Effects of the twin-row planter with subsoiling on soybean growth and yield in northern China

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Abstract

Twin-row ridge cultivation is widely used in soybean planting in northern China. In order to find the optimal parameters of soybean agronomy, the twin-row planter with subsoiling was designed. Field experiments were conducted to evaluate the effects of plant arrangements and cluster densities on soybean growth and grain yield under different tillage treatments. The experiment used a randomised complete block design consisting of 20 treatments in a 2×2×5 factorial arrangement. Two tillage treatments were inter-row subsoiling and no subsoiling. Each tillage treatment included the combination of plant arrangements (side-by-side arrangement and triangular arrangement) and cluster densities (one, two, three, four, and five plants). The variables measured included soil moisture content, seedling emergence, biomass accumulation and allocation, and grain yield. We have concluded that the performance of inter-row subsoiling treatment was much better than that of no subsoiling treatment. Meanwhile, the triangular arrangement and two plants per cluster were the best choices for soybean biomass accumulation and grain yield in northern China. This study provided a reference for the innovative design of the twin-row planter with subsoiling and the optimisation of soybean agronomy.

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Key words: Soybean planter; twin-row ridge cultivation; seedling emergence; biomass accumulation and allocation; grain yield.

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Introduction

Soybean is the crop with the highest protein content and the primary source of vegetable fat, providing 60% vegetable protein and 30% fat for the world (Thuzar *et al*., 2010; Tilman *et al*., 2011). China is one of the leading soybean-producing areas in the world, and soybean production in China ranks fifth in the world (Wu *et al*., 2015). Soybean planting areas are mainly concentrated in northern China, where the twin-row ridge cultivation is generally adopted (Song and Zhang, 2020). The cultivation requires that two rows are planted on one 65-70 cm wide ridge, and the row spacing is 10-15 cm. Compared with single-row ridge cultivation, twin-row ridge cultivation could increase grain yield by 15-20% and increase fertiliser use efficiency by 10% (Liu *et al*., 2010).

Plant arrangement and density are two important factors affecting crop growth and yield. Scholars at home and abroad have conducted a series of in-depth studies on the two factors. Amzad *et al*. (2005) reported that to reduce weed interference and obtain a higher yield, turmeric should be planted in a 30-cm-triangular arrangement on a twin-row ridge in a 75-100 cm width. Qin *et al*. (2015) found that the yield of spring maize in the triangular arrangement was 5.3% higher than that in the equal distance arrangement. Langdon *et al*. (2008) showed that the twin-row triangular layout gave better results than the single-row layout for golden finger bananas (*Musa* spp., AAAB). The relatively uniform plant density led to rational dry matter partitioning and high yield (Bruin and Pedersen, 2009; Qi *et al*., 2009). Kuai *et al*. (2015) found that a higher plant density produced fewer pods and reduced the yield per plant, but the wider row spacing at higher plant densities increased seeds per pod and the 1000-seed weight, resulting in a higher yield per plant. It can be seen that there were many studies on plant arrangement and plant density, but there was no report on the influence of plant arrangement and plant density and their interaction on the emergence and growth of soybean under the twin-row ridge cultivation.

Another important factor affecting crop growth and yield is subsoiling, which generally refers to tillage with a working depth of 25 cm or more. Subsoiling is an important technique to improve soil properties, especially for farmland with a plow pan resulting from long-term rotary tillage and shallow plough. Subsoiling tillage could loosen the soil, fracture the plough pan, increase the infiltration of soil moisture and nitrogen in subsoil layers, improve the vertical and horizontal extension of the maize root system in the soil, and increase the soil grain yield (Feng *et al*., 2018). Thériault *et al*. (2009) found that subsoiling could improve soil physical properties of cultivated histosols in the short term. Guaman *et al*. (2016) reported that inter-row subsoiling improved soil penetration resistance, root length density and nitrogen uptake, and increased potato yield. Sun *et al*. (2017) reported that subsoiling practices changed root distribution and increased post-anthesis dry matter accumulation and yield in summer maize. However, there is no report on the interaction of subsoiling with plant arrangement and plant density on soybean growth.

