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Weed Suppression and Plant Interaction in Foxtail Millet and Mung Bean Intercropping System

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Abstract:

The intercropping of cereal crops and legumes might increase yield and improve farmland ecological environment, so it is adopted in many regions, especially in organic management fields. However, the knowledge on the interaction among foxtail millet (*Setaria italica* L.) and mung bean (*Vigna radiata* L.) intercropping and weeds is relatively limited. The field study was conducted in 2021 and included four planting patterns: (1) treatment F1M1, one row of foxtail millet and one row of mung bean; (2) treatment F2M1, two rows of foxtail millet and one row of mung bean; (3) foxtail millet monoculture and (4) mung bean monoculture. In order to clarify the interaction between weed and crop, their emergence, plant height, biomass and yield were investigated. The results showed that the two intercropping patterns both reduced weed emergence amount, significantly suppressed weed density and biomass compared with its monoculture. In intercropping treatment, the plant height, biomass per plant and yield of foxtail millet were higher than that of monoculture, and the biomass and yield of mung bean was lower than that of monoculture. The total yield of treatment F1M1 and F2M1 was 56.0% and 101.6% higher than that of monocultures. The land equivalent ratio of treatment F1M1 and F2M1 were 3.85 and 5.39, respectively. The aggressivity and competitive ratio of foxtail millet in the intercropping system was higher than that of mung bean and the indices of foxtail millet in treatment F2M1 was higher than F1M1. It meant foxtail millet was the dominant species in the intercropping system and foxtail millet in treatment F2M1 had more advantageous than F1M1. To sum up, the foxtail millet and mung bean intercropping patterns could enhance the weed suppression effects by the crops, and increasing the seedling density of the dominant crop foxtail millet could improve the integrative yield, but this could not substantially alter the weed suppression outcomes of the intercropping system. The data and results of this study are helpful to understand the competitive relationship among crops and weeds in foxtail millet and mung bean intercropping system.

***Keywords**: Foxtail millet, Mung bean, Weed suppression, Plant interaction, Competition.*

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I. INTRODUCTION

Foxtail millet and mung bean are suitable for planting in semi-arid areas with barren land and limited input because they are drought tolerant and nutritious [1-4]. Foxtail millet has the characteristics of high photosynthetic efficiency of C4 plants [5], and can be used as food, forage or industrial raw materials after production in China, India, Africa, Japan, the United States, Europe, Australia, the Korean Peninsula and other countries or regions [6-9]. The intercropping of cereal crops and legumes usually improves the biodiversity and functional diversity of the agricultural ecosystem, effectively uses natural resources such as sunlight, heat and precipitation, inhibit weeds, pests and diseases, and improves land use efficiency, so as to increase food production and meet the growing food demand of the population [10-14].

As an important member of farmland ecosystem, weeds have ecological functions such as protecting natural enemies, soil and water conservation, nutrient cycling, eliminating environmental pollution and so on[15]. However, foxtail millet was at a disadvantage in the competition with weeds. On the other hand, though foxtail millet is well known for its potential abiotic stress-tolerance, it is sensitive to most herbicides and lacks safe and efficient herbicides [16,17]. For those reasons, it was hard to control weeds and easy to form weed disaster in the foxtail millet field, resulting in a sharp decline in farmers' economic income. Foxtail millet monoculture and continuous planting would increase the density of weeds year by year and significantly reduce the yield. Therefore, foxtail millet monoculture and continuous planting should be avoided [18]. The application of foxtail millet and peanut intercropping in northern China could alleviate the problems of insufficient production capacity of oil crops and farmland wind erosion, because this intercropping improved the efficiency of light energy utilization [19,20]. The shorter crop could be regarded as cover plant to varying degrees in the intercropping system, and the interactions of crops with weeds were complexly regulated by species traits and environmental resources besides crop biomass [21].

Using the functional diversity of intercropping between foxtail millet and other crops to develop sustainable, ecologically based weed management system [22], so as to reduce the dependence on chemical herbicides, which has important value to the sustainable development of agriculture. At present, the knowledge on the intercropping of foxtail millet and mung bean is limited. Therefore, the purpose of the study was to: (1) clarify the effects of foxtail millet and mung bean intercropping on the emergence and growth of weeds; (2) analyze the effects on the crops growth and yield in foxtail millet and mung bean intercropping system under weed competition; (3) explore the competitive relationship among foxtail millet, mung beans and weeds.

