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RESEARCH ARTICLE

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Ecological effect analysis of pumpkin and oil sunflower intercropping in arid area of northwest Hebei Province: I. moisture analysis

Abstract Experiments were conducted during 2007–2008 at the Zhangbei Agricultural Resource and Ecological Environment Key Field Research Station, Hebei Province, China to study water-efficient pumpkin planting patterns in this area. Four treatments of pumpkin and oil sunflower intercropping were used to study the problem of water resource scarcity and inefficient water use in the plateau of northern Hebei Province. The four treatments were: pumpkin sole cropping (Sp), oil-sunflower sole cropping (So), intercropping one row oil sunflower (IC_1) or two rows (IC_2) between pumpkin rows. The results showed that oil sunflower competed for soil water with pumpkin during late growth stage of pumpkin in IC_2, but there was no water competition in IC_1. Total rainfall during the growing season was 201.6 mm and the soil water balance differed between treatments. In all cases the water percolation was low and soil moisture storage always negative. Nearly all water loss was through evapotranspiration, which varied by treatment. The seasonal evapotranspiration of IC_1 was less than So, Sp and IC_2, 46.57%, 41.22% and 46.73%, respectively. Economic yield of pumpkin decreased from 30.00% (IC_1) to 71.42% (IC_2). However, yield per plant of intercropping oil sunflower increased from 190.71% to 241.26%, as compared with So, because oil sunflower showed remarkably partial advantage. The Land Equivalent Ratio (LER) of pumpkin-oil sunflower was 1.08–1.22, and the Water Equivalent Ratio (WER) of pumpkin-oil sunflower was 1.07–1.26. Economic value of sole pumpkin was greatest but did not differ from treatment IC_1. Other treatments had significantly less economic value. In this region of rain-fed dry land farming, a sparse planting of sole pumpkin with high efficiency production could realize water resources most effectively in the Plateau of northern Hebei Province.

Keywords pumpkin, oil sunflower, intercropping, soil moisture, water use

1 Introduction

Water shortages and infertile soils are the main restricting factors in the agricultural development of arid regions (Wen et al., 2002). Efficient rainfall utilization is the core of agriculture in most arid regions. Many studies have been conducted on efficiently using water resources with various cultivation methods (Wen et al., 2006; Huang et al., 2007) and evaluating production systems on crop drought tolerance by changing crop planting layouts (Zhang et al., 2008). Land synthesis productivity could be enhanced by taking advantage of the differences in water absorption in space and time between various complex alternations of forest and agricultural crops (Ma et al., 1997; Li and Wan, 2002; Liu and Zeng, 2007). Zhao et al. (2006) intercropped Chinese date trees between crops in wide rows. Studies on the character of farmland water usage in sandy soils of the north-west high plateau of Hebei Province indicated that there were no large differences in farmland water consumption during the growing season (Zhang et al., 2001), though some crop yields had differences. The most important factor for

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highly efficient farmland water usage was selecting suitable crops and their layout.

In this research oil sunflower was used to intercrop with sparsely planted pumpkins to study the changes in soil water distribution, water balance, and water use efficiency in the ecologically frail plateau area of northern Hebei Province. This study can provide theoretical and technological foundations for readjusting crop layout to achieve an efficient use of soil and water resources.

2 Materials and methods

2.1 Background of the trial

Field experiments were conducted during 2007–2008 at Zhangbei Agricultural Resource and Ecological Environment Key Field Research Station, Ministry of Agriculture of China (41°11.35′N, 114°51.20′E) at 1400–1700 m above sea level, in Hebei Province, China. This area has a cold and dry climate with an annual temperature of 2.6°C and an annual precipitation about 393.2 mm. Evaporation per year is 1693.0 mm, and dry index is 2.0. On average, the frost-free period is 110 days (Liu and Zhang, 2004). The tested soil was a sandy chestnut soil and its physical characteristics are given in Table 1.

2.2 Experimental design

High stalk oil sunflower and sprawling pumpkins were selected as materials. Rows of oil sunflower (zero, one or two) were intercropped between two rows of pumpkins to create levels of water competition. The changes of field water were measured over time. Four treatments were set and the planting modes are given in Table 2. Each treatment was randomly arranged with 3 replications and each plot was 24 m^2 (6 m × 4 m) in size.