In order to realise seeding and subsoiling at the same time, some researchers have studied the relevant machinery. Lu *et al*. (2019) designed a no-tillage and subsoiling planter to adapt to the condition of a large amount of wheat straw mulch, and the experimental results showed that the straw removal rate was 85%, the subsoiling depth was 30-35 cm. Liu *et al*. (2022) designed a planter with strip subsoiling and layer fertilisation, which solved the straw clogging problem of furrow openers in Northeast China. Rahimov and Ponomariva (2008) optimised the parameters of the shovel seeders and offered a new scheme of the vibrating distribution device for shovel seeders. However, no relevant studies have been found on the soybean planter with subsoiling under twin-row ridge cultivation.

In order to realise twin-row ridge cultivation and inter-row subsoiling simultaneously, the twin-row planter with subsoiling was designed and built to study the effect of plant arrangement and plant density on plant density on soybean growth and yield under two different tillage treatments.

Materials and methods

Twin-row planter with subsoiling

In order to adapt to the agronomic requirements of soybean planting in northern China, the twin-row planter with subsoiling was designed (Figure 1). The machine could complete the operations of fertilisation, subsoiling, twin-row seeding, soil covering, and soil compaction at one time. The main technical parameters of the machine are shown in Table 1.

The air-suction seed metering device with the integrated double-cavity structure is the key component to realising soybean twin-row planting in one ridge, and its structure is shown in Figure

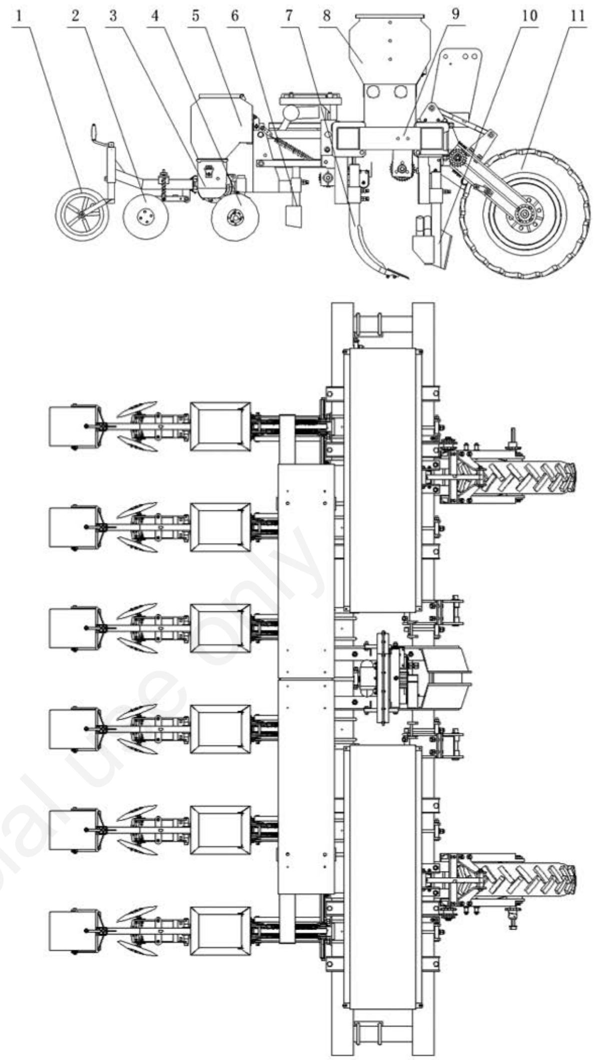

Figure 1. Twin-row planter with subsoiling for soybean: (1) press roller, (2) covering device, (3) seed metering device, (4) seed furrow opener, (5) seed box, (6) straw cleaner, (7) subsoiler, (8) fertiliser box, (9) frame, (10) fertiliser furrow opener, (11) land wheel.

Table 1. Main technical parameters of the twin-row planter with subsoiling for soybean.

