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PRODUCTIVITY ENHANCEMENT AND WATER USE EFFICIENCY OF PEANUT-MILLET INTERCROPPING

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Abstract

Peanut-millet intercropping is a new planting pattern in northeastern China to deal with scarce oil-bearing crops' products and severe wind erosion in peanut fields. Land productivity and water use efficiency are the important factors that affect the application of this planting pattern. In this research, two peanut-millet intercropping patterns were studied in comparison with sole planting pattern of peanut or foxtail millet to reduce water consumption and improve water use efficiency. One intercropping system was 2P2M (2-row peanut with 2-row millet), and the other was 4P2M (4-row peanut with 2-row millet). Some indices were calculated to characterize the intercropping efficiency of land and water use as compared to those of sole crops of peanut and foxtail millet. The results showed that land equivalent ratio (LER) of two peanut-millet intercropping patterns ranged from 1.15 to 1.19, while water equivalent ratio (WER) ranged from 1.17 to 1.22, and △WU, the relative departure of actual water use in intercropping from expected use, was close to zero, indicated that peanut-millet intercropping increased the productivity but didn't increase the water consumption. The foxtail millet in the intercropping population gained more water compared with peanut; the soil water of foxtail millet strips in the 2P2M and 4P2M increased 69% and 45%, respectively, as compared with that of peanut strips after a 58.8mm rainfall during the mid-term of crops growth. These findings suggest that the rainfall's distribution in the soil of different crops was optimized in the peanut-millet intercropping system.

Key words：Intercropping; Crop productivity; Land equivalent ratio (LER); Water equivalent ratio (WER); Water use efficiency (WUE).

Introduction

The intercropping is one of the essences of the traditional Chinese exquisite agricultural technologies. The proper intercropping pattern makes the usage of the light, heat, water and nutrient resources in high efficiency with the advantage of high and stable yield (Zhou *et al.*, 2008; Chen *et al*., 2012; Usmanikhail *et al.*, 2013). At the same time, the intercropping can decrease the impact of diseases, pests and weeds, reduce the usage of chemical fertilizers and pesticides, improve the ecological environment of the field, decrease the production cost, and increase the population yield and economic benefit (Midmore, 1993; Li *et al.*, 2001; Li *et al.*, 2003; Usmanikhail *et al.*, 2012; Hussain *et al.*, 2013; Li *et al.*, 2014; Guo *et al.*, 2014). In recent decades, the soybean (Glycine max Merrill) planting area in the northeastern China has been reduced rapidly. Facing the urgent domestic need of the oil-bearing crops, the planting areas of soybean-substituted crops have increasingly based on peanut (*Arachis hypogaea* L.). Because the peanut is drought and poor soil-resistant, it is planted in vast areas in the northern semi-drought regions in China (the annual rainfall is less than 500 mm). But the fields were severely wind-eroded for the loose earth's surface is covered with no remains in autumn after the harvest, winter, and spring before emerging, added the wind is frequent, and the rain is less in the region. This region has China's largest sandy land—Horqin sandy land, with the gross area of 4.23 $\times 10^4$ km^2. Currently, this sandy area is increasing at a speed of 1.9% per year (Water resources in northeast China project group, CAE. 2006). The intercropping peanut with grass family's crops is regarded as the active pattern to prevent the wind-erosion in peanut fields (Li N. *et al.,* 2013). Foxtail millet (*Setaria italica* L. Beauv.) is one of the principal crops in the northern China. The intercropping stripe is not very wide in the peanut-millet intercropping system, which is suitable for the production system of Chinese small range-operated household. The sowing time of peanut and foxtail millet is also the same, and therefore the intercropping pattern is welcomed by farmers (Feng *et al.*, 2013; Feng *et al.*, 2014). Drought is a frequent problem occurs in northeastern China (Zhang *et al*., 2015; Wang *et al*., 2015), so the yield and water use efficiency are the highlights for people to decide whether to use this cropping pattern.