The seedling transplant method was used for both pumpkin and oil sunflower. Seeds were planted in a small arch shed nursery on May 13. The seedlings were transplanted when two leaves had spread (June 3). Before transplant 2 kg of diammonium hydrogen phosphate per plot was applied. At planting 1 kg of water was used for every plant of pumpkin and oil sunflower. Pumpkins were planted in a ridged plot of 60 cm wide with a ridge height of 5–7 cm. Pumpkins were planted at the ridge base, the same level as the field. Plastic film mulching (80 cm wide) was used on the ridge. Flat plots were used in oil sunflower sole cropping (So). Field management was conducted as for a high yield field, and the crops were harvested on August 22. No irrigation was given during the whole growing season. To measure soil moisture movement, four percolation sinks were built with dimensions of 3 m long, 2 m wide and 1 m deep.

2.3 Measurement and methods

Soil water content was measured at 10-day intervals during the whole growth stage at the pumpkin planting row (P_0), 50 cm (P_1) and 100 cm (P_2) distant from the pumpkin plant and to 80 cm in depth, sampling every 10 cm. Soil percolation amount (mm) (D) was measured by percolation sink.

Water balance was calculated by the following equation: $P = R + E + \triangle W$, where P is precipitation; R is underground percolation; and E is evapotranspiration calculated by the equation: $E = P - R - \triangle W$ (Kang et al., 1992). $\triangle W$ is the change of soil water content.

Soil water content can be calculated by layers using the formula $W_i = 0.1 h_i f_i d_i$ (Meng et al., 2001), where W_i is water content (mm) in layer i; h_i is soil thickness in layer i; f_i is water content (weight percentage) in soil layer i; d_i is soil volume weight (g·cm^{-3}) in layer i.

Farmland water usage (WU) = (P) precipitation in growing season + ($\triangle W$) changes of soil water content between sowing and harvest − (D) soil water percolation amount.

Table 1 Physical characteristics of the tested soil

depth of soil/cm	bulk density/(g·cm^{-3})	total porosity/%	field capacity/%	wilting moisture/%	soil available water/mm
0–20	1.54	41.89	19.72	4.07	31.30
20–40	1.57	40.75	10.27	3.11	14.32
40–60	1.78	32.83	9.65	3.52	12.26
60–80	1.65	37.74	13.16	3.27	20.78
80–100	1.62	38.87	20.61	3.21	34.80

Table 2 Planting patterns of treatments

treatment	spacing of oil sunflower/cm	spacing of pumpkin/cm
oil sunflower sole cropping (So)	50 × 25	–
pumpkin intercropping with one row oil sunflower (IC_1)	200 × 25	200 × 45
pumpkin intercropping with two rows oil sunflower (IC_2)	150 × 25 50 × 25	200 × 45
pumpkin sole cropping (Sp)	–	200 × 45

Land Equivalent Ratio $(LER) = Y_1/Y_1' + Y_2/Y_2' + ... + Y_i/Y_i'$, where Y_i is yield of every crop in intercropping system, Y_i' is yield of every crop under the same sole cropping conditions, i is individual crop in the intercropping system (Liu and Zhang, 2006).

Intercropping water equivalent ratio $(WER) = W_1/W_1' + W_2/W_2' ... + W_i/W_i'$, where W_i is yield of every crop per unit water in intercropping system, W_i' is yield of every crop per unit water under the same sole cropping conditions, i is individual crop in the intercropping system.

The total yield of pumpkin and oil sunflower plants per plot was measured and 5 plants were randomly selected from every plot to get the fresh and dry weight, percentage of dry weight, and the dry biomass of both plants.

All data processing and statistical analysis were performed using the following software: Excel, DPS 7.05 for windows.