Main technical parameter	Value or type
Overall dimension, L×W×H (mm×mm× mm)	3380×4850×1780
Mass (kg)	2700
Matched power (kw)	88.2
Number of sowing units	6
Number of subsoilers	7
Type of connection with the tractor	Three-point quick-attaching coupler
Fertiliser opener	Sliding knife opener
Subsoiler	Chisel subsoiler
Seed opener	Double-disc opener
Covering device	Disk coverer
Press wheel	Cylindrical roller with rubber surface

2A. When the seed metering device is working, a negative pressure air flow is introduced into the air chamber, and at the same time, the left and right sucking plates rotate under the drive of the shaft. Under the action of the negative airflow pressure, the seeds are adsorbed on the hole to rotate with the left and right sucking plates. The left and right cleaners remove the excess adsorbed seeds around the hole, and the seed remaining on the hole continues to rotate until it reaches the end of the air chamber. At this time, the negative pressure air flow disappears, and the seed begins to fall under the action of gravity and centrifugal force. Finally, the seeds of the left and right seed cavities fall into different seed furrows to realise twin-row soybean planting in one ridge. In addition, different seed arrangements and cluster densities can also be adjusted in the seed metering device. The triangular arrangement can be realised by staggering the right sucking plate from the left one by a specific angle. The different cluster densities can be adjusted by changing different seed-sucking plates, whose structures are shown in Figure 2B.

Study site

The experimental site is the test field of Jilin University (43.95°N, 125.25°E, elevation 249 m) in Changchun, Northeast China. The average temperature from April to October is 14.9-24.2°C. The former crop of the plot was maize, and there was no stalk and stubble mulching on the ground. The soil's physical and chemical properties of the experimental site are shown in Table 2.

The precipitation significantly impacts crop growth, so it is necessary to understand the local precipitation during the growing season. The monthly average precipitation during the growing season is shown in Table 3. The actual precipitation during the 2020 year growing season was more sufficient than that during the 2019 year and the 10-year average.

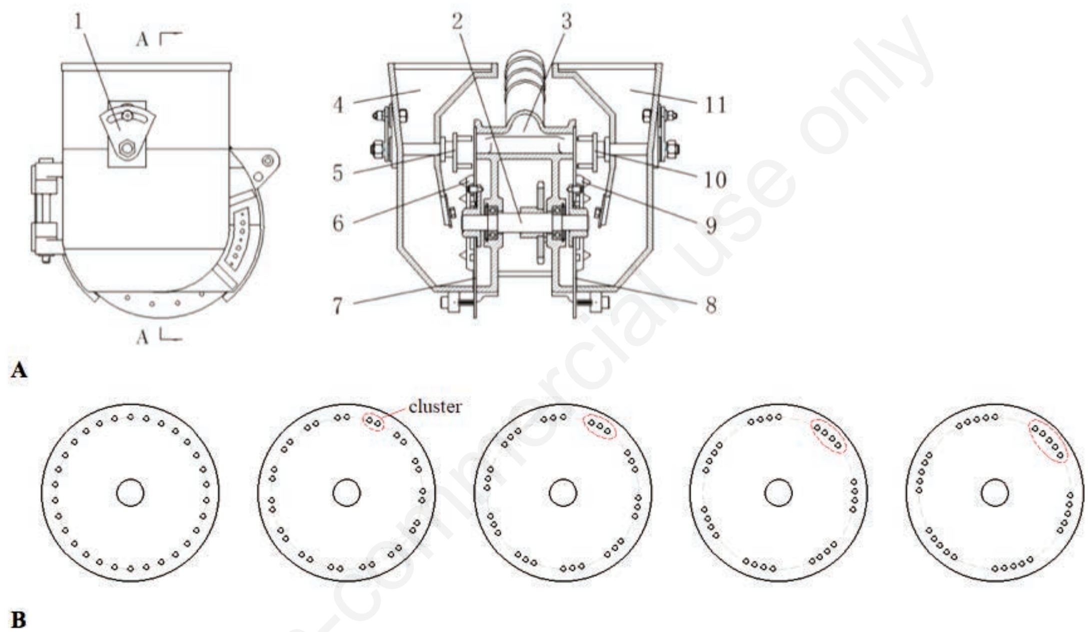

Figure 2. Air-suction seed metering device with the integrated double-cavity structure. A) Seed metering device: (1) Seed cleaning regulator, (2) shaft, (3) air chamber, (4) left seed cavity, (5) left cleaner, (6) left churning plate (7) left sucking plate, (8) right sucking plate, (9) right churning plate, (10) right cleaner, (11) right seed cavity. B) Seed-sucking plates with the various cluster densities.