II. MATERIALS AND METHODS

2.1 Experiment Site and Materials

The field experiment was conducted from June 28 to October 12, 2021. The plots were located in Mazhuang (longitude 114°47′E, latitude 37°55'N, altitude 59 m above sea level) from 50 km southeast of Shijiazhuang, Hebei Province. The precipitation received in Mazhuang was 598.8 mm in the cropping

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season Fig 1. The total nitrogen, total phosphorus, available nitrogen, available phosphorus, available potassium and organic matter in the topsoil (0-15 cm) were 1.1 $g\cdot kg^{-1}$, 2.0 $g\cdot kg^{-1}$, 76.1 $mg\cdot kg^{-1}$, 22.1 $mg\cdot kg^{-1}$, 142.4 $mg\cdot kg^{-1}$ and 12.6 $g\cdot kg^{-1}$, respectively. The agricultural management conditions such as watering, fertilization, insecticidal and sterilization were the same. The weeds in the field were evenly distributed, including goosegrass (*Eleusine indica* L.), giant foxtail (*Setaria faberii* Herrm.), redroot pigweed (*Amaranthus retroflexus* L.), purslane (*Portulaca oleracea* L.), which could represent the local weed composition.

The foxtail millet variety was Yugu 18, which was provided by Institute of Millet Crops, Hebei Academy of Agriculture and Forestry Sciences (HAAFS). The mung bean variety was Jilv 19, which was provided by Institute of Cereal and Oil Crops, HAAFS.

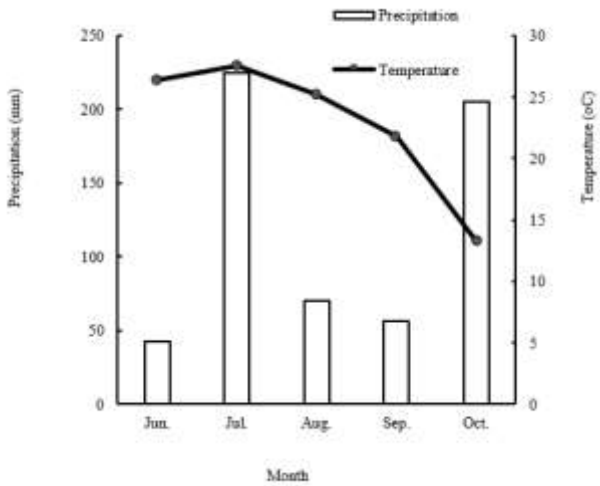

Fig 1: Monthly average precipitation and temperature in the cropping season in Mazhuang

2.2 Intercropping System and Experimental Design

The study was a randomized complete block design with four treatments: (1) treatment F1M1, one row of foxtail millet and one row of mung bean, the interspace was 20 cm, the seedling density of foxtail millet and mung bean were thinned to 416700 $plants\cdot hm^{-2}$ and 178600 $plants\cdot hm^{-2}$ respectively Fig 2a; (2) treatment F2M1, two rows of foxtail millet and one row of mung bean, foxtail millet row spacing 35 cm, one row of mung bean was intercropped in the middle of each two rows of foxtail millet, the seedling density was thinned to 476200 $plants\cdot hm^{-2}$ and 119000 $plants\cdot hm^{-2}$, respectively Fig 2b; (3) treatment MB, mung bean monoculture, row spacing was 40 cm and the seedling density was thinned to 178600 plants hm^{-2}; (4) treatment FM, foxtail millet monoculture, row spacing 40 cm and the seedling density was thinned to 416700 plants hm^{-2}. The thinning operation was executed 19 day after sowing (DAS). Each treatment was replicated 4 times, and each plot size was 5 m long by 5 m wide.

Foxtail millet and mung beans were sown on the same day on June 28, 2021. After sowing, the weeds in the field were allowed to grow freely, and all the weeds in the field were pulled out by hand on August 18. From July 27 to harvest, the plots were covered with a bird proof net to avoid the yield loss caused by birds.