Regarding the issue of that the intercropping could decrease the water consumption of the field, the results on different crops in different regions are not the same. For example, Mao *et al.* (2012) reported that the population water consumption increased (+10%) significantly in the 2-row: 4-row of the maize (*Zea mays* L.) and pea (*Pisum sativum* L.). Miao *et al.* (2016) found that actual evapotranspiration, irrigation water use, crop transpiration, and groundwater contribution of intercropping systems were larger than those of the sole crops, which led to significantly higher yields of intercropping than those of single crops. However, some of the previous research results showed that intercropping improved crop productivity and water use efficiency. Hu *et al*. (2016) found the wheat (*Triticum aestivum* L.)-maize intercropping used more water but increased grain yields by 142% over the sole wheat and by 23% over the sole maize, thus, enhancing water use efficiency by an average of 26%. Zhang *et al.* (2010) found that the actual field evapotranspiration of maize-soybean intercropping was 15.37 mm and 29 mm lower than that of the sole maize or soybean planting system, and the water deficit of the maize-soybean intercropping was 45.54mm and 5.68mm lower than that of sole soybean and maize, respectively. Chimonyo *et al.* (2016) proved that intercropping sorghum with either cowpea (*Vigna unguiculata* L.) or bottle gourd (*Lagenaria siceraria* Standl.) resulted in better productivity and water use efficiency. However, there are few types of research on the water consumption characteristics and water utilization efficiency of the peanut-millet intercropping system currently.

For these reasons, the objective of this research was to investigate the influence of peanut-millet intercropping to the increasing of the utilization efficiency of soil resource and field water resource and estimate the water distribution and utilization system of the intercropping.

Materials and Methods

Site description: A three-year field research was conducted in Fuxin Scientific Observing and Experimental Station of Agro-Environment and Arable Land Conservation, Ministry of Agriculture, P.R.China (Fuxin, Liaoning province, northeast China, 42º8'N, 121º46'E,). The altitude of this experimental station is 270m with the average annualtemperature of 6.9ºC, 154 frost-free days, average annual rainfall of 481mm, average annualevaporation capacity of 1789 mm. There were 231 days with the temperature over 0ºC with the actively accumulated temperature of 3667.8ºC, 169 days whose temperature was not less than 10ºC with the valid accumulated temperature of 3298.3ºC, and 144 frost-free days. The total solar radiation of the year was 579.87 kJ/cm^2 with the photosynthetic active radiation of 284.28 kJ/cm^2. The average yearly sunshine duration was 2865.5 hours. The sunshine duration of the crop growth period from May to September was 1295.8 hours, which accounts for 65% of the year. The relative humidity was 58.0%～59.0% with the average yearly wind speed of 3.7～4.6 m/s. The rainfalls during the peanut's and foxtail millet's growth period were 331.5mm in 2011, 417.9 mm in 2012, 358.6 mm in 2013, and the crops were not irrigated during the three years.

Experimental design: This field research was implemented from 2011 to 2013. There were three treatments in 2011: sole peanut, sole millet, intercropping 2-row peanut with 2-row millet. There were four treatments in 2012 and 2013: sole peanut, sole millet, intercropping 2-row peanut with 2-row millet, intercropping 4-row peanut with 2-row millet. Each treatment was repeated for three times with the plot area of 120 m^2 (10 by 12 m plots) and the row distance of 50cm. Crops were sown on May 15 in 2011 and 2012, while on May 13 in 2013. The crops were harvested on September 22 during the three years. The planting density of peanut monoculture and intercropping strips was 24×10^4/ha, and that of millet monoculture and intercropping strips was 48×10^4/ha. Fertilizer (the contents of N, P_2O_5, and K_2O were 15%, respectively) was applied at a rate of 100kg/ha and synchronized with sowing.

Sample collection and measurements: The measurement of crops dry matter accumulation was started at 30 days after sowing. The samples were taken around every 15 days. We fetched 1 m^2 plants of peanut and foxtail millet to separate the blade, stem-sheath, roots and fruit, to weigh them separately after air drying. In regard of the peanut strips of 4P2M intercropping, the samples were taken in line 1 and line 2 near millet-side. After the maturity of the crops, we randomly selected three 10m^2 plots. The peanut and foxtail millet were handled and acquired practically, measuring the yield after the air drying. In regard of the 4P2M intercropping, we measured the peanut yield of line 1 and line 2 close to the millet-side separately and calculated its average value. We also fetched plants of three 1m^2 plots, conducted the indoor seed-testing after the air drying. Concerning the peanut, we mainly tested its character indices including pod number per plan, ripe pod ratio, hundred-pod weight, hundred-kernel weight, and shelling percentage. Regarding the foxtail millet, we mainly tested its character indices including spike number per unit area, panicle length, panicle weight, grain weight per spike, and thousand grain weight.