3 Results and analysis

3.1 Soil water content over time and distance from pumpkin plants

Soil water content variations in 0–40 cm layers sampled at three locations from pumpkin plants are shown in Fig. 1. There were no significant differences among treatments in water content of soil between pumpkin plants at seedling stage (June 3–June 23). Soil water content in IC_1 and IC_2 were higher than that in Sp during vine extending and flowering stage, and by the end of this stage it was 6.99 mm and 9.59 mm more than that of Sp; water content of IC_1 was higher than that of Sp during fruiting stage (June 23–July 23), and it was 0.58 mm more than that of Sp in 0–40 cm layer at harvest; while in IC_2 the water content was lower than that of Sp during the fruiting stage. It decreased about 4.19 mm at harvest. Oil sunflower was highly competitive with pumpkin for water.

The water content at P_1 was similar to P_0. Soil water content at P_2 was affected by both the vine shading and water consumed by oil sunflower roots. It was low in Sp as there was no vine shading before flowering (July 4), while in IC_1 and IC_2 it was 7.26 mm and 3.27 mm, respectively, higher than that of Sp on 4 July. Soil water content at P_2 was influenced by vine shading between rows and transpiration by oil sunflower, and it was high in Sp and low in intercropping modes. The water content of Sp was 2.09 mm and 5.69 mm, respectively, more than that of IC_1 and IC_2 at harvest.

The changes in water content in the 40–80 cm layer of Sp, IC_1, and IC_2 are shown in Fig. 2. The changes were similar to those in 0–40 cm layer (Fig. 1) and the main differences were that the atmospheric effects weakened with the soil depth and the change of water content of every treatment at different positions also decreased. Figure 2 shows that under the IC_2 regime water was consumed by oil sunflower with great strength and the pumpkin was also affected by competition for water at the fruit setting stage (July 23). The water content of IC_2 in the 40–80 cm soil layer at P_0 was about 7.43 mm lower than that of Sp at harvest stage, while it was 7.02 mm lower than that of Sp at P_2. Water content in IC_1 was about 6.39 mm higher than Sp at P_0. No competition for water existed between pumpkin and oil sunflower in IC_1.

3.2 Effect of intercropping on soil water content at different positions and times

Changes of soil water content were measured at different locations for each treatment (Table 3). There was a significant difference ($P < 0.05$) of soil water content at different soil positions during the early pumpkin growing

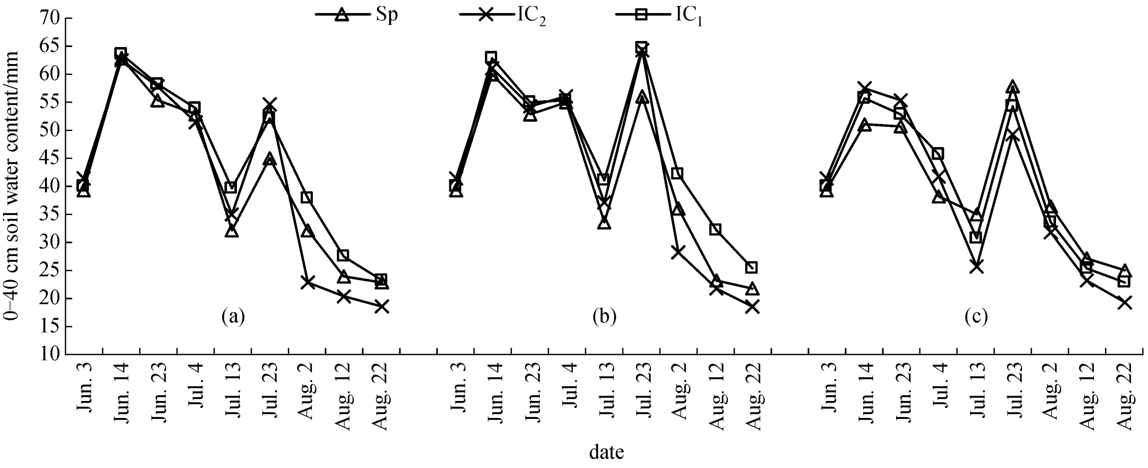

Fig. 1 Soil water content of 0–40 cm at different sites of pumpkin strip in different treatments

Note: (a) represents planting row of pumpkin (P_0), (b) represents 50 cm from planting row of pumpkin (P_1), (c) represents 100 cm from planting row of pumpkin (P_2), which is the same as below.