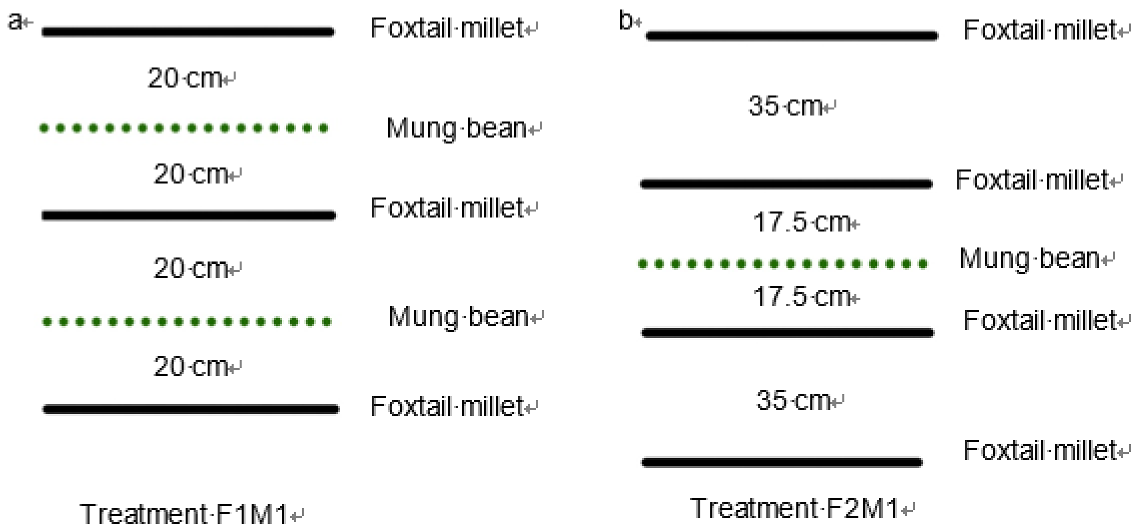

Fig 2: Sketch map of foxtail millet and mung bean intercropping patterns for treatment F1M1 (a) and treatment F2M1 (b)

2.2.1 Weed suppression

Five sampling points of 0.25 m^2 were set on the diagonal of each plot. From 14 DAS, the species and number of weeds in the sampling points were investigated every 7 days until the weeds no longer emerged. After counting, the weeds were manually removed.

Weed species, number and biomass were investigated from another 1 m^2 in the middle of each plot on 35 DAS.

2.2.2 Crop interaction and competition

35 DAS (August 2), 10 plants of foxtail millet and mung bean were selected respectively from each plot, and the plant height and biomass were measured.

The mature mung bean pods of the whole plot were repeatedly harvested twice on September 7 and October 12, respectively. And the pods from the two harvests were then mixed together. The foxtail millet was harvested on October 12, and the ears of the whole plot were cut at the time of harvest. After drying and threshing the harvested mung bean pods and foxtail millet ears, the grain weight of foxtail millet and

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mung bean was weighed respectively.

Land equivalence ratio (LER) is used to compare the utilization efficiency of environmental resources between intercropping and monoculture. When LER is greater than one, it means that the intercropping system promotes the growth and yields of intercropping crops. When LER is less than one, it means that the intercropping system negatively affects the growth and yields of intercropping crops [23, 24]. The formula for calculating LER was:

$$LER = (LER_f + LERm) \quad (1)$$

$$LER_f = \frac{Y_{fi}}{Y_f} \quad (2)$$

$$LER_m = \frac{Y_{mi}}{Y_m} \quad (3)$$

where Y_{fi} and Y_{mi} are the yields of foxtail millet and mung bean in intercropping, respectively, Y_f and Y_m are the yields of foxtail millet and mung bean monoculture, respectively.

The aggressivity index indicates how much the relative yield of crop A is higher than that of crop B in the intercropping system. The calculation formula is [24]:

$$A_{fm} = \frac{Y_{fi}}{Y_f Z_{fi}} - \frac{Y_{mi}}{Y_m Z_{mi}} \quad (4)$$

where Z_{fi} and Z_{mi} are the sowing percentages of foxtail millet and mung bean in the intercropping system, respectively. When A_{fm}=0, the competitiveness of the two crops is equal. When A_{fm} is positive, it means that foxtail millet is the dominant species in the intercropping system, otherwise, mung bean is the dominant species.

The competition rate (*CR*) can evaluate the competition among crops in the intercropping system. The greater the *CR* value, the higher the competitiveness of the crop in the intercropping system. The calculation formula is:

$$CR_f = \frac{LER_f Z_{mi}}{LER_m Z_{fi}} \quad (5)$$

$$CR_m = \frac{LER_m Z_{fi}}{LER_f Z_{mi}} \quad (6)$$

2.3 Statistical Analyses

Randomized block analysis of variance (ANOVA) was performed on the data using SPSS v26.0. Significant differences among treatment means were separated by Tukey's multiple comparison test at the

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0.05 probability level.