The soil water contents of 0-100 cm deep were measured using an earth boring auger and oven drying method, and the soil was divided into ten 10cm-thick layers. After the weighing of the moist soil samples, they were put into the drying oven for 48 hours at the temperature of 105ºC. After that, we net-weighed the samples and calculated the water content of the soil. The sampling spot was under the row of the planted crops. In regard of the 2P2M intercropping, the sampling was conducted under the rows of peanut and foxtail millet separately. In regard of the 4P2M intercropping, the sampling was performed under the row of foxtail millet, and the peanut row of line 1 and line 2 close to the foxtail millet separately.

Data analysis: The actual water use (approximate evapotranspiration, ET_a, mm), we applied the soil water balance equation to conduct the calculation (Gao *et al.*, 2009).

$$ET_{\mathrm{a}} = I + P - RO - DP + CR \pm \Delta SF \pm \Delta SW \quad (1)$$

In the formula: I and P refer to the irrigation amount and rainfall amount (mm) in this period, respectively. RO is the surface runoff volume (mm) of the soil during the rainfall and irrigation (for this test had no balk in the field, it was ignored). DP is leakage amount of deep soil (mm). CR is the underground water amount from capillary fringe to root area (for the underground water level of the testing field was relatively low, which was more than 20m under the ground, it was ignored). ΔSF is the side leakage amount of the soil water (mm), including side inflow amount SF_{in} and outflow amount SF_{out} (this test was ignored). ΔSW is the variation amount of the soil water content (mm).

Land equivalent ratio (*LER*) is an evaluation of the land utilization efficiency of the intercropping (Rao and Willey, 1980).

$$LER = LER_A + LER_B = \frac{Y_{\text{int},A}}{Y_{mono,A}} + \frac{Y_{\text{int},B}}{Y_{mono,B}} \quad (2)$$

In the formula: $Y_{int,A}$ and $Y_{int,B}$ are the intercropping yield of crop A (peanut) and crop B (foxtail millet), respectively. $Y_{mono,A}$ and $Y_{mono,B}$ are the monoculture yield of crop A and crop B, respectively. LER_A and LER_B are the partial land equivalent ratio of crop A and crop B. The land equivalent ratio refers to the ratio between the benefit from the mixed-cropping of two or more than two crops in the same field and the benefit from the monoculture of every crop. It is the indication of the ratio value between the needed lands for the monoculture to acquire the same yield with intercropping and the lands needed for the intercropping. If *LER* is more than 1, it indicates that the land utilization efficiency of the intercropping is higher than that of monoculture.

Regarding the water utilization efficiency of the intercropping population, we applied another evaluation index *WER* (Water Equivalent Ratio) (Mao *et al.*, 2012).

$$WER = WER_A + WER_B = \frac{(Y_{\text{int},A} / WU_{\text{int}})}{(Y_{mono,A} / WU_{mono,A})} + \frac{(Y_{\text{int},B} / WU_{\text{int}})}{(Y_{mono,B} / WU_{mono,B})} = \frac{WUE_{\text{int},A}}{WUE_{\text{mono},A}} + \frac{WUE_{\text{int},B}}{WUE_{mono,B}} \quad (3)$$

The definition of *WER* is similar to *LER*,

Analogous to LER, WER quantifies the amount of water that would be needed in single crops to achieve the same yield as produced with one unit of water in intercrop. If the $WER > 1$, it suggests that the water utilization efficiency of intercropping is higher than that of monoculture. If $WER < 1$, it shows that water utilization efficiency of intercropping is lower than that of monoculture. Where $WUE_{mono,A}$ and $WUE_{mono,B}$ are the water use efficiencies of monocultures of species A and B. $WUE_{int,A}$ and $WUE_{int,B}$ are water use efficiencies of species A and B in the intercrop. These *WUEs* are calculated as the yield of crop A or B per unit of total water used in the intercrop (analogous to the definition of LER). *Y* is yield. WU_{int} is the actual evapotranspiration of whole intercropping system, $WU_{mono,A}$ and $WU_{mono,B}$ are the actual evapotranspiration of crops A and B in monocultures.