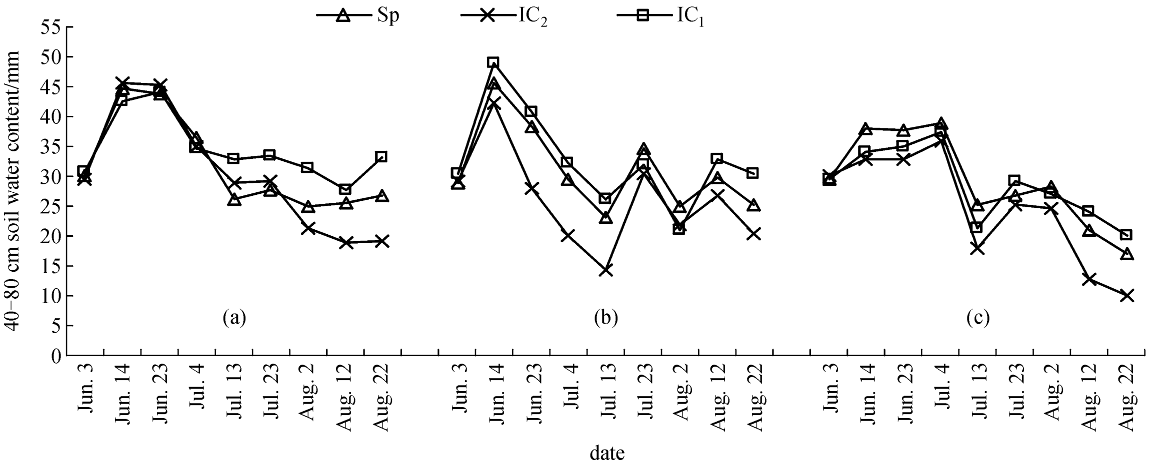

Fig. 2 Soil water content of 40–80 cm at different sites of pumpkin strip in different treatments

Table 3 Soil water content of pumpkin at different sites during different periods (mm)

treatment	seedling stage (Jun. 3–Jun. 23)			vine-extending and flowering stage (Jun. 23–Jul. 23)			fruits growing stage (Jul. 23–Aug. 22)		
	0 cm	50 cm	100 cm	0 cm	50 cm	100 cm	0 cm	50 cm	100 cm
Sp	91.98	88.14	82.03	80.63	79.74	77.60	57.18	62.96	59.75
IC$_1$	93.15	90.56	82.39	87.31	86.71	76.48	66.56	70.06	58.97
IC$_2$	94.02	85.42	83.45	84.28	76.16	70.96	51.28	58.05	48.97

period (June 3–June 23). The water protecting effects of film mulching on the water content at P_0 in the treatment of Sp, IC$_1$, and IC$_2$, were about 3.84 mm, 2.59 mm, and 8.6 mm, respectively, higher than those at P_1. At P_2, it was 9.95 mm, 10.76 mm, and 10.57 mm, respectively, lower than those in P_0. The soil water evaporated heavily during the windy and low humidity weather during the spring on the plateau in northern Hebei Province.

Pumpkin and intercropped oil sunflower grew quickly during the middle stage of pumpkin growing (June 23–July 23), and this stage was also the rainy season of this area. The soil water content changed with the rainfall. The water content at different positions are shown as $P_0 > P_1 > P_2$; and at P_0 the film mulching still showed good water protecting effect.

During the late stage of pumpkin growing (July 23–August 22) the amount of rainfall dropped and it was also a high water consuming stage. It can be found from Table 3 that the water content at every position dropped fast, and the average water content was 51.28–66.56 mm, 58.05–70.06 mm, and 48.97–59.97 mm, respectively, for Sp, IC$_1$, and IC$_2$ at P_0, P_1, and P_2. In Sp the water content also dropped to 59.75 mm in P_2, where there were few roots to consume water. This data shows that high soil surface evaporation consumed much water and decreasing the evaporation and maintaining the transpiration were key measures for water management in this area.

