground competition between intercropped winter wheat *Triticum aestivum* and white clover *Trifolium repens*. J. Appl. Ecol. 43, 237–245.

Tong, P.Y., 1994. Achievements and perspectives of tillage and cropping systems in China. Cropping Syst. Cult. Tech. 77, 1–5 (in Chinese).

Willey, R.W., 1979. Intercropping its importance and research needs. I. Competition and yield advantages. Field Crop Abstr. 32, 1–10.

Xu, B.C., Shan, L., Huang, Z.B., Liu, G.B., 2003. Comparative of photosynthetic characteristics of Old World bluestems (*Bothriochloa ischaemum*) and switchgrass (*Panicum virgatum*) in loess hily-gully region of China. Grassland China 25 (1), 1–4 (in Chinese).

Xu, B.C., Shan, L., Li, F.M., 2005. Aboveground biomass and water use efficiency of an introduced grass, *Panicum virgatum*, in the semiarid loess hilly-gully region. Acta Ecol. Sin. 25 (9), 2206–2213 (in Chinese with English abstract).

Xu, B.C., Gichuki, P., Shan, L., Li, F.M., 2006a. Aboveground biomass production and soil water dynamics of four leguminous forages in semiarid region, northwest China. South Afr. Bot. 72, 507–516.

Xu, B.C., Li, F.M., Shan, L., MA, Y.Q., Ichizen, N., Huang, J., 2006b. Gas exchange, biomass partition, and water relationships of three grass seedlings under water stress. Weed Biol. Manage. 6, 79–88.

Yang, W.Z., Shao, M.A., 2000. Study on Soil Water on the Loess Plateau. Science Press, Beijing, pp. 23 (in Chinese).

Zhang, F.S., Li, L., 2003. Using competitive and facilitative interactions in intercropping systems enhances crop productivity and nutrient-use efficiency. Plant Soil 248, 305–312.