INTERNATIONAL JOURNAL OF AGRICULTURE & BIOLOGY
ISSN Print: 1560–8530; ISSN Online: 1814–9596
20–0836/202x/00–0–000–000
DOI: 10.17957/IJAB/15.1574
http://www.fspublishers.org

Full Length Article

Maize-Soybean Strip Intercropping Improved Lodging Resistance and Productivity of Maize

Xifeng Chen[1†], Ning Sun[2†], Yan Gu[1*], Yaliang Liu[1], Jianfeng Li[1], Chunsheng Wu[1*] and Zhenmin Wang[1*]
[1]*Department of Agronomy, Jilin Agricultural University, Changchun, 130118, P.R. China*
[2]*Agricultural Resources and Environment Institute, Jilin Academy of Agricultural Sciences, Changchun, 130118, P.R. China*
[*]For correspondence: guyan810831@163.com; wangzhenmin2004@sina.com; wcs8131587@126.com
[†]Contributed equally to this work and are co-first authors
Received 01 June 2020; Accepted 04 July 2020; Published __________________

Abstract

Maize yield is limited by lodging, which increases with increased planting density. The aim of this study was to assess whether lodging could be reduced by changing the planting density through intercropping maize with soybean. Therefore, this study was conducted to evaluate the effects maize-soybean strip intercropping, compared with sole cropping of maize, on stem and root characters, lodging resistance and yield of maize. Maize was sown in strips intercropping as: M_2S_2 (maize-soybean intercropping with 2 row strips of each), M_4S_2 (maize-soybean intercropping with 4 row strips of maize and 2 row strips of soybean), M_4S_4 (maize-soybean intercropping with 4 row strips of maize and soybean) and M_6S_6 (maize-soybean intercropping with 6 row strips of maize and soybean) taking sole maize (M) and sole soybean (S) as control. Compared with its traditional sole cropping, maize-soybean strip intercropping changed the stem characteristics and root architecture of maize populations and significantly improved the lodging resistance. Specifically, plant height, ear height, and center of gravity height of strip intercropped maize was significantly lower; and stem diameter, average stalk crushing strength, and lodging resistance index of each node below the ear level were higher than that of sole cropping. The internode diameter, internode unit fresh matter weight, internode crushing strength, and internode unit bending force of stem internodes (2–10) of strip intercropped maize were higher than that of its sole cropping. Nodes 3–6 affected the lodging resistance of plants, and bar intercropping significantly enhanced the lodging resistance of the above key node positions. Morphological and physiological indexes of the intercropped maize roots were significantly higher than that of sole cropped maize and were positively correlated with stalk resistance index but negatively correlated with lodging rate. The composite yield of crops under different strip intercropping systems was in order as $M_4S_2 > M > M_4S_4 > M_6S_6 > M_2S_2$. Moreover, the land equivalent ratio (LER) of all the strip intercropping treatments was greater than 1.0. In conclusion, strip intercropping of maize with soybean seemed an effective and novel way to resolve lodging in maize coupled with its higher yield. © 2020 Friends Science Publishers

Keywords: Maize-soybean strip intercropping; Sole cropping; Stem characters; Root architecture; Lodging resistance

Introduction

Songliao Plain is an important grain production region and export base in China. It is known as one of the ‘three golden corn belts’ in the world along with those in the United States and Ukraine at the same latitude (Zhang *et al*. 2011). Over the past several decades, the maize (*Zea mays* L.) planting pattern in this area has improved yearly, and the yield has greatly increased (Li *et al*. 2016). Increased planting density plays a key role in improving maize yield (Yang *et al*. 2013). However, in recent years, production density has reached the upper limit under the traditional sole-cropping mode and is often accompanied by the occurrence of field lodging. Therefore, lodging has become the primary factor limiting the increase of planting density and maize yield in Songliao Plain. Many studies have shown that a reasonable increase in density is still an important way to improve maize yield. Historically, records of high maize yield competitions at nationally and abroad were set under the conditions of high density (79500–109500 plants ha^{-1}) (Tollenaar and Lee 2002; Li *et al*. 2016). However, with increased density, the internal structure of the population changes, the development space of a sole plant becomes limited, and the probability of lodging increases. Thus, solving the lodging problem under high-density conditions is a difficult problem in the production of maize. Therefore, many studies have been carried out to determine the causes of maize lodging, regulation measures, selection of lodging resistance indexes, and improvement of maize varieties (Peng *et al*. 2010).

To cite this paper: Chen X, N Sun, Y Gu, Y Liu, J Li, C Wu, Z Wang (202x). Maize-soybean strip intercropping improved lodging resistance and productivity of maize. *Intl J Agric Biol* 00:000–000