Table 2. Some physical and chemical properties at soil depths 0-100 mm and 100-200 mm from the experimental site before the test.

Properties	Values	
	0-100 mm depth	100-200 mm depth
Texture values	Clay	–
Cloddiness (mm)	11.8	–
Cone index (MPa)	0.851	3.918
Bulk density ($g \cdot cm^{-3}$)	1.184	1.252
Soil moisture content (%, volume)	13.2	14.3
Mean annual temperature of soil (°C)	14.8	13.9
pH value	7.02	7.04
Soil organic matter (%)	2.37	2.45
Total soil N (%)	0.27	0.25
Available P (P_2O_5, mg/kg)	16.9	16.1
Available K (K_2O, mg/kg)	155.6	162.5

Treatment methods

Before the experiment, the land preparation was carried out in early April 2020. A combined land preparation machine was used to complete rotary tillage, ridging, and surface compaction simultaneously, finally forming the smooth ridges with a width of 70 cm and a height of 20 cm. The experiment used a randomised complete block design, with 20 treatments, in a 2×2×5 factorial arrangement. The treatments consisted of the interactions between the following factors: tillage treatments, plant arrangements, and cluster densities.

Tillage treatments included inter-row subsoiling and no subsoiling. In the inter-row subsoiling treatment, a chisel subsoiler was used to work in the ridge ditch, and the theoretical depth of subsoiling operation was set to 30 cm. The subsoiler was removed from the machine during the work process in the no subsoiling treatment. Two plant arrangements were applied to each block, a side-by-side arrangement and a triangular arrangement, as shown in Figure 3. The plant arrangements were also the seed arrangements after sowing, which was achieved by adjusting the relative positions of the left and right sucking plates in the seed metering device. In the side-by-side arrangement treatment, the left and right sucking plates perpendicular to the axis were completely symmetrical. In triangular arrangement treatment, the left and right sucking plates perpendicular to the axis were staggered at a specific angle equal to half of the angle between two adjacent holes in the same sucking plate. Five kinds of cluster densities, including one plant (1P), two plants (2P), three plants (3P), four plants (4P), and five plants (5P), were carried out in each block. The nearby plants (seeds) were seen as a whole, that is, cluster and the number of plants (seeds) on each cluster is called the cluster density, as shown in Figure 3. The cluster density was adjusted by replacing the different sucking plates, where the hole distributions were different.