We also applied the $\triangle WU$ (Morris & Garrity, 1993) to evaluate the water utilization efficiency of the intercropping related with the monoculture. $\triangle WU$ quantifies the relative difference between the actual water uptake in intercropping ($WU_{int,obs}$) and the expected water use calculated from the water use of the two crop species in single crop multiplied by weights that express their share in the intercropping ($WU_{int,exp}$).

$$\triangle WU = \frac{WU_{\text{int},obs}}{WU_{\text{int,exp}}} - 1 = \frac{WU_{\text{int},obs}}{LER_A WU_{mono,A} + LER_B WU_{mono,B}} - 1 = \frac{WU_{\text{int},obs}}{(Y_{\text{int},A} / WUE_{mono,A}) + (Y_{\text{int},B} / WUE_{mono,B})} - 1 \quad (4)$$

This formula expresses the hypothesis that the expected water use in intercropping is proportional to the water uses of either species in monoculture and the relative yield compared to sole crop (partial *LER*) realized in intercrop. Another way to express this hypothesis is that expected water use in the intercropping is the sum of expected water uses by the component species, calculated as their observed yield in intercrop, divided by the water use efficiency as determine in the sole crop.

Results

Grain yields and land equivalent ratio: The yields were significantly different under different treatment of peanut and foxtail millet from 2011 to 2013 (Table 1). The average peanut yield of 2P2M was 1.7t ha^{-1} (44% of the peanut monoculture). The 4P2M peanut yield was 2.6t ha^{-1} (65% of the peanut monoculture, which was the average value of 2012 and 2013). The 4P2M peanut yield of 2012 and 2013 was 44% higher than that of 2P2M peanut yield in average. The foxtail millet average yield of 2P2M was 3.8t ha^{-1}(75% of millet monoculture). The 4P2M millet yield was 2.7t ha^{-1} (51% of millet monoculture, which was the average value of 2012 and 2013). The 4P2M millet yield of 2012 and 2013 was 31% lower than that of 2P2M millet yield in average.

In the 2P2M intercropping system, the planting area of peanut and foxtail millet was 50% of the monoculture area respectively to produce 44% peanut and 75% foxtail millet related with the monoculture. This finding indicated that this kind of intercropping mode has advantages in the aspect of land utilization (44%+75%＞100%). In the 4P2M intercropping system, the planting area of peanut and foxtail millet was 67% and 33% of the monoculture area respectively to produce 65% peanut and 51% foxtail millet related with the monoculture. It also indicated that this kind of intercropping mode has advantages in the aspect of land utilization (65%+51%＞100%).

We further estimated the land equivalent ratio (LERs) of different planting patterns. The result showed that the land equivalent ratio variation range of two planting patterns was 1.15-1.19. The difference of the land equivalent ratio of two planting patterns was not obviously (Table 2), indicated that these two intercropping modes have the advantage of improving the land utilization efficiency.

Table 1. Grain yields of peanut and foxtail millet for different cropping systems, sole and intercropping, in 2011, 2012 and 2013.

Cropping system	Peanut yield(t ha^{-1})			Millet yield(t ha^{-1})		
	2011	2012	2013	2011	2012	2013
Sole peanut (SP)	3.7 ± 0.3a	3.8 ± 0.4a	4.2 ± 0.2a			
Sole millet (SM)				4.8 ± 0.3a	5.4 ± 0.3a	5.1 ± 0.4a
Intercrop 2P2M	1.6 ± 0.2b	1.7 ± 0.1c	1.8 ± 0.2c	3.5 ± 0.2b	3.9 ± 0.2b	3.9 ± 0.3b
Intercrop 4P2M		2.5 ± 0.1b	2.7 ± 0.2b		2.7 ± 0.3c	2.6 ± 0.2c

Values followed by the same letter within a column were not significantly different according to LSD at 0.05 level, the same below

Table 2. Land equivalent ratio (based on grain yield) in peanut-millet intercrops in 2011, 2012 and 2013.

Year	Cropping system	LER_A	LER_B	LER
2011	Intercrop 2P2M	0.43 ± 0.05	0.73 ± 0.04	1.16 ± 0.07
2012	Intercrop 2P2M	0.45 ± 0.05	0.72 ± 0.04	1.17 ± 0.06
	Intercrop 4P2M	0.66 ± 0.02	0.50 ± 0.05	1.16 ± 0.07
2013	Intercrop 2P2M	0.43 ± 0.05	0.76 ± 0.03	1.19 ± 0.07
	Intercrop 4P2M	0.64 ± 0.06	0.51 ± 0.04	1.15 ± 0.05

Table 3. Yield components of peanut and foxtail millet for different cropping systems, sole and intercropping, two years of average in 2012, 2013.