Lodging is considered the main limiting factor for high yield, stable yield, and high quality of maize and the main quantitative traits controlling maize yield (Bai *et al*. 2010). It is estimated that yield loss due to the lodging of maize can be around 5–25% or even higher (Tollenaar and Lee 2002). Lodging can be divided into stem lodging and root lodging based on the organ parts where it occurs. Of these, the harm caused by stem folding is more severe (Wilkinson and Davies 2002). Lodging is closely related to crop varieties, climate, soil conditions, and cultivation measures (Novacek *et al*. 2013). First, plant morphological characteristics have a significant effect on the lodging resistance performance. Under adverse conditions, such as low light, plant height increases, while internode elongation, and stem diameter and dry matter accumulation decreases, which increase the lodging risk (Wang *et al*. 2019). Lodging is negatively correlated with aboveground parts such as ear height and center of gravity height and underground traits, such as root weight, root length, and root number (Liu *et al*. 2012). Among them, stem strength contributes the most to lodging followed by root weight (Han 1990). The coordinated growth of stems and roots within the plant population is the primary way to alleviate lodging (Takayuki and Ken 2004). Secondly, the chemical composition and related enzyme activity of the stems are also closely related to lodging (Zhou *et al*. 2007). Studies have shown that the increase of lignin, cellulose and auxin content in maize stalks and the expression of related enzyme genes can enhance the anti-inversion ability of maize stalks (Ma *et al*. 2019). A study on the mechanical properties and anatomical structure of maize stems revealed that the crushing strength, puncture strength and bending strength of the stem are negatively correlated with the lodging rate (Jampatong *et al*. 2000; Robertson *et al*. 2014). Moreover, the anatomical structure of stems, such as the epidermal mechanical cells, mechanical tissues, and vascular bundles, directly affected the mechanical properties of the stems (Xue *et al*. 2016). Additionally, quantitative trait loci analysis revealed that the key genes affecting lodging are located on chromosome 3 (Teng *et al*. 2013; Li *et al*. 2014).

Currently, the methods to improve maize lodging resistance mainly include the selection of lodging-resistant varieties, reasonable planting densities, scientific fertilization, strengthening the prevention and control of disease grass, and spraying plant growth regulators (Liu *et al*. 2012). Although these methods effectively reduce the lodging rate, lodging still cannot be effectively resolved under high-density cultivation conditions. In this study, it was tested that whether strip intercropping pattern of maize and soybean (*Glycine max* L.) can influence lodging resistance of maize, even if the maize is grown at high densities under this cropping pattern. Current studies on this cropping model focus on the efficient utilization of photothermal responses and water resources; the prevention and control of diseases, insect pests, and weeds; and the regulation of nutrient elements in the root system. The effect of strip intercropping on the lodging resistance ability of maize has not been investigated. Therefore, this two-year field study was designed to evaluate the effects of maize-soybean strip intercropping on lodging resistance, productivity and LER of maize crop. This study may provide a theoretical basis and technical support for achieving high-density lodging resistance during maize production in Songliao Plain.

Materials and Methods

Experimental site description

The experiment was conducted in 2016 and 2017 at the agricultural college experiment base of Jilin Agricultural University. The soil was a typical black with an excellent fertility level, rich in organic matter content of 26.9 g kg^{-1}, alkali-hydrolyzed nitrogen of 120 mg kg^{-1}, available phosphorus of 16.5 mg kg^{-1}, available potassium of 122 mg kg^{-1}, total nitrogen of 1.65 g kg^{-1}, total phosphorus of 0.85 g kg^{-1}, and pH of 6.8. The maize variety 'xianyu 335' provided by Denghai pioneer company and soybean variety 'jinong 40' provided by Department of Agriculture, Jilin Agricultural University was used as testing material.

Experimental details

Maize and soybean were sown in strips intercropping as: M_2S_2 (maize-soybean intercropping with 2 row strips of each), M_4S_2 (maize-soybean intercropping with 4 row strips of maize and 2 row strips of soybean), M_4S_4 (maize-soybean intercropping with 4 row strips of maize and soybean) and M_6S_6 (maize-soybean intercropping with 6 row strips of maize and soybean) taking sole maize (M) and sole soybean (S) as control (Table 1). The experiment was laid out following randomized complete block design with 3 replicates of each treatment and net plot size of 65 m^2 (M and S), 52 m^2 (M_2S_2), 78 m^2 (M_4S_2), 104 m^2 (M_4S_4) and 156 m^2 (M_6S_6).

Crop husbandry

Maize and soybean crops were sown on April 28 and 29 during 2016 and 2017, respectively on well prepared seedbed. April 29. After the emergence of seedlings, the seedlings were fixed according to the plant to plant distance of maize (19.23 cm) and soybean (7.6 cm) under sole cropping and strip intercropping condition. Row spacing of maize and soybean all were 65 cm and row spacing of adjacent maize and soybean was 65 cm in strip intercropping. The quantity of fertilizer applied to maize strip was 90 kg nitrogen (N) ha^{-1}, 120 kg phosphorus (P_2O_5) ha^{-1} and 160 kg potassium (K_2O) ha^{-1} before sowing. Additional N fertilizer was applied with a quantity of 140 kg N ha^{-1} for each treatment on 16 June 2016 and 22 July 2017.

The quantity of fertilizer applied to soybean strip was 60 kg P_2O_5 ha^{-1} and 25 kg K_2O ha^{-1} before sowing.

The plants were not irrigated during the whole experimental period, because there was enough rainfall during the growing season. After maize and soybean were sown and before emergence, the plots were sprayed with a pre-emergence herbicide common to maize and soybean for closed soil weeding. The harvest dates were September 28, 2016 and September 30, 2017.

Determination of items and methods

Determination of plant morphological index: The morphological indexes of plants were investigated at the filling period and five successive plants were chosen to measure plant height, ear height, stem diameter (measured at the first internode near the surface), internode length and diameter of 1–10 internodes above ground were measured by tape and Vernier caliper. The height of the center of gravity is the distance from the base of the stem to the equilibrium fulcrum of the stalk (ear, leaf and sheath). The units are in centimeters. Internode fresh weight (1–10 internodes) is weighed using a scale. Internode length/diameter, fresh weight to length of internode (FWLI) was calculated. The calculation formula is as follows:

$$FWLI\ (g/cm) = IFW / IL$$

Here IFW is internode fresh weight and IL is internode length.

Root bleeding quantity and root index investigation

During the filling period, five successive plants were chosen, the main stem was cut off from the basic stem node, and a wound bag filled with absorbent cotton was put on, and collected and weighed for 12 h from 18:00 to 6:00 a.m. the next day. Meanwhile, the number and diameter of aerial roots in soil were investigated. After that, the underground roots were dug out according to the soil volume of 30 cm in length, 30 cm in width and 40 cm in depth. Then, the root related indexes were investigated by washing clean, including the root fresh weight, root diameter, number of root layers, number of nodal roots, and the fresh weight of aerial roots into the soil.

Stalk crushing strength

During the fulling period, five successive plants were chosen, YYD-1 digital dynamometer produced by Aili instrument co., LTD was used to measure the crushing strength of stalk. The measurement method is to place the two ends of each node at the base of 1–10 internodes in the groove of a fixed width support frame, and then slowly press down until the stem is crushed. At this time, the value read is the crushing strength of the node. The formula is as follows:

$$LRI = CS / HCG$$

Here LRI is lodging resistance index, CS is crushing strength and HCG is height of center of gravity.

$$IUBRS = ICS / IL$$

Here IUBRS is internode unit breaking-resistant strength, ICS is internode crushing strength and IL is internode length.

Lodging rate

In the tasseling stage and the mature stage, the percentage of lodging rate of each treatment was investigated. The number of maize plants with stem lodging and root lodging and number of maize plants in the whole plot were recorded. The calculation formula is as follows:

$$LR = NLP / NWP$$

Here LR is lodging rate, NLP is number of lodging plants and NWP is number of whole plants.

Crop yield and Land equivalent ratio

At mature stage, maize and soybean soles were harvested in the middle 2 rows of their plots. The yield of different strip intercropping treatments were calculated in the maize strip by harvesting all the maize in the maize sowing strip and in the soybean strip by harvesting all soybean in the soybean sowing strip. After which, the compound yield of strip intercropping was calculated according to the proportion of maize and soybean area by different treatments and the yield in each strip. Land equivalent ratio (LER) is used to calculate the land use advantage provided by intercropping (Mao *et al.* 2012), as follows:

$$LER = Y_{im} / Y_{mm} + Y_{is} / Y_{ms} \quad (5)$$

Here Y_{im} and Y_{is} are yields of intercropped maize and soybean, and Y_{mm} and Y_{ms} are yields in soled maize and soybean, respectively. They express for each crop species the area of land that would be needed in sole cropping to achieve the same yield as one-unit area of intercrop. When the LER is greater than 1, there is a land use advantage of intercropping.

Statistical analysis

All statistical analyses of the data were done with the (Microsoft Excel 2007 and S.P.S.S. 13.0) after verifying the homogeneity of error variances following one-way ANOVA. Multiple comparisons among the treatments were analyzed with least-significant difference (LSD) test at the 0.05 level of probability.

Results

Yield and land equivalent ratio (LER) comparison

The yield of maize strip under strip intercropping was significantly higher than sole maize (Table 2). In two years, the maize yield in the maize strip intercropping was in order

Table 1: Experiment treatment

Treatment	Maize seeding strip				Soybean seeding strip				Maize and soybean composite area (m^2)
	Strip width (m)	Rows in strip	Plant to plant distance (cm)	Strip area (m^2)	Strip width (m)	Rows in strip	Plant to plant distance (cm)	Strip area (m^2)	
M	6.5	10	19.23	65	--	--	--	--	65
S	--	--	--	--	6.5	10	7.6	65	65
M_2S_2	1.3	2	19.23	13	1.3	2	7.6	13	26
M_4S_2	2.6	4	19.23	26	1.3	2	7.6	13	39
M_4S_4	2.6	4	19.23	26	2.6	4	7.6	26	52
M_6S_6	3.9	6	19.23	39	3.9	6	7.6	39	78

Row spacing of maize and soybean all were 0.65 m, and row spacing of adjacent maize and soybean was 0.65 m in strip intercropping
M= Maize sole cropping; M_2S_2= Maize-soybean 2:2 intercropping; M_4S_2= Maize-soybean 4:2 intercropping; M_4S_4= Maize-soybean 4:4 intercropping; M_6S_6= Maize-soybean 6:6 intercropping

Table 2: Comparison of yield and land equivalent ratio (LER) between strip intercropping and sole cropping of maize and soybean

Year	Treatment	Yield of maize seeding strip (kg ha^{-1})	Yield of soybean seeding strip (kg ha^{-1})	Maize and soybean composite yield (kg ha^{-1})			LER
				Maize	Soybean	Composite yield	
2016	S	--	2948.5a	--	2948.5a	2948.5e	1.000c
	M	11578.5e	--	11578.5ab	--	11578.5b	1.000c
	M_2S_2	19208.3a	1684.6d	9604.1c	842.3c	10446.4c	1.115b
	M_4S_2	17485.2c	1572.2d	11656.8a	524.1d	12180.9a	1.184ab
	M_4S_4	18746.3b	2393.4c	9373.2c	1196.7b	10569.9c	1.215a
	M_6S_6	16827.6d	2685.1b	8413.8d	1342.6b	9756.3d	1.182ab
2017	S	--	2764.6a	--	2764.6a	2764.6e	1.000c
	M	10680.9e	--	10680.9b	--	10680.9b	1.000c
	M_2S_2	18432.8a	1482.9d	9216.4c	741.5d	9957.8c	1.131b
	M_4S_2	16883.7c	1343.6d	11255.8a	447.9e	11703.7a	1.216a
	M_4S_4	17919.0a	2198.6c	8959.5c	1099.3c	10058.8c	1.236a
	M_6S_6	15970.8d	2469.7b	7985.4d	1234.9b	9220.2d	1.194ab

Means with same letters differ non-significantly at $P \leq 0.05$
M= Maize sole cropping; M_2S_2= Maize-soybean 2:2 intercropping; M_4S_2= Maize-soybean 4:2 intercropping; M_4S_4= Maize-soybean 4:4 intercropping; M_6S_6= Maize-soybean 6:6 intercropping

of $M_2S_2 > M_4S_4 > M_4S_2 > M_6S_6 > M$; however, compared with sole maize the yield increased by 69.2, 64.8, 54.5 and 47.4%, respectively. By comparing the compound yield of crops under intercropping and sole cropping, the compound yield of M_4S_2 was higher than that of maize sole cropping. The composite yield of crops under different treatments from high to low was $M_4S_2 > M > M_4S_4 > M_6S_6 > M_2S_2$, sole maize between other treatments reached a significant level. The LER of strip intercropping treatments were more than 1.000, the LER value of M_4S_4 treatment was the highest, the two-year average was 1.23. The LER of different strip intercropping treatment was in order: M_4S_4> M_4S_2> M_6S_6> M_2S_2 (Table 2).

Effects of strip intercropping on plant characteristics and lodging

After strip intercropping, the plant height, ear height, and center of gravity height of the aboveground parts and lodging rate were significantly lower (ranging from large to small were $M > M_6S_6 > M_4S_2 > M_4S_4 > M_2S_2$), while the lodging resistance index, the stem diameter and stalk crushing strength were significantly higher than those of sole cropping (Table 3). The maximum resistance index of strip intercropping was 3.02, while that of sole cropping was only 1.58. From the tasseling to maturity stage, the average lodging rate of the sole cropping increased rapidly from 6.0 to 34.5%, while that of the strip intercropping increased from 0.2 to 1.5 (Table 3). Strip intercropping significantly improved the lodging resistance ability of maize through these stages. All the indexes under strip intercropping were significantly higher than sole cropping. The comparison of four intercropping treatments showed that all the indexes of M_2S_2, M_4S_2, and M_6S_6 treatments reached to a significant level.

Changes in maize stalk internode length under strip intercropping

The internode length of each internode from 2 to 10 was smaller in intercropping than in sole cropping and showed the following pattern: $M_2S_2 < M_4S_4 < M_4S_2 < M_6S_6 < M$ (Fig. 1A). The average length of each internode from 2 to 10 of the four intercropping treatments respectively decreased by 28.63, 14.76, 12.42, 17.77 and 14.75% as compared to the corresponding internodes in sole cropping. The plant height, ear height, and center of gravity height of maize were significantly lower in the intercropping than in the sole cropping, mainly owing to the shortening of each internode length after intercropping.

The maximum internode length was usually located at the 4th node. The LSD $_{(P<0.05)}$ of the low nodes (4^{th}: 2.1393) was generally greater than that of the high node (10^{th}: 0.80). This indicates that the effect of strip intercropping was greater on the length of the lower nodes than on the higher nodes.

Table 3: Maize plant characteristics and lodging rate under different strip intercropping treatments with soybean

Year	Treatment	Plant height(cm)	Ear height (cm)	Centre of gravity height (cm)	Stem diameter (cm)	SCS(N)	Lodging resistance index	Lodging rate (%)	
								Tasseling stage	Maturity stage
2016	M	332.53a	160.23a	127.07a	2.21e	200.61e	1.58e	5.67a	32.67a
	M_2S_2	307.57c	121.20d	112.44d	2.76a	339.66a	3.02a	0.00b	0.00c
	M_4S_2	321.30b	135.60c	120.60b	2.60c	279.19c	2.31c	0.00b	1.33c
	M_4S_4	312.20c	122.87d	116.93bc	2.69b	304.29b	2.60b	0.00b	0.67c
	M_6S_6	325.25b	151.10b	122.83b	2.34d	240.43d	1.96d	0.67b	3.00b
	$LSD_{(P \leq 0.05)}$	2.85	2.14	1.69	0.05	41.82	0.18	0.07	1.42
2017	M	328.50a	151.40a	125.10a	2.00d	165.48e	1.32e	6.33a	36.33a
	M_2S_2	300.83d	118.67e	107.83e	2.44a	321.40a	2.98a	0.00b	0.33d
	M_4S_2	313.87bc	131.60c	114.20c	2.19c	244.42c	2.14c	0.00b	1.67c
	M_4S_4	309.57cd	123.63d	110.83d	2.27b	302.94b	2.73b	0.00b	0.66cd
	M_6S_6	320.90b	138.20b	117.36b	2.16c	215.48d	1.84d	1.00b	4.33b
	$LSD_{(P \leq 0.05)}$	4.40	4.40	1.87	0.04	40.02	0.16	0.07	1.54

Means with same letter differ non-significantly at $P \leq 0.05$

M= Maize sole cropping; M_2S_2= Maize-soybean 2:2 intercropping; M_4S_2= Maize-soybean 4:2 intercropping; M_4S_4= Maize-soybean 4:4 intercropping; M_6S_6= Maize-soybean 6:6 intercropping; SCS= Stalk crushing strength (average of basal 2-10 internodes); LSD= Least significant difference

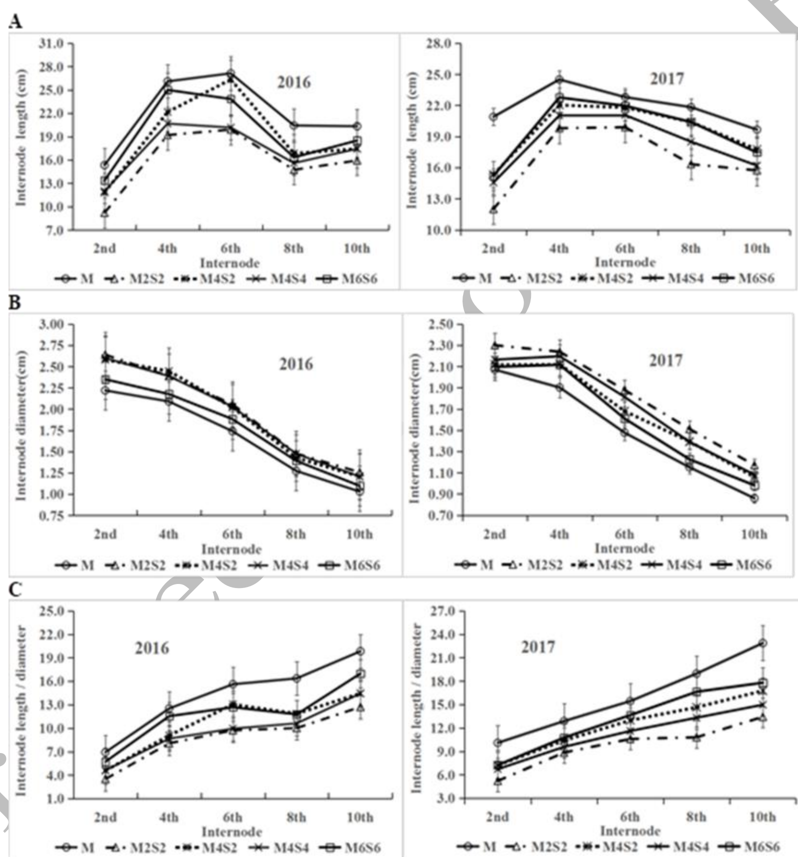

Fig. 1: The change of internode length (**A**), internode diameter (**B**) and internode length /diameter (**C**) under different treatments

2^{nd}= Basal second internode; 4^{th}, 6^{th}, 8^{th} and 10^{th}= fourth, sixth, eighth and tenth internode; M= Maize sole cropping; M_2S_2= Maize-soybean 2:2 intercropping; M_4S_2= Maize-soybean 4:2 intercropping; M_4S_4= Maize-soybean 4:4 intercropping; M_6S_6= Maize-soybean 6:6 intercropping

Changes to the internode diameter of the stalk under strip intercropping

The internode diameters of nodes 2–10 were greater in intercropping than sole cropping (Fig. 1B). In contrast to the pattern observed for the internode lengths, the specific order of the internode diameters for the various treatments, from the largest to smallest, was $M_2S_2 > M_4S_4 > M_4S_2 > M_6S_6 >$ M. The average diameters of internodes 2–10 of the four intercropping treatments were increased respectively by 9.9, 13.3, 16.5, 16.4 and 19.9%, respectively, relative to those of the corresponding internodes in the sole cropping treatment. By comparing the different strip widths of the intercropping treatments, it was found that the average internode diameter of M_2S_2 increased by 3.87, 5.93, and 12.98% as compared to M_4S_4, M_4S_2, and M_6S_6, respectively. The average internode diameter of M_4S_4 was increased by 2.2 and 9.0% as compared to M_4S_2 and M_6S_6, respectively. The diameters of internodes 2–10 increased with both the decrease of the intercropping maize strip width and the increase of the adjacent soybean strip width.

Changes to the internode length/diameter of the stalk under strip intercropping

The internode length/diameter value of M treatment was the highest, followed by the ratio of M_6S_6, with the ratio of M_2S_2 being the lowest, the specific expression was M > M_6S_6 > M_4S_2 > M_4S_4 > M_2S_2 (Fig. 1C). The length/diameter values of internodes 2–10 in M treatment increased by 51.9, 32.1, 31.9, 41.9 and 40.6% relative to the average values of corresponding internodes in strip intercropping. The average internode length/diameter value of M_2S_2 decreased by 12.5, 20.7 and 27.1% compared to M_4S_4, M_4S_2, and M_6S_6, respectively, and the average internode length/diameter value of M_4S_4 decreased by 9.4 and 16.7% compared to M_4S_2 and M_6S_6, respectively.

Changes to internode fresh weight under strip intercropping

For all treatments, the maximum value of internode fresh weight was usually located at the 4th internode (Table 4). The average internode fresh weight followed the order of M_2S_2 > M_4S_4 > M_4S_2 > M_6S_6 > M. The fresh weight of internodes 2–10 of M stalk reached significance with the corresponding internodes of M_2S_2, M_4S_2, and M_4S_4. Compared with the four intercropping treatments, the fresh weight of internodes 2–10 of the M_2S_2 stalk reached significance with those of M_4S_2 and M_6S_6. The LSD $_{(P<0.05)}$ values of internode fresh weight at the low internodes (2^{nd}, 4^{th}) were greater than that at the high internodes (8^{th}, 10^{th}). Strip intercropping had a more significant effect on the internode fresh weight at the low internode.

Comparison of fresh weight per unit internode length under strip intercropping

Table 4 shows that the fresh material weight per unit internode length from internodes 2–10 of intercropping was greater than that of sole cropping (M_2S_2 > M_4S_4 > M_4S_2 > M_6S_6 > M). The difference of the 2^{nd}–10^{th} internodes between M and strip intercropping treatments were reached significance. The comparison of four intercropping treatments showed that, the difference of the 2^{nd}–10^{th} internodes between M_2S_2 and M_4S_2 and M_6S_6 reached significance. The LSD value shows that strip intercropping had a more significant effect on the fresh material weight per unit internode length at the low internode.

Changes in the internode crushing strength under strip intercropping

Comparing the overall average of the 2^{nd}–10^{th} internodes of the four intercropping treatments over two years with the sole cropping showed that the internode crushing strengths of M_2S_2, M_4S_2 and M_4S_4 were significantly higher than M, respectively (Table 4). The overall performance was M_2S_2 > M_4S_4 > M_4S_2 > M_6S_6 > M. The comparison of four intercropping treatments showed that, the difference of the 2^{nd}–6^{th} internodes between M_2S_2 and M_4S_2 and M_6S_6 reached significance. Strip intercropping had a greater influence on the crushing strength of maize stalks at the low internodes.

Comparison of internode unit breaking resistance strength under strip intercropping

The internode unit breaking resistance strength from internodes 2–10 of intercropping were all greater than sole cropping (M_2S_2 > M_4S_4 > M_4S_2 > M_6S_6 > M) (Table 4). M_2S_2, M_4S_2 and M_4S_4 were significantly different from M, respectively. The internode of M_4S_2 and M_6S_6 were significantly different from M_2S_2, respectively. Strip intercropping had a greater influence on the internode unit breaking resistance strength at the low internodes.

Comparison of the root traits of maize under strip intercropping

After strip intercropping, the root fresh weight, root diameter, diameter of aerial roots in soil, fresh weight of aerial roots in soil and root bleeding quantity were significantly greater than those of sole cropping (M_2S_2 > M_4S_4 > M_4S_2 > M_6S_6 > M) (Table 5). And the treatment of M_4S_2, M_4S_4 and M_6S_6 were significantly different from M_2S_2, respectively. The fresh weight of aerial roots in soil of M_2S_2 was 66.72% higher than M_4S_4, M_4S_4 was 13.54% higher than M_4S_2, M_4S_2 was 30.76% higher than M_6S_6 and M_6S_6 was 19.46% higher than M. The root traits of maize increased with both the decrease of the intercropping maize strip width and the increase of the adjacent soybean strip width.

Correlation between lodging and plant traits

The lodging rate was significant negatively correlated with the stalk crushing strength (-0.79**), the lodging resistance index (-0.78**), internode diameter (-0.70*) and internode fresh weight (-0.62*) (Table 6). The lodging rate was positively correlated with the internode length (0.80**), internode length/diameter (0.79**), ear height (0.77**), and the center of gravity height (0.74**). Therefore, the two indexes of stalk crushing strength and internode length could be used to measure the lodging-resistance ability of plants. The lodging rate was significant negatively correlated with the diameter of aerial roots in

Table 4: Comparative of different treatments on the fresh weight, fresh weight to length, stalk crushing strength and unit internode fracture resistance of maize internode

Trait	Year	Treatment	Internode				
			2nd	4th	6th	8th	10th
Fresh weight of internode (g)	2016	M	43.27c	44.43c	27.10d	15.83c	10.57d
		M_2S_2	58.06a	54.08a	41.30a	22.74a	15.03a
		M_4S_2	50.93b	53.4ab	34.37c	19.41b	12.06c
		M_4S_4	55.15a	54.18a	36.62b	20.30b	12.83b
		M_6S_6	45.65c	49.34b	33.47c	19.76b	11.83c
		LSD $_{(P<0.05)}$	3.21	4.43	2.12	1.72	0.51
	2017	M	39.99c	35.96e	20.54d	9.36d	5.09c
		M_2S_2	42.93a	51.09a	37.35a	18.63a	10.05a
		M_4S_2	41.50b	42.81c	28.85b	16.19b	7.08b
		M_4S_4	42.53ab	50.29b	30.73b	16.58b	9.37a
		M_6S_6	39.79c	38.82d	25.67c	12.70c	5.94bc
		LSD $_{(P<0.05)}$	2.13	2.61	2.13	1.35	0.78
Fresh weight per unit internode length (g/cm)	2016	M	2.83d	1.71c	1.00c	0.78c	0.52c
		M_2S_2	6.31a	2.82a	2.09a	1.55a	0.95a
		M_4S_2	4.32b	2.42b	1.31b	1.15b	0.69b
		M_4S_4	4.60b	2.63ab	1.82a	1.30b	0.74b
		M_6S_6	3.43c	1.98c	1.40b	1.22b	0.64b
		LSD $_{(P<0.05)}$	0.33	0.16	0.22	0.13	0.04
	2017	M	1.91c	1.47c	0.90d	0.43d	0.26c
		M_2S_2	3.58a	2.58a	1.88a	1.14a	0.64a
		M_4S_2	2.71b	1.94b	1.32bc	0.79bc	0.40b
		M_4S_4	2.92b	2.39a	1.46b	0.90b	0.58a
		M_6S_6	2.62b	1.71b	1.17cd	0.62c	0.34bc
		LSD $_{(P<0.05)}$	0.18	0.13	0.11	0.06	0.05
Internodecrushing strength (N)	2016	M	214.30d	181.47c	141.07c	127.63c	85.67d
		M_2S_2	399.17a	321.13a	230.50a	203.17a	117.70a
		M_4S_2	331.07b	265.07b	183.23b	146.83b	100.53c
		M_4S_4	356.20b	289.70a	223.47a	174.47b	106.33b
		M_6S_6	273.12c	205.80bc	181.63b	141.02bc	93.92cd
		LSD $_{(P \leq 0.05)}$	37.14	27.19	26.67	31.79	14.64
	2017	M	216.43d	139.23c	93.00c	72.37bc	45.03c
		M_2S_2	443.43a	272.67a	200.50a	101.30a	65.87a
		M_4S_2	360.00b	194.10b	153.33b	97.83ab	64.30ab
		M_4S_4	423.00b	266.37a	163.93a	98.67ab	62.73ab
		M_6S_6	289.17c	166.97bc	115.10c	88.53b	51.17bc
		LSD $_{(P \leq 0.05)}$	15.69	11.07	17.16	9.13	7.58
Unit internode fracture resistance (N/cm)	2016	M	14.06d	6.98d	5.19c	6.34d	4.22e
		M_2S_2	43.42a	16.79a	11.68a	13.81a	7.43a
		M_4S_2	28.11c	12.00c	6.96b	8.73c	5.77c
		M_4S_4	29.86b	14.11b	11.10a	11.17b	6.58b
		M_6S_6	20.58c	8.25d	7.63b	8.65c	5.08d
		LSD $_{(P \leq 0.05)}$	3.11	1.64	1.08	1.52	0.58
	2017	M	10.36d	5.68c	4.08c	3.31c	2.29d
		M_2S_2	36.95a	13.77a	10.08a	6.20a	4.19a
		M_4S_2	23.48c	8.81b	7.03b	4.80b	3.62b
		M_4S_4	29.04b	12.66a	7.78b	5.33a	3.87ab
		M_6S_6	19.02c	7.33b	5.24c	4.34b	2.93c
		LSD $_{(P \leq 0.05)}$	1.89	1.45	1.08	0.56	0.42

Means with same letters differ non-significantly at $P \leq 0.05$

2nd= Basal second internode; 4th, 6th, 8th and 10th= fourth, sixth, eighth and tenth internode; M= Maize sole cropping; M_2S_2= Maize-soybean 2:2 intercropping; M_4S_2= Maize-soybean 4:2 intercropping; M_4S_4= Maize-soybean 4:4 intercropping; M_6S_6= Maize-soybean 6:6 intercropping; LSD= Least significant difference

the soil (-0.74**), fresh weight of aerial roots in the soil (-0.65*) and the root bleeding quantity (-0.61*). The key root traits affecting the lodging rate included diameter of aerial roots and fresh weight of aerial roots in the soil.

Discussion

Many studies have shown that the lodging rate is positively correlated with plant height, ear height, center of gravity height, and basal internode length (Sangoi *et al*. 2002; Fallah 2012). Conversely, the lodging rate is negatively correlated with the stem thickness, internode cross-sectional area, basal internode weight, and other morphological traits (Zhang *et al*. 2018). Usually, with increased plant density, the stem internode length increases, and the stem thickness significantly decreases, which results in the decline of the

Table 5: Comparison of root-related traits under different maize-soybean intercropping systems

Years	Treatments	Root fresh weight (g)	Root diameter (cm)	The root layer (layer)	Number of nodal root (loaf)	Number of aerial roots in soil (loaf)	Diameter of aerial roots in soil (cm)	Fresh weight of aerial roots in soil (g)	Root bleeding quantity (g)
2016	M	91.53e	2.21d	6.00b	44.67c	15.33c	0.47c	14.30e	35.48e
	M_2S_2	206.99a	2.80a	7.33a	58.00a	23.00a	0.61	41.02a	68.27a
	M_4S_2	127.60c	2.61b	6.67ab	48.33b	18.00b	0.53c	21.91c	46.37c
	M_4S_4	145.84b	2.70ab	6.67ab	50.33b	18.67b	0.57b	25.03b	52.00b
	M_6S_6	109.09d	2.34c	6.00b	45.67c	15.67c	0.49d	17.054d	40.15d
	LSD $_{(P \le 0.05)}$	16.32	0.12	0.10	1.77	1.50	0.03	0.56	2.64
2017	M	80.45e	2.07d	6.00b	43.33d	14.67c	0.46e	12.60e	32.32e
	M_2S_2	190.94a	2.45a	7.00a	56.67a	22.00a	0.60a	38.50a	60.60a
	M_4S_2	115.04c	2.19bc	6.33ab	45.67c	17.67b	0.54c	20.10c	40.92c
	M_4S_4	135.37b	2.28b	6.67ab	48.6Bb	18.33b	0.57b	22.67b	45.69b
	M_6S_6	92.94d	2.17c	6.00b	44.33cd	15.33c	0.49d	15.08d	36.76d
	LSD $_{(P \le 0.05)}$	18.65	0.12	0.10	1.88	0.91	0.02	0.74	4.74

Means with same letters differ non-significantly at $P \le 0.05$
2nd= Basal second internode; 4th, 6th, 8th and 10th= fourth, sixth, eighth and tenth internode; M= Maize sole cropping; M_2S_2= Maize-soybean 2:2 intercropping; M_4S_2= Maize-soybean 4:2 intercropping; M_4S_4= Maize-soybean 4:4 intercropping; M_6S_6= Maize-soybean 6:6 intercropping; LSD= Least significant difference

Table 6: Correlation between lodging rate and plant traits (degree of freedom= 9)

Crop traits		Lodging rate (%)
Stem	Plant height (cm)	0.74**
	Ear height (cm)	0.77**
	Centre of gravity height (cm)	0.74**
	Stem diameter (cm)	-0.62*
	Length of internode (cm)	0.80**
	Internode diameter (cm)	-0.70*
	Internode length /diameter	0.79**
	Internode fresh weight (g)	-0.62*
	SCS (N)	-0.79**
	LRI	-0.78**
Root	Fresh root weight (g)	-0.61*
	Diameter of aerial roots in soil (cm)	-0.74**
	Weight of aerial roots in soil (g)	-0.65*
	Root bleeding quantity (g)	-0.61*

*and** denote significance at 5% and 1% probability levels, respectively
SCS= Stalk crushing strength; LRI= Lodging resistance index

stem's lodging resistance (Zhao *et al*. 2009; Ignacio and Tony 2011). Presently, plant growth regulators are widely used in maize production to improving the stem lodging resistance (Zhang *et al*. 2014; Xu *et al*. 2017). In this study adopted the planting mode of maize-soybean strip intercropping was used to significantly improve the lodging resistance of maize. Strip intercropping to make the plant height, ear height, the center of gravity height, the internode length and the internode length/diameter of maize plants significantly lower than those of sole cropping. Strip intercropping could reduce plant height, ear height, and height of center of gravity height by shortening the length of internodes 2–10. The internode diameter, fresh weight, and unit fresh matter weight of internodes were all greater in the intercropping than in the sole cropping. Ma *et al*. (2016) found that the stem diameter had the greatest influence on the lodging-resistance ability of plants. Kaack *et al.* (2003) believed that lodging was not significantly correlated with plant height and that the ear height coefficient is an important index to evaluate the lodging resistance of plants. Thus, the evaluation index of stem lodging resistance of maize is still controversial. In this study, the internode length of 3rd–6th internodes of maize were considered an important index to evaluate lodging resistance. Chen *et al*. (2011) suggested that with the decrease of the longest internode and the substantial increase of each internode length, plants were prone to lodging. Similar results were observed in the current study; after intercropping, the shortening of the internode length and an increase of the internode fresh weight and crushing strength of maize were more obvious at the lower internodes (2nd–4th internodes) than at the higher internodes (6th–10th). These effects on the morphology of different nodes, mechanical properties, and assimilate partition enhanced the lodging-resistance ability of plants under strip intercropping.

Stem mechanical properties were significant negatively correlated with the lodging rate (Robertson *et al.* 2014), which is usually measured by the puncture strength of hard skin, crushing strength, and bending resistance strength (Dudley 1994; Kang *et al*. 1999). Maize densification increased the competitive pressure among the individual plants and affecting the anatomical structure and mechanical strength of the stems (Han 1990; Novacek *et al*. 2013). Thomison *et al*. (2011) believed that at higher the densities there is a greater decrease of stem crushing strength and the more obvious colony lodging was. In the current study, intercropping maize with soybean improved the stem mechanical properties and significantly increased the internode crushing strength, internode unit bending force, and comprehensive lodging-resistance index of internodes 2–10. The increased mechanical resistance was owing to the increase of the internode diameter and the internode unit fresh weight. Feng *et al*. (2008) also believed that stalk thickness below the ear level was significantly correlated with stalk strength, in which the 3^{rd} internode was the most closely correlated with lodging (Gaarcia *et al*. 2003). Other studies have shown that the lodging rate can be effectively reduced by spraying plant growth control agents, mainly by significantly increasing the stem folding resistance and stem skin puncture strength in sections 3, 4, and 5 aboveground (Xu *et al*. 2019). In the current study, the mechanical resistance indexes of the 3^{rd}–6^{th} stem internodes significantly improved after intercropping, which contributed the most to improving the plant's comprehensive lodging resistance. Therefore, in this study considered the 3^{rd}–6^{th} internodes to be the key nodes affecting lodging. In future cultivation and breeding research, the crushing strength, resistance index, and internode length of the 3^{rd}–6^{th} internodes of the aboveground stem can be used to measure the lodging-resistance ability of a plant.

The traits of the aboveground stems and belowground roots were the two major factors affecting lodging (Fan *et al*. 2012). The number of aerial roots, the number of layers, and root quality were important indicators of the root resistance to lodging (Liu *et al*. 2011). Spraying plant growth regulators could increase the number of aerial rooting layers and strips, improve the quality of dry matter and root activity, and thus, improve the lodging-resistance ability of spring maize (Lan *et al*. 2011; Xu *et al*. 2014). In the current study, the adoption of strip intercropping had significantly increasing indexes such as the root fresh weight, traits of aerial roots in the soil, and root bleeding quantity relative to those in sole cropping. All root traits were significantly negatively correlated with the lodging rate. Some researchers have suggested that the number of aerial roots in the soil had the most significant effect on lodging (Feng *et al*. 2008). In the current study, the diameter and fresh weight of aerial roots in the soil had the most significant effect on lodging. There were also differences in the ability to resistance lodging under different intercropping treatments, mainly caused by the action of the stem and root traits resistance to lodging. With the increase of in the width of the maize sowing band, the lodging-resistance ability of the maize plants decreased gradually and became similar to that in the sole cropping. When the width of the maize strip was fixed, the lodging-resistance ability of maize increased with the increasing width of the adjacent soybean bands. In the cultivation of maize, we can reasonably adjust the width of the two crops according to this concept and seek the best lodging-resistance model. The overall lodging-resistance ability of plants under the different treatments was M_2S_2 > M_4S_4 > M_4S_2 > M_6S_6 > M. The land equivalent ratios of maize-soybean strip intercropping were all greater than 1, which had the advantage of intercropping.

Conclusion

Results revealed that lodging resistance of maize plants was increased by strip intercropping relative to its sole cropping. Under high-density conditions, maize-soybean strip intercropping seemed an effective and novel way to resolve sole crop lodging and to increase the green yield in Songliao Plain. Moreover, the lodging resistance ability of maize differed between different strip widths; therefore, appropriate density and ratio of strip widths in intercropping should be studied further to maximize densification resistance along with higher yield.

Acknowledgements

This research was supported by Project of Education Department in Jilin (No. JJKH20190934KJ), by China national key research and development plan (No.2017YFD0300607), by the innovation and entrepreneur ship project for college students of Jilin Agricultural University (No.201810193022).

Author Contributions

X Chen, Y Gu and C Wu planned the experiments, Y Gu and Z Wang interpreted the results, X Chen, N Sun and Y Gu made the write up, Y Liu and J Li statistically analyzed the data and made illustrations.

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