3.3 Effect of intercropping on soil water content with layers at different times

Changes of soil water content at different soil depth layers during the growing season are shown in Fig. 3. The water content varied with the depth of the layers; the soil in 0–20 cm layer was easily affected by atmospheric factors, and the water content increased soon after a rainfall. The water content was also easily affected by evaporation and plant transpiration, so the soil water content change in this layer was wide. Similar but smaller changes were found in the 20–40 cm layer. Water consumed in the deeper soil layer of 40–60 cm layer was relatively less affected compared with the top layer but was also influenced by slow percolation.

The change of deep, 60–80 cm, soil water content was relatively small. As the soil water content decreased by root absorbing and since water moves upward only slowly, the moisture content of this layer was quite stable. In this farming area soil in the 60–80 cm layer normally receives little water by downward percolation due mostly to little rainfall during the season. The soil moisture changed little over the growing season and the treatments also had little effect.

It can be seen from Fig. 3 that the water content at different layers on August 2 showed the same trend, i.e. 0–40 cm > 40–60 cm > 60–80 cm, regardless of the treatment.

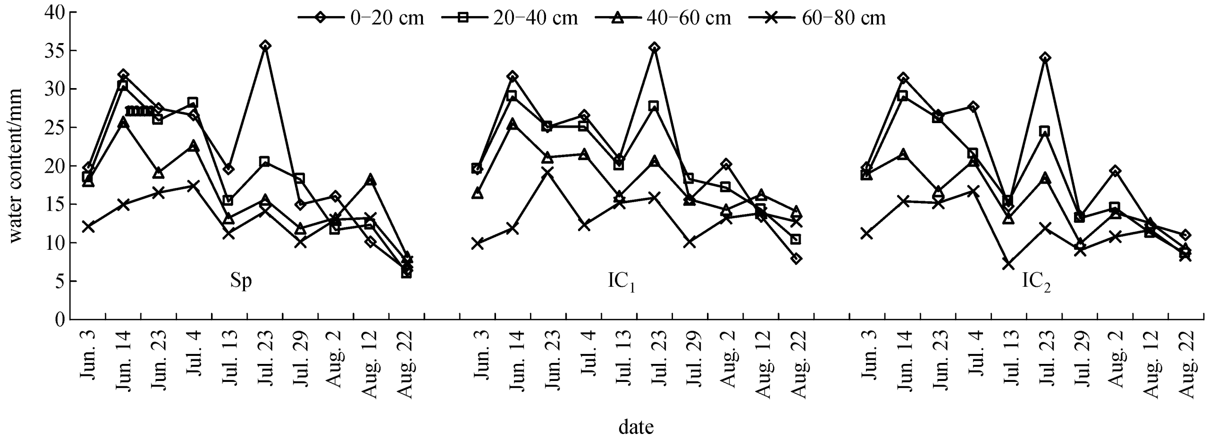

Fig. 3 Soil water content of different soil layers over time by treatments Sp, IC_1, and IC_2

The soil water situation changed after August 2 and we see that the water content in the soil below 40 cm was higher than the above layer. That was because soil in layer 0–40 cm received very little rainfall and soil water evaporation and plant transpiration consumed much water, and these factors had far less influence in the deep layer, 40–80 cm.

3.4 The water balance analysis in intercropping farmland

Changes in every factor of water balance at different growing stages of cropping modes are shown in Table 4. The evapotranspiration was low at the seedling stage of pumpkin (June 3–June 23), only about 6.93%–11.16% of the total. The soil surface was mostly bare in the Sp treatment so evapotranspiration was high and accounted for about 60.58% of moisture loss. During the seedling stage the soil stored water in every treatment.