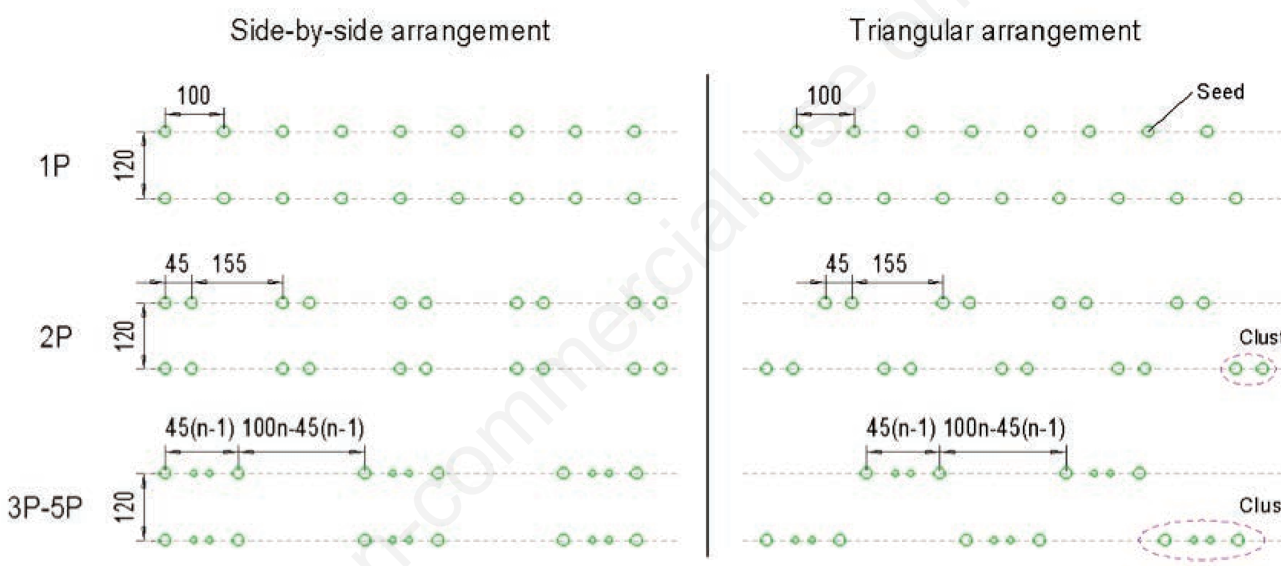

Figure 3. Diagram of plant arrangements (side-by-side arrangement and triangular arrangement) and cluster densities [1, 2, 3, 4, and 5 plants (P)]. The spacing between two clusters (100*n*) was calculated based on the same amount of sowing per acre in different treatments. The value of n was 3-5, and all data units were mm.

Table 3. Monthly total precipitation was measured at a weather station in Changchun, China, during the 2020 and 2019 year growing seasons and 10-yr average precipitation.

Month	Monthly total precipitation (mm)		
	2020	2019	10-yr average (2009-2018)
April	0.6	9.1	34.0
May	83.6	78.6	65.6
June	205.4	61.6	123.7
July	125.6	86.2	197.7
August	169.7	205.5	123.8
September	43.3	79.7	33.8
October	22.2	38.7	25.0
Total	650.4	559.4	603.6

The experimental plot was divided into 20 blocks, each consisting of three 100-m-long ridges. The experiment started in April 2020. The twin-row soybean seeds (Hefeng 50) were planted on the ridge, where the row spacing was 12 cm, and the seed depth was 3-5 cm. The planting density was 28-29 plants/m^2 in the experimental plot. A diammonium phosphate fertiliser (18% N, 46% P) was used at a rate of 100-150 kg/ha. The machine and experimental plot are shown in Figure 4.

Measurements methods

Soil moisture content

From the beginning (the 10th day after planting) to the end (the 30th day after planting) of seedling emergence, the soil moisture content (SMC) was measured every two days using TDR300 Soil Moisture Meter (Spectrum Equipment, USA). Each block was measured separately in 3 randomly picked locations using 12-cm probes, and the average value was used as the final result.

Seedling emergence

During seedling emergence, the number of seedlings was counted every two days at a 5-m long ridge and repeated 3 times in each block. As a result, the mean emergence time (MET) and percentage of emergence (PE) are calculated as follows (Wang *et al*., 2021).

$$\mathrm{MET} = \frac{\mathrm{N_1T_1 + N_2T_2 + \cdots + N_nT_n}}{\mathrm{N_1 + N_2 + \cdots + N_n}} \tag{1}$$

$$\mathrm{PE} = \frac{\mathrm{S_{te}}}{\mathrm{m}} \times 100\% \tag{2}$$

where $N_{1,...,n}$ is the number of seedlings since the time of the previous count, $T_{1,...,n}$ is the number of days after sowing, S_{te} is the number of seedlings per 5 m, and m is the number of seeds sown per 5 m.

Biomass accumulation and allocation

Root biomass (RB) and aboveground biomass (AB) were measured by the soybean samples obtained at the R5 (Dent) phenological stage. First, sampling was conducted as follows: with the target plant as the centre, a square area of 20×20 cm^2 was formed. Next, the soil around the square was removed to obtain a quadrat of 20×20×20 cm^3 (Iqbal *et al*., 1998). The soybean sample contained root systems and aboveground parts (leaves and stems). After removal of the aboveground parts, the root systems were soaked in water to remove the soil and then washed using a low-pressure jet. Finally, the aboveground parts and washed roots were oven-dried at 75°C for 48 h, respectively (Pirnajmedin *et al*., 2015). Root shoot ratio (RSR) was the ratio of RB to AB (Tereza and Tomá, 2018), reflecting the correlation between root biomass and aboveground biomass. Plants with a higher root shoot ratio had strong root function activity, short and strong stalks, and strong stress resistance.