III. RESULTS AND DISCUSSION

3.1 Weed Emergence

There were two obvious peaks of weed emergence in all treatments, which appeared at 14 d and 29 d after sowing, respectively. The weed number of the second peak was more than the first peak. After that the number of weeds emerging significantly decreased Fig 3. The number of weeds in different treatments was different in different periods. Among them, the number of weeds that emerged in the first peak of emergence of treatment FM was higher than that of other treatments, and the number of weeds that emerged in the second peak of treatment MB was higher than that of other treatments. The total emerged weeds in different periods of F1M1 and F2M1 were 554.85 and 570.80 plants·m^{-2}, respectively, which were lower than 706.45 plants·m^{-2} and 610.35 plants·m^{-2} in mung bean and foxtail millet monoculture Table I. The results of variance analysis showed that the total number of weeds in mung bean monocropping was significantly higher than that in the intercropping systems F1M1 and F2M1. There was no significant difference in total emerged weeds among F1M1, F2M1 and foxtail millet monocropping.

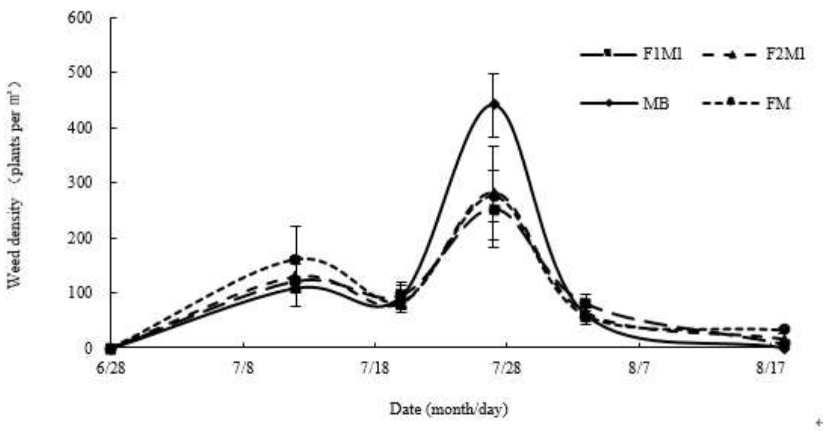

Fig 3: Effects on the regulation of weed emergence

3.2 Weed Density and Biomass

35 days after sowing, the weed density and biomass of F1M1 treatment were 19.86% and 39.73% lower than those of foxtail millet monoculture treatment, respectively, and the weed density and biomass of F2M1 treatment were 23.97% and 38.75% lower than those of foxtail millet monoculture treatment Table I. The results of variance analysis showed that the field weed density and biomass of the intercropping treatments F1M1 and F2M1 were significantly lower than those of the sole cropping treatments. There was no significant difference in the weed density and biomass between the sole crop treatments.

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TABLE I. Amount of weed emergence, density and biomass (35 DAS)

TREATMENT	EMERGENCE (plants·m^{-2})	DENSITY (plants·m^{-2})	BIOMASS (g·m^{-2})
F1M1	554.85±74.27b	117.00±6.61b	991.05±25.44b
F2M1	570.80±81.67b	111.00±5.32b	1007.15±45.38b
MB	706.45±64.55a	139.50±4.43a	1588.6±58.53a
FM	610.35±45.04ab	146.00±2.94a	1644.25±29.99a

Means in a column with the same letters are not significantly different at P =0.05. Below is the same.

Maximize the use of agrobiodiversity function to enhance the complementarity and synergy of beneficial crop traits, of which increasing yield and suppressing weeds are the two main effects. Higher above-ground biomass and a taller canopy were the most suppressive crop stand types [22]. Another study showed that the difference of crop diversity measures caused by different regions can reduce the weed density in the short term and increase the weed diversity in the long term without reducing the weed density [25]. Foxtail millet plants are taller, but the growth rate is slower than weeds at the seedling stage; mung bean grows faster at the seedling stage but lower plant height. Moreover, the field cannot form canopy closure in time as the larger row interspace. The two crops are all at a disadvantage in competition with weeds when they are planted alone because of the above reasons. In the competition with weeds, generally increasing the density of crops, reducing the time of canopy closure and increasing the degree of canopy closure can increase the inhibitory effect on weeds, which was also related to the spatial distribution of crops [26-28]. Community biomass was a major constraint on the maximum diversity of local communities, and more crop biomass means greater weed suppression [29]. Foxtail millet and mung bean intercropping system could make full use of the beneficial traits of each component, thus forming an effective weed suppression compared with monocropping. The total crop density of the two intercropping patterns in this study was the same; however, the former had higher suppression effect on the total amount of weed emergence and biomass than that of the latter, although the difference in the weed suppression was not significant. It implicated that the crop biomass and equal row spacing might involve the weed suppression.

3.3 Crop Growth

The plant height of foxtail millet in F2M1 was the highest, which was 95.25 cm, followed by that in F1M1, which was 91.75 cm, and the plant height of foxtail millet monoculture was the lowest, which was 82.75 cm. The plant height of mung bean in F2M1 was the highest, which was 75.25 cm. The plant height of mung bean in F1M1 was similar to that in mung bean monoculture, which were 69.75 cm and 70.75 cm respectively. The plant height of foxtail millet and mung bean in different treatments were statistically analyzed. The results of analysis of variance showed that there were significant differences in plant height between different treatments, and the P values of plant height of foxtail millet and mung bean were 0.067 and 0.006, respectively; There was no significant difference between replicates, and the P values were 0.38 and 0.16, respectively. The Tukey's results showed that the plant height of foxtail millet and mung bean of

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F2M1 was significantly different from that of foxtail millet monoculture and mung bean monoculture, but not from that of F1M1 Fig 4a.

The intercropping system increased the plant biomass of foxtail millet and inhibited that of mung bean. The biomass per plant of foxtail millet in treatment F1M1 and F2M1 were 22.45 g and 24.50 g, respectively, which increased by 37.22% and 49.76% respectively compared with the foxtail millet monoculture. The biomass of mung beans were 39.82 g and 35.32 g per plant, respectively, which were 21.23% and 30.13% lower than that of mung bean monoculture. The biomass of foxtail millet and mung bean in different treatments were statistically analyzed. The results of analysis of variance showed that there were significant differences in the biomass of crops between different treatments, and the P values of foxtail millet and mung bean were 0.007 and 0.005, respectively. There was no significant difference between foxtail millet and mung bean biomass repetition, and the P values were 0.376 and 0.754, respectively. The results of multiple comparisons showed that there was no significant difference in the biomass of crops between F1M1 and F2M1, which was significantly different from that of foxtail millet monoculture and mung bean monoculture, respectively Fig 4b.

The total biomass of foxtail millet and mung bean in treatment F1M1 and F2M1 were 62.27 g and 59.82 g, respectively, and the former was 4.10% higher than the latter.

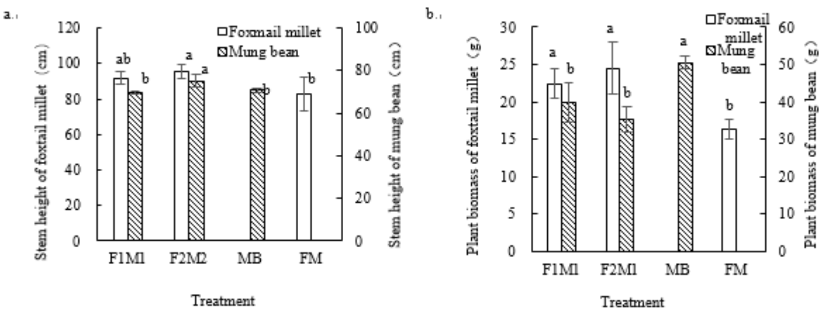

Fig 4: Stem height (a) and plant biomass (b) of crops

3.4 Crop Yield

The seedling of foxtail millet per hectare in F1M1 was the same as that in monoculture pattern, with 416700 plants, and seedlings of foxtail millet per hectare in F2M1 was 476200. The foxtail millet yield of F2M1 was the highest, and the yield was 2143.1 kg·hm^{-2}, which was mainly due to the maximum number of foxtail millet seedlings and weed suppression. Followed by F1M1, yield was 1345.8 kg·hm^{-2}. The foxtail millet monoculture treatment had the lowest yield, only 423.6 kg·hm^{-2}, due to the maximum competitive pressure from weeds. The results of variance analysis showed that the differences among the three treatments containing foxtail millet were significant (p=0.000), and the differences between replicates were not significant (p=0.902) Table II.

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The number of mung bean seedlings in F1M1 was the same as that of mung bean monocropping, both 178,600 plants per hectare. The number of mung bean seedlings in F2M1 was the fewest, at 119,000 plants per hectare. Although mung bean monocropping had the highest total weed emergence amount, the mung bean yield of MB treatment was the highest at 766.8 kg·hm^{-2}, and the mung bean yields of F1M1 and F2M1 were 510.7 kg·hm^{-2} and 251.7 kg·hm^{-2}, respectively. It might be because the mung bean in the treatment of F1M1 and F2M1 not only had the competition of weeds, but also foxtail millet. The results of variance analysis showed that the differences among the three treatments including mung bean were significant (p=0.000), and the difference between replicates was not significant (p=0.696). The results of multiple comparisons showed that there were significant differences in mung bean yield among treatments MB, F1M1 and F2M1.

Table II. Treatment effects on yields of component crops in the intercropping system

TREATMENTS	YIELD (kg·hm^{-2})			CONTRIBUTION (%)	
	FOXTAIL MILLET	MUNG BEAN	TOTAL	FOXTAIL MILLET	MUNG BEAN
F1M1	1345.8±83.2 b	510.7±32.5 b	1856.5±103.6 b	72.49	27.51
F2M1	2143.1±110.7 a	251.7±29.2 c	2394.8±88.9 a	89.49	10.51
MB	-	766.8±46.5 a	766.8±46.5 c	-	100.00
FM	423.6±73.4 c	-	423.6±73.4 d	100.00	–

3.5 Land-use Efficiency and Competition Indexes

The LERs of foxtail millet in the intercropping system were all greater than one, indicating that foxtail millet had higher land use efficiency and better utilization of resources during growth in the intercropping system Table III. The LERs of the intercropping systems were all greater than one, indicating that the land use efficiency of foxtail millet and mung bean intercropping was better than that of the two crops monoculture separately. The aggressivity of foxtail millet in the intercropping system was all positive, and the aggressivity of mung bean was all negative, indicating that foxtail millet occupied a dominant position in the intercropping system. The *CR* of foxtail millet was significantly higher than that of mung bean, which further indicated that foxtail millet had strong competition than mung bean. In addition, the LER, Aggressivity, and *CR* of foxtail millet in F2M1 were higher than those in F1M1, which implicated that the land use efficiency of F2M1 was higher, and the competitive advantage of millet in F2M1 to mung bean was greater than that in F1M1.

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Table III. Land equivalent ratio, aggressivity and competitive ratio for intercropping of foxtail millet with mung bean

TREATMENTS	LER			AGGRESSIVITY		COMPETITIVE RATIO	
	FOXTAIL MILLET	MUNG BEAN	TOTAL	FOXTAIL MILLET	MUNG BEAN	FOXTAIL MILLET	MUNG BEAN
F1M1	3.18	0.67	3.85	5.02	-5.02	4.75	0.21
F2M1	5.06	0.33	5.39	6.60	-6.60	7.67	0.13
MB	0.00	1.00	1.00	-	-		
FM	1.00	0.00	1.00	-	-		

The mechanism of weed suppression and yield increase in intercropping systems was not well understood due to the difficulty of monitoring intercropping/weed utilization of multiple resources during the growing season [30]. The effect of increasing yield after intercropping of upland rice and mung bean was mainly due to the increase of nitrogen absorption and the spatial compensation effect after mung bean harvest [31]. Grain yield and LER of foxtail millet and mung bean intercropping system were better than sole culture of each crop species, the reason was its significant weed suppression. Foxtail millet occupied a dominant position in the intercropping system, and the main factors were its higher plant height and population density. Mung bean was subject to the dual competition of foxtail millet and weeds, and its yield and biomass were lower than those of monoculture. The total yield of treatment F2M1 was higher than that of F1M1, mainly because the higher planting density of foxtail millet, the dominant crop in the intercropping system in F2M1, increased by 14.3% compared with F1M1, although the density of mung bean decreased by 33.3%. In the corn and soybean intercropping system, the corn that occupies the dominant ecological niche was in the dominant position in the competition, not only had the space advantage, but also absorbed more nutrients [32]. In this study, the dominant crop millet contributed more than 70% to the total yield, and mung bean was less than 30%.

IV. CONCLUSION

Emergence, density and biomass of weeds were significantly suppressed in the foxtail millet and mung bean intercropping system. Foxtail millet was the dominant species and improved yield in the intercropping system. Intercrop mung bean was subject to the dual competition of foxtail millet, and yield was declined. Due to the weed suppression by the foxtail millet and mung bean intercropping system, the total crop yield and land use efficiency were significantly higher than that of sole cropping. The results and data of this study are helpful to understand foxtail millet and mung bean intercropping and the competition relationship with weeds, and to establish an intercropping system with better weed control effect. However, the effect of foxtail millet and mung bean long-term intercropping on weed community is still worthy of further study.

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