During the vine extending and flower stages the evapotranspiration increased and was about 40.21%–53.87% of the total moisture loss and in every case the soil water storage amount changed from surplus to shortage. Because the shading effect and relatively small oil sunflower biomass of IC_1 and the evapotranspiration were small, the soil water content increased 9.28 mm in this stage. The coefficient of evapotranspiration of So was 126.04% at this stage and soil water content decreased 25.63 mm. Plants grew fast during the fruit growing stage and the evapotranspiration took about 39.21%–50.53% of the total moisture loss. Soil was the main server for

Table 4 Comparison of water balance in different treatments

stage	rainfall/mm	treatment	payout/mm			percolation coefficient/%	(variation of soil water storage/ rainfall)/%	(evaporation/ rainfall)/%
			water percolation	variation of soil water storage	evaporation			
seedling stage	41.2	So	0.016	25.26	15.92	0.04	61.31	38.64
		Sp	0.016	16.22	24.96	0.04	39.37	60.58
		IC_1	0.084	20.78	20.33	0.20	50.44	49.34
		IC_2	0.013	20.63	20.56	0.03	50.07	49.90
vine-extending and flowering stage	98.1	So	0.08	–25.63	123.67	0.08	26.12	126.04
		Sp	0.121	1.12	96.88	0.12	1.14	98.74
		IC_1	0.619	9.28	88.22	0.63	9.46	89.91
		IC_2	0.142	–0.33	98.31	0.14	0.34	100.19
fruits growing stage	62.3	So	0.043	–27.76	90.02	0.07	44.56	144.49
		Sp	0.006	–39.48	101.77	0.01	63.37	163.35
		IC_1	0.13	–48.71	110.88	0.21	78.19	177.98
		IC_2	0.08	–47.88	110.10	0.13	76.85	176.72
total	201.6	So	0.139	–28.13	229.59	0.07	14.04	113.88
		Sp	0.143	–22.14	223.60	0.07	10.98	110.91
		IC_1	0.833	–18.65	219.42	0.41	9.25	108.84
		IC_2	0.235	–27.59	228.96	0.12	13.69	113.57

evapotranspiration due to rainfall shortage. Because the sunflower treatments, IC$_2$ and IC$_1$ were heavy comsumers of soil water, the soil water content decreased by 47.88 mm and 48.71 mm, respectively. Because oil sunflower consumed much water from the soil at the early stage, there was little water remaining in the soil later in the season and the lower leaves of the plant wilted.

The percentage of percolation of rainfall during the growing stage was small, only 0.07%–0.41%. Rainfall supplied 87.81%–91.88% of evapotranspiration from the land. Soil water played an important role in the crop yield formation, especially in the late growing stage. Much soil water was consumed in the two intercropping systems and pumpkins took the weak position in the competition for water.

3.5 Yield and water use efficiency in sole and intercropping system

Under intercropping field conditions the yield of the compound population was determined by the competition of oil sunflower and pumpkin both above ground for sunlight and underground for water and nutrition. Table 5 shows the yield and water use efficiency of different treatments. The pumpkin yield decreased remarkably as the number of oil sunflower increased. Compared with Sp the yield of pumpkin in IC$_1$ and IC$_2$ decreased by 30.00% and 71.42%, respectively. On the contrary, the plant yield of oil sunflower in the intercropping system increased remarkably compared with So, the yield in IC$_2$ and IC$_1$ increased by 190.71% and 241.26%, respectively.

Crop yields between solo plantings and intercropping differed and oil sunflower showed a strong competitive ability for limited resources and gained a partial advantage. Comparing the production yield by the limited resources we can find that the increased yield of oil sunflower over compensated the loss of the pumpkin; the LER of IC$_2$ and IC$_1$ was 1.08 and 1.22, respectively. Considering the yield from the limited water resources available in this arid region, the WER in IC$_2$ and IC$_1$ was 1.07 and 1.26, respectively.

The economic benefit of pumpkin alone was 1.43 times than that of oil sunflower alone. As the yield of oil sunflower increased in intercropping conditions the economic yield of Sp and IC$_1$ was nearly the same, while for IC$_2$ the economic value decreased by 20.69%. The WUE of IC$_1$ and Sp were nearly the same, while for IC$_2$ and So it decreased by 22.55%–33.14% compared with Sp.

4 Discussion

The environment in the high plateau of northwest Hebei Province is dry and water is usually the main factor that limits the agricultural development of this area. Therefore, selection for drought tolerant crops, reasonable planting modes and readjusting the planting structure are necessary.

Pumpkins with early-maturing and drought-tolerant traits were cultivated under water collection, fertilizer gathering and film mulching conditions. The water supply from rainfall and its loss through evaporation and transpiration were approximately equal. Rainfall filters into the soil and is used in the root area. Soil water evaporation was gradually lessened by the coverage of the pumpkin vines.

The experiment showed that the effect of competition for water was not very serious in intercropping, especially in IC$_1$, but the yield of pumpkin decreased by 30%. The reason might not only be related to crop competition for soil resources, but also for light and energy resources (Meng and Zhou, 1996; Pei et al., 1998). This mechanism is now under further research.

Morris and Garrity (1993) adopted the following method to calculate the water consumed and WUE in sole and intercropping systems: the water captured in intercropping contrasted to sole cropping could be calculated as: $(\triangle WU) = [WU_{ic} / (P_a WU_{sa} + P_b WU_{sb})] - 1$; while for the WUE: $(\triangle WUE) = \{(Y_{ic}/WU_{ic})/[(P_a Y_a/WU_{sa}) + (P_b Y_b/WU_{sb})]\} - 1$; Where ic is crop a and b intercropping; sa and sb is sole cropping a and b; P_a and P_b are the proportions of crop a and b in intercropping system; Y is yield. This way, it is very convenient for two crops that grow parallel upwards

Table 5 Yield and water use efficiency of different treatments

item	Sp pumpkin	IC$_1$		IC$_2$		So oil sunflower
		pumpkin	oil sunflower	pumpkin	oil sunflower	
dry biomass yield/(kg·hm^{-2})	3922.22aA	2986.66bB	4744.7cC	1387.57cB	7520.0bB	10320.0aA
economic yield/(kg·hm^{-2})	10277.78aA	7194.44bA	1530.0cC	2937.50cB	2606.7bB	3586.7aA
per plant economic yield/(g·plant^{-1})	920aA	740bA	108.15aA	450cC	85.50bA	44.83cB
economic value /(yuan·hm^{-2})	20555.6aA	20508.9aA		16301.8bB		14346.8cB
wsater consumption/mm	223.60a	219.42a		228.96a		229.59a
WUE of economics /(yuan·mm^{-1}·hm^{-2})	91.93	93.47		71.20		62.49
LER of biomass	1.00	1.22		1.08		1.00
WER of biomass	1.00	1.26		1.07		1.00

Note: Figures followed by different capital and small letters represent significance at 0.01 and 0.05 probability levels, respectively, according to LSD test.

but it is very difficult to apply when the intercropping crops have very different growing habits as then it is difficult to fix the proportion between crops, as in the oil sunflower and pumpkin intercropping in this experiment. Hence, in this paper a new concept of Water Equivalent Ratio (WER) is proposed to measure the total water needed for sole cropping to acquire the same yield with intercropping. This provides an easy way to calculate the WUE for irregular intercropping contrasted to sole cropping.

In our study of pumpkin and oil sunflower intercropping systems, only one of these crops grows straight up from the soil surface making it hard to calculate the proportion of the crops. Therefore, the WER was used to calculate the WUE of the complex planting system, and the WER was about 1.07–1.26; this result was mainly due to oil sunflower possessing a strong competitive ability for water.

From Table 5 we can see that the WER, comparing only the biomass, was greatest in the IC_1 treatment and each of the other three treatments was about 25% less. However, since pumpkins are a more valuable crop than sunflowers a reduction in pumpkin yield was detrimental. The sole pumpkin and pumpkin plus one row of sunflower treatments, Sp and IC_1, did not differ in economic return. However, as the number of sunflowers increased, IC_2 and So, the economic return significantly declined. This is an example of a situation where production and economic advantage conflict with each other as economic benefit decreases in the intercropping system of low benefit tall stalk plant intercropped with dwarf high benefit plant (Sui et al., 2007).

Hence, using the crop with high production and economic advantage intercropped with suitable subsidiary crops is very important for a successful intercropping.

5 Conclusions

There was no significant competition for water in the oil sunflower-pumpkin intercropping system in the plateau of northwest Hebei Province, though some competition appeared at the late growing stage, especially in the treatment of intercropped 2 rows of oil sunflowers between the pumpkins. The yield of pumpkin in the intercropping system decreased by 30.00%–71.42% compared with pumpkin sole cropping. Hence, the pumpkin sole cropping mode that took much of the space and less land area was the most effective way of economic and high efficient production in this area.

References

Huang W, Zhang J H, Chen J X, Zhang L F (2007). The effect of potassium nutrition on yield and photosynthetic characteristic of small cashew under plastic film mulch cover. Acta Agriculturae Boreali-Sinica, 22(5): 86–89 (in Chinese)

Kang W X, Tian D L, Wen S Z, Chen X Y, Sheng L Y (1992). Studies on water balance and laws of evapotranspiration in a China fir plantation. Acta Phytoecologica ET Geobotanica Sinica, 16(2): 187–196 (in Chinese)

Li J X, Wan Z L (2002). Microclimatic effect and soil moisture change of poplar-wheat intercropping systems in Huaibei. Chinese Journal of Applied Ecology, 13(4): 390–394 (in Chinese)

Liu X Y, Zeng D H (2007). Research advances in interspecific interactions in agroforestry system. Chinese Journal of Ecology, 26 (9): 1464–1467 (in Chinese)

Liu Y H, Zhang L F (2004). Actual productivities of different vegetations in northwest plateau of Hebei Province and strategies of converting farmland to forest and pasture land. Chinese Journal Applied Ecology, 15(11): 2113–2116 (in Chinese)

Liu Y H, Zhang L F (2006). Quantitative evaluation of land use efficiency in different cropping patterns. Scientia Agricultura Sinica, 39(1): 57–60 (in Chinese)

Ma X L, Lu G M, Xu Z L, Song Z M, Meng P, Zhang J S (1997). Distribution characteristic of the root system of forest belt and crop within the composite system of agriculture and forestry. Journal of China Agricultural University, 2(1): 109–116 (in Chinese)

Meng G T, Lang N J, Fang X J, Li G X, Yuan C M, Wen S L (2001). Hydrological properties and water balance of *Pinus armandii* plantation in Central Dian plateau, Yunnan Province. Forest Research, (14): 78–84 (in Chinese)

Meng Y L, Zhou Z G (1996). Studies on growing characteristics of intercropping cabbage with wheat. China Vegetables, (5): 15–17 (in Chinese)

Morris R A, Garrity D P (1993). Resource capture and utilization in intercropping: water. Field Crop Research, 34: 303–317

Pei B H, Jia Y B, Wang W Q, Yuan Y X, Zhang Z J (1998). Light intensity, soil water content and crop output under poplar-crop intercropping system. Journal of Agricultural University of Hebei, 21 (2): 28–33 (in Chinese)

Sui P, Xu C, Qi F, Gao W S (2007). Research of soil water consumption and it's sustaining evaluation of poplar ‖(wheat-corn)-agroforestry in Haihe low plain. Chinese Agricultural Science Bulletin, 23(10): 66–71 (in Chinese)

Wen H D, Li S W, Bi S Q, Zhang L F, Huang Y F (2006). Effects of film mulching on ridge and over furrow for rainwater harvesting and increasing soil thickness on water consumption and yield of pumpkins. Transactions of the CSAE, 22(11): 53–57 (in Chinese)

Wen H D, Liu Y Z, Li X L, Li S W, Wang D W (2002). Water and fertilizer coupling and arid agricultural sustainable development. Soil and Environmental Sciences, 11(3): 315–318 (in Chinese)

Zhang L F, Bian X J, Liu Y H (2001). Studies on water consumption characteristics and effects of crops rotation in plateau of North Hebei Province. Scientia Agricutura Sinica, 34(1): 1–4 (in Chinese)

Zhang W Y, Liu B H, Peng H C, Li A G, Li Y Q (2008). Study on inheritance of the drought-resistance identification indices in wheat varieties. Acta Agricultural Boreali-Sinica, 23: 92–95 (in Chinese)

Zhao Y, Zhang B, Wang M Z (2006). Assessment of competition for water, fertilizer and light between components in the alley cropping system. Acta Ecologica Sinica, 26(6): 1792–1801 (in Chinese)