Grain yield

Soybean grains of each block were harvested separately using Kubota 4LZ-2.5 harvester from October 2 to 3, 2020. The soybean grains obtained were naturally dried to a moisture content of 12.5% and weighed to obtain grain yield (GY) in each treatment.

Statistical analyses

Analysis of variance (ANOVA) was used to analyse the variance of the obtained data. Means were compared using the least significant difference (LSD). All statistical analyses were performed using SPSS version 19.0 software and Origin 9.1 software.

Results and discussion

The ANOVA of all variables with their means, levels and F-test results are shown in Table 4.

Soil moisture content

From Table 4 and Figure 5, the effect of tillage treatments on soil moisture content (SMC) was significant (P<0.01). In the tillage treatments, the SMC was 18.60% in the inter-row subsoiling treatment and 16.52% in the no subsoiling treatment (Table 4; Figure 5). Compared with the no subsoiling treatment, the SMC was higher in the inter-row subsoiling treatment. The reason was that the inter-row subsoiling fractured the hard plow pan and deepened the tillage layer, which increased soil moisture infiltration in the subsoil layer. In addition, compared with previous years, there was more precipitation during the soybean growing season, which

Figure 4. Twin-row planter with subsoiling and experimental plot.

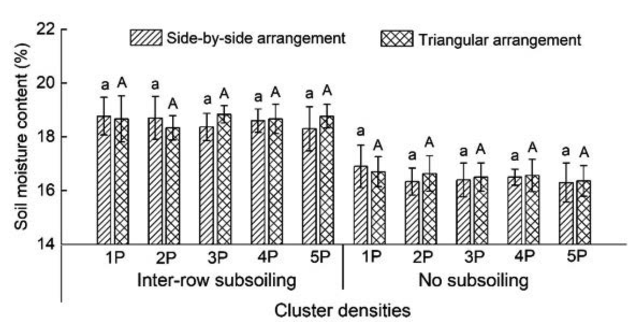

Figure 5. Effect of plant arrangements and cluster densities on soil moisture content under different tillage treatments. Means followed by different lowercase letters or uppercase letters are significantly different (P<0.05); error bars are standard deviations.

allowed much rainwater to penetrate the deeper soil layer and ensured a higher SMC. However, on the plots without subsoiling, most rainwater flowed along the plough pan instead of being absorbed by the soil in the rainy season. Therefore, the SMC was significantly lower in the no subsoiling treatment than in the inter-row subsoiling treatment (Schjønning *et al*., 2020; Wang *et al*., 2020). However, the effects of plant arrangements, cluster densities, and all interactions on the soil moisture content (SMC) were not significant (P≥0.05) (Table 4). Among all treatments, the highest SMC (18.83%) appeared in the combination treatment of inter-row subsoiling, triangular arrangement, and three plants (Figure 5).

Seedling emergence

The mean emergence time (MET) and percentage of emergence (PE) both responded significantly to the tillage treatments (P<0.01) (Table 4). The MET and PE were 8.48 days and 97.10% in the inter-row subsoiling treatment, respectively, and were 9.06 days and 87.13% in the no subsoiling treatment, respectively. Compared with the no subsoiling treatment, the inter-row subsoiling treatment significantly shortened the MET and increased the PE (Table 4; Figure 6). This was because the inter-row subsoiling treatment produced a higher soil moisture content, which promoted the germination and rooting of soybean seeds. Similarly, Voorhees *et al*. (1985) and Saffih-Hdadi *et al*. (2009) reported that a higher soil moisture content around the seeds could effectively reduce emergence time and increase the emergence percentage. However, the effects of plant arrangements, cluster densities, and all interactions on MET and PE were not significant (P≥0.05) (Table 4). It showed that the effects of plant arrangements and cluster densities on the seedling emergence could be ignored. Wang *et al*. (2014) also came to a similar conclusion.