Crops		Sole	Intercrop 2P2M	Intercrop 4P2M
Peanut	Pod number per plan	12.6 ± 1.0a	10.7 ± 0.6b	11.9 ± 0.8ab
	Ripe pod ratio (%)	83.0 ± 1.8b	89.5 ± 2.4a	86.3 ± 1.9ab
	Hundred-pod weight (g/100-pod)	131.8 ± 3.4a	120.8 ± 4.1b	129.8 ± 2.6a
	Hundred-kernel weight (g/100-kernel)	91.9 ± 2.1a	80.2 ± 2.3b	88.7 ± 3.5a
	Shelling percentage (%)	69.9 ± 2.9a	66.0 ± 3.1a	68.3 ± 1.7a
Millet	Spike number per unit area (/m^2)	79.2 ± 4.3b	88.6 ± 3.1a	93.2 ± 2.6a
	Panicle length (cm)	17.0 ± 2.1a	18.4 ± 1.6a	18.7 ± 1.9a
	Panicle weight (g)	8.4 ± 0.7b	10.0 ± 1.0a	11.2 ± 0.8a
	Grain weight per spike (g/spike)	7.2 ± 0.4b	8.7 ± 0.6a	9.2 ± 0.8a
	Thousand grain weight (g/1000-grain)	2.5 ± 0.1b	2.8 ± 0.2a	3.0 ± 0.2a

We compared the relative indices of the yields of peanut and foxtail millet in different planting methods (Table 3). The decreasing of the land productivity in 2P2M peanut intercropping strip (44% peanut produced in 50% land related to monoculture) was because the per pod number, hundred-pod weight, hundred-grain weight decreases, while its fruit-rate was higher than that of monoculture. Every composition character of 4P2M peanut intercropping yield was no significant difference with that of monoculture. While the hundred-pod weight and hundred-grain weight of the 4P2M intercropping was higher than that of 2P2M intercropping.

The increasing of the land productivity in 2P2M intercropping strips (75% foxtail millet produced in 50% land related to monoculture) and 4P2M intercropping strips (51% foxtail millet produced in 33% land related to monoculture), in the aspect of yield character, mainly reflected that the indices like ear number, ear weight, ear grain weight and 1000-grain weight were higher than that of monoculture.

Dry matter accumulation: Before the 44 days after sowing, the difference of dry matter accumulation volume between the intercropping and monoculture of the peanut and foxtail millet was not significant. After that, the dry matter accumulation speed of sole peanut or foxtail millet per unit was considerably faster than that of intercropping (Fig. 1). We calculated the dry matter growth speed of the sole peanut, 2P2M and 4P2M peanut intercropping was 61 kg ha^{-1} d^{-1}, 25 kg ha^{-1} d^{-1} and 38kg ha^{-1} d^{-1}, respectively. The dry matter growth speed of the sole millet, 2P2M and 4P2M millet intercropping was 123 kg ha^{-1} d^{-1}, 88 kg ha^{-1} d^{-1} and 69 kg ha^{-1} d^{-1}, respectively. The dry matter growth speed of 2P2M and 4P2M peanut intercropping was 40% and 62% of that of monoculture, respectively; and the dry matter growth speed of 2P2M and 4P2M millet intercropping was 72% and 56% of that of monoculture, respectively. That was consistent with the difference on the yield of different planting methods.

Rainfall distribution: By observing during the rainfall, we found (Fig. 2a) that in the intercropping system, the canopy area of foxtail millet was much larger than that of peanut. During the rainfall, the canopy of foxtail millet intercepted and captured more precipitation, and it flowed to the root of foxtail millet along with the leaf and stem. It was to make the rainfall in asymmetrical distribution in the intercropping system. Therefore, the foxtail millet gained more precipitation. However, the peanut monoculture (Fig. 2b) and millet monoculture (Fig. 2c) didn't exhibit such an effect.

By investigating the pre-rain and post-rain soil water content variation, we found that the soil water increasing amount of the 2P2M and 4P2M millet intercropping strips were much higher than that of the relative peanut strips (Table 4). The soil water increasing of the foxtail millet strips was 1.69 times and 1.45 of that of the peanut, respectively.

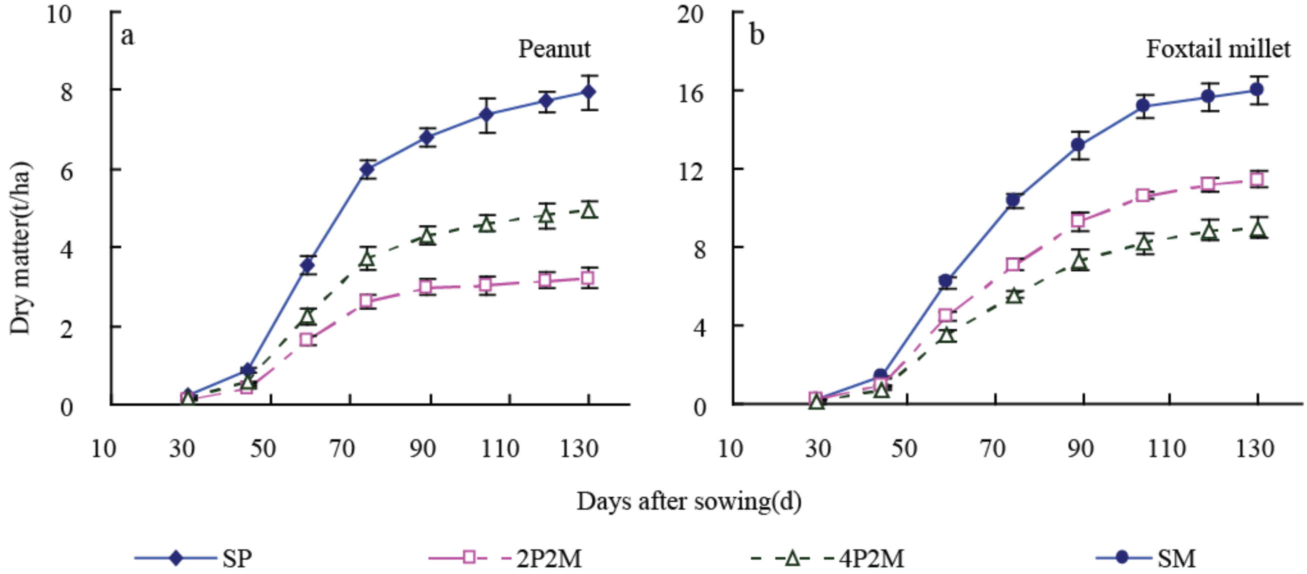

Fig. 1. Growth patterns of peanut (a) and foxtail millet (b) after sowing in 2012.

a 2P2M **b SP** **c SM**

Fig. 2(a, b, c). Field picture during the rainfall of different planting systems. In Aug.2nd, 2012, a one-time rainfall capacity was 58.8mm.

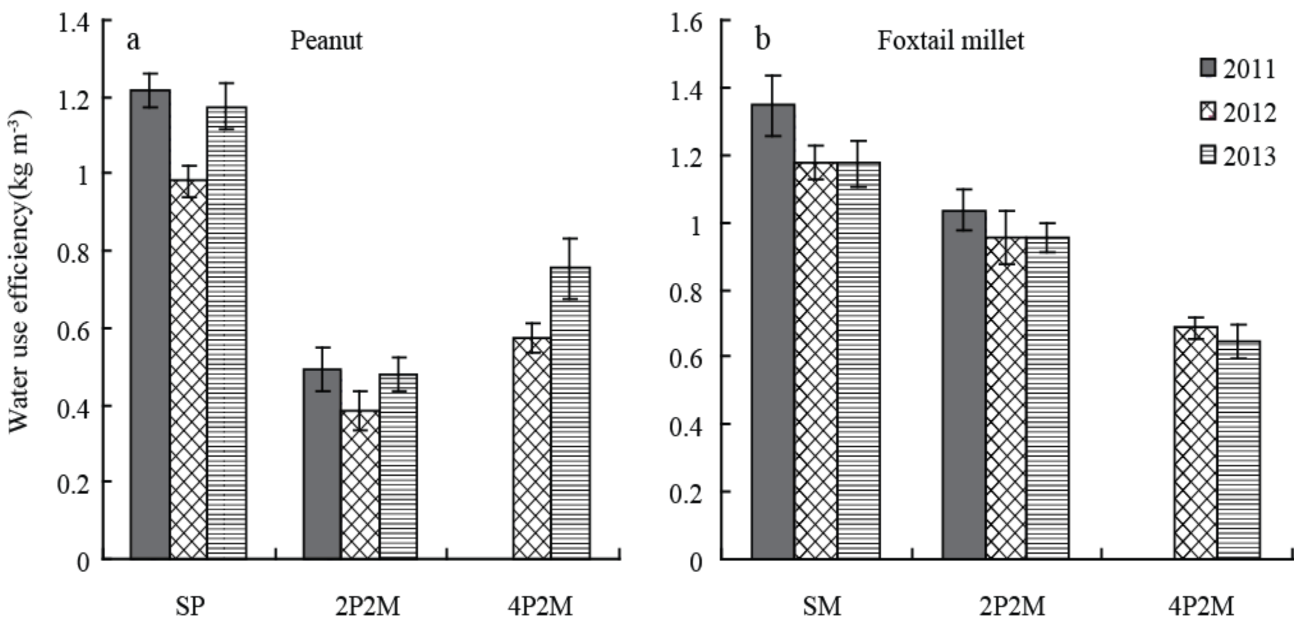

Fig. 3. Water use efficiency of peanut (a) and foxtail millet (b) in monoculture and intercropping in 2011, 2012 and 2013. Water use efficiency in intercrops is expressed as the yield of one crop divided by the total water use of the whole intercrop system.

Table 4. The variation of pre-rain and post-rain 1 meter-deep soil water storage content, 2012 (mm).

Cropping system	Before the rain (1 August)		After the rain (3 August)		Soil moisture increase	
	Peanut	Millet	Peanut	Millet	Peanut	Millet
Sole peanut(SP)	243.7 ± 6.4a	-	274.4 ± 8.3a	-	30.7 ± 5.6a	-
Sole millet(SM)	-	211.4 ± 6.7b	-	245.7 ± 9.7b	-	34.3 ± 6.3b
Intercrop 2P2M	234.3 ± 8.3b	223.8 ± 8.1a	259.1 ± 6.5b	267.6 ± 10.0a	25.8 ± 4.2b	43.8 ± 5.0a
Intercrop4P2M	238.6 ± 6.7b	227.7 ± 6.8a	268.0 ± 5.4b	270.4 ± 6.6a	29.4 ± 3.9a	42.7 ± 4.5a

Table 5. Indices for water use efficiency in peanut-millet intercrops in 2011, 2012 and 2013.

Year	Cropping system	△WU(%)	WER_A	WER_B	WER
2011	Intercrop2P2M	0.45 ± 2.48a	0.40 ± 0.02a	0.77 ± 0.04a	1.17 ± 0.06a
2012	Intercrop2P2M	0.36 ± 3.54a	0.39 ± 0.03b	0.81 ± 0.08a	1.21 ± 0.11a
	Intercrop4P2M	-0.80 ± 2.67a	0.65 ± 0.05a	0.53 ± 0.09b	1.18 ± 0.08a
2013	Intercrop2P2M	-0.59 ± 2.42a	0.41 ± 0.04b	0.81 ± 0.02a	1.22 ± 0.09a
	Intercrop4P2M	-2.35 ± 4.10a	0.64 ± 0.11a	0.55 ± 0.06b	1.19 ± 0.08a

Advantage in water use and productivity by intercropping: There was the significant difference in WUE of different planting ways (Table 5), the order of peanut WUE was as follows: SP＞2PSM＞4PSM (Fig. 3a), while the order of foxtail millet WUE was: SM＞4PSM＞2PSM (Fig. 3b). By two indices of WER and △WU, we evaluated intercropping system's effect on the enhancement of water utilization efficiency. If WER＞1 and △WU＜0, it indicates that the water consumption amount of the intercropping system is lower than that of monoculture, while the water utilization efficiency of the intercropping is higher than that of monoculture. On the contrary, if WER＜1 and △WU＞0, it indicates that the water consumption amount of the intercropping system is higher, and the water utilization efficiency is lower. In this research, WERs of intercropping system were all greater than 1 (Table 6), which indicated that the water utilization efficiency of the intercropping was higher than that of monoculture. △WUs were not over 0 obviously or less than 0 (Table 6), which indicated that the water consumption amount of intercropping system didn't increase or decrease obviously as compared to that of monoculture. At the same time, the difference between 2P2M and 4P2M was not significant, which was relatively consistent with the result of LER (Table 2). It indicated that both of intercropping patterns had same functions and effects in the aspect of water utilization efficiency. WER_B (partial WER of foxtail millet) was more than WER_A (partial WER of peanut) in 2P2M intercropping system, and WER_A was more than WER_B in 4P2M intercropping system. By comparing the partial LER of peanut and foxtail millet with partial WER, we found that the differences between the average partial LER of peanut and partial WER (0.44vs0.40) in three years, the partial LER of foxtail millet and partial WER (0.74 vs0.80), the average partial LER of 4P2M peanut and partial WER (0.65vs0.65) in two years, the partial LER of foxtail millet and partial WER (0.51 vs0.54) were not significant, suggesting that the increasing of the productivity of peanut-millet intercropping was not at the cost of consuming more water.

Discussion

One of the important reasons for Chinese farmers to practice intercropping is increasing land productivity and improving resources utilization efficiency (Feike *et al*., 2010). Some intercropping patterns, such as intercropping maize with winter wheat, with poor WUE, but widely popularized in northern China, because of it significantly raised yield (Gao *et al*., 2009). In our research, we found the LER variation range of two peanut-millet intercropping patterns was 1.15-1.19 and the WER variation range was 1.17-1.22, which indicated the intercropping had the potential to increase the utilization efficiency of land and water in large extent, comparing with the single crops. In other words, the same land and water of the intercropping may provide the relatively high yield. So the intercropping peanut with foxtail millet was more consistent with the expectations of farmers. One of reasons for improving LER and WER is that intercropping makes better use of one or more agricultural resources both in time and in space (Rodrigo *et al*., 2001), such as greater interception of sunlight and more efficient conversion of the intercepted radiation (Li *et al*., 2006), more efficient root distribution in space plays (Gao *et al*., 2010), mutually beneficial effects of allelopathy or phenological characteristics (Khan *et al*., 2002; Li *et al*., 2013), and so on. While in arid and semi-arid areas, the key factor to improve the productivity of crops is water (Fan *et al*., 2016).

Foxtail millet is a C4 crop, has high water utilization efficiency for the carbon assimilation efficiency of its water per unit is relatively higher. While peanut is a C3 crop, the water utilization efficiency and water consumption are not high (Feng, 2010). In this study, soil water content of foxtail millet strips of 2P2M and 4P2M intercropping had increased 69% and 45% water compared to that of peanut respectively in a 58.8 mm rainfall in the middle period of crops growth, which made the rainfall get optimized distribution in the soil. This finding also suggested that the higher water efficiency crop got more water. Thus, it was one of the important reasons for the increase in water use efficiency in peanut-millet intercropping system. In general, foxtail millet needs more water than peanut under normal rain-fed conditions (Feng *et al*., 2010), so how to balance the need of crops for water from farmlands by creating an intercropping population between peanut and foxtail millet is important. And, there are some other effective regulation measures to achieve optimization effect of soil moisture, e.g. tillage, irrigation and rational density (Weldeslassie *et al*., 2016; Ren *et al*., 2016), so the benefit potential of intercropping will be greater if combined with these methods.

The advantages of foxtail millet and the disadvantage of peanut were existed in the peanut-millet intercropping system. Compared with the monoculture, yield and biomass per unit land of foxtail millet strips increased in the intercropping system, while that of peanuts strips decreased. And the decreasing of per unit land yield in the 2P2M peanut intercropping strip (44% peanut produced in the 50% land related with monoculture) was mainly because the per pod number, hundred-pod weight, and hundred-grain weight decrease. Researchers noted the same results in maize-peanut intercropping (Li *et al.,* 2013). For intercropping peanut was in the inferior position in water competition, water stress affected the differentiation of flower bud, which leads to the decreasing of per pod number (Upadhyaya, 2005). While, the differences of peanut yield components between 4P2M and sole peanut were no significant. So, the choice of intercropping pattern has a great influence on crops yield.

Conclusions

Overall, results suggest that peanut-millet intercropping effectively use water and land resources. Land equivalent ratio (LER) of two peanut-millet intercropping patterns ranged from 1.15 to 1.19, while water equivalent ratio (WER) ranged from 1.17 to 1.22, and $\triangle$WU, an index to evaluate the water utilization efficiency of the intercropping related with the monoculture, was close to zero, indicated that peanut-millet intercropping increased the population but didn't increase the water consumption. The rainfall distribution in the soil of different crops was optimized, that was one of the reasons for the increase in water use efficiency in peanut-millet intercropping system. Foxtail millet is a kind of high water efficiency crop, with the competitive advantage in the peanut-millet intercropping system, and achieved more water to use. The decreasing of per unit land yield in the 2P2M peanut intercropping belt (44% peanut produced in the 50% land related with monoculture) is mainly because of the reduced per pod number, hundred-pod weight, and hundred-grain weight. In 2012 and 2013, the average peanut yield of 4P2M intercropping increased by 44% compared with that of 2P2M. The increasing of the peanut yield was at the cost of the 31% decreasing of the foxtail millet yield. Therefore, we can choose the proper intercropping pattern according to the crops yield expectation and the crops production price.

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