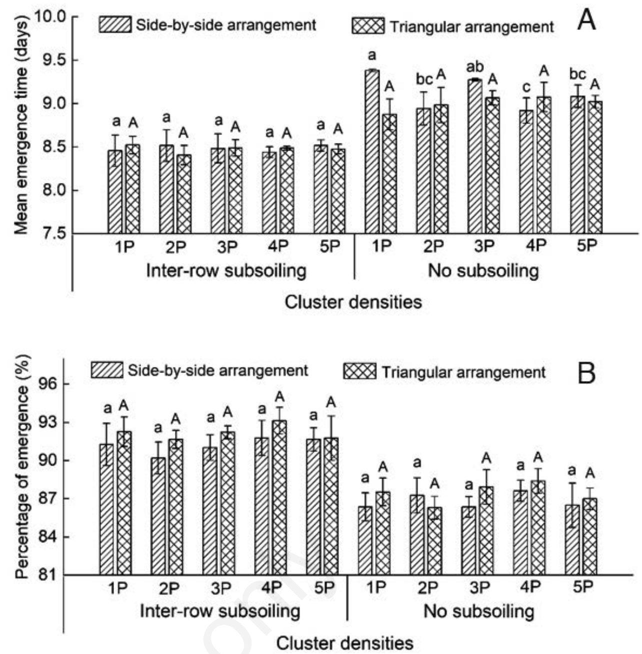

Figure 6. Effect of plant arrangements and cluster densities on seedling emergence under different tillage treatments. A) Mean emergence time; B) percentage of emergence. Means followed by different lowercase letters or uppercase letters are significantly different (P<0.05); error bars are standard deviations.

Table 4. Summary of statistical analysis for the different variables studied under different treatments and their interactions.

Factors	Variables						
	SMC (%)	MET (days)	PE (%)	RB (g)	AB (g)	RSR	GY (kg)
Tillage treatments							
Inter-row subsoiling	18.60^{a}	8.48^{b}	97.10^{a}	6.75^{a}	64.05^{a}	0.107^{b}	49.02^{a}
No subsoiling	16.52^{b}	9.06^{a}	87.13^{b}	6.35^{b}	53.49^{b}	0.122^{a}	45.37^{b}
Plant arrangements							
Side-by-side arrangement	17.51^{a}	8.80^{a}	89.01^{a}	6.37^{b}	54.52^{b}	0.120^{a}	45.63^{b}
Triangular arrangement	17.60^{a}	8.74^{a}	89.82^{a}	6.73^{a}	63.02^{a}	0.109^{b}	48.76^{a}
Cluster densities							
One plant	17.76^{a}	8.81^{a}	89.36^{a}	6.97^{a}	65.48^{a}	0.108^{b}	48.53^{b}
Two plants	17.50^{a}	8.71^{a}	88.86^{a}	7.12^{a}	67.74^{a}	0.107^{b}	51.08^{a}
Three plants	17.53^{a}	8.83^{a}	89.39^{a}	6.45^{b}	60.02^{b}	0.112^{ab}	50.43^{ab}
Four plants	17.58^{a}	8.73^{a}	90.23^{a}	6.25^{bc}	51.42^{c}	0.123^{a}	44.61^{c}
Five plants	17.43^{a}	8.77^{a}	89.23^{a}	5.96^{c}	49.18^{c}	0.124^{a}	41.33^{d}
Standard deviation	1.23	0.35	2.78	0.76	12.43	0.018	5.39
Overall mean	17.56	8.77	89.42	6.55	58.77	0.115	47.20
Coefficient of variation	7.00	3.99	3.11	11.60	21.15	15.65	11.42
F-test							
Tillage treatments (F1)	118.89**	158.97**	111.64**	9.65**	48.788**	16.24**	86.94**
Plant arrangements (F2)	0.21^{ns}	1.72^{ns}	3.57^{ns}	7.478**	31.65**	9.47**	63.97**
Cluster densities (F3)	0.33^{ns}	0.92^{ns}	1.09^{ns}	11.04**	23.96**	4.19**	88.90**
F1×F2	0.01^{ns}	1.40^{ns}	0.24^{ns}	4.70*	6.60*	1.64^{ns}	4.99*
F1×F3	0.07^{ns}	0.54^{ns}	0.11^{ns}	2.62*	7.02**	1.55^{ns}	16.03**
F2×F3	0.20^{ns}	1.26^{ns}	0.28^{ns}	0.27^{ns}	0.15^{ns}	0.11^{ns}	1.14^{ns}
F1×F2×F3	0.26^{ns}	2.04^{ns}	0.38^{ns}	3.51*	3.74*	0.78^{ns}	30.81**

SMC, soil moisture content; MET, mean emergence time; PE, percentage of emergence; RB, root biomass; AB, aboveground biomass; RSR, root shoot ratio; GY, grain yield. $^{a-d}$Means followed by the same letter in the column do not differ significantly by LSD's test (P≥0.05); **significant at 1% probability (P<0.01); *significant at 5% probability (P<0.05); ns, non-significant (P≥0.05).

Biomass accumulation and allocation

From Table 4 and Figure 7, the effects of the three factors on biomass accumulation and allocation (RB, AB, and RSR) were significant (P<0.01). In addition, the interaction terms involving tillage treatments had significant effects on the root biomass (RB) and aboveground biomass (AB) (P<0.05), but all interaction terms had no significant effect on the root shoot ratio (RSR) (P≥0.05).

In the tillage treatments, the RB and AB in the inter-row subsoiling treatment were 6.30% and 19.74% higher than those in the no subsoiling treatment, respectively (Table 4; Figure 7A and B). The possible reason was that the inter-row subsoiling treatment reduced the soil cone index of the subsoil layer (from 3.95 MPa to 1.53 MPa), increased the permeability of air and water, and improved the root growth environment, that being conducive to the growth and extension of root systems (Czyż, 2004). At the same time, the rapid growth of root systems allowed more water, minerals, amino acids, and other substances to be transported to aboveground parts, which also promoted the growth of the aboveground parts (Magaia *et al*., 2016). Therefore, the inter-row subsoiling enhanced the mutual promotion of root systems and aboveground parts. This was in contrast to the conclusion reached by Müller *et al*. (2020) that subsoiling provided lower root growth. From Table 4 and Figure 7C, the root shoot ratio (RSR) in the inter-row subsoiling treatment was 12.30% lower than in the no subsoiling treatment. This was because although the inter-row subsoiling treatment promoted the growth of the root systems, the aboveground parts also grew rapidly, and the growth rate was faster, resulting in a smaller RSR in the inter-row subsoiling treatment (Silva *et al*., 2012). In the plant arrangements, the RB and AB in the triangular arrangement were 5.65% and 15.59% higher than those in the side-by-side arrangement (Table 4; Figure 7A and B). This was because the triangular arrangement enabled soybean plants to make reasonable use of space, reducing the intensity of competition among plants to promote faster root growth (Moore, 1991; Zhao *et al*., 2010). Moreover, the triangular arrangement improved the light utilisation and ventilation effect to promote the photosynthesis of soybean plants so that the aboveground parts grew rapidly, which fed back to the root systems to make them stronger (Qin *et al*., 2015). In addition, the RSR in the triangular arrangement was 9.17% lower than that in the side-by-side arrangement (Table 4; Figure 7C). Again, the reason was that the growth rate of the aboveground parts was greater than that of the root systems, so the RSR was smaller in the inter-row subsoiling treatment.

In the cluster densities, the largest RB and AB appeared in the two plants treatment, while the smallest RB and AB appeared in the five plants treatment (Table 4). With the increase in cluster densities, the RB and AB both showed a decreasing trend (Figure 7A and B). Zhao *et al*. (2010) also reached a similar conclusion. From Table 4 and Figure 7C, with the increase in cluster densities, the RSR showed an increasing trend. The reason may be that the lower cluster densities promoted the growth of root systems, especially the growth of aboveground parts, resulting in a small RSR in the one plant treatment or the two plants treatment. However, the increase in cluster densities inhibited root growth. In order to ensure the balance between the water absorption of root systems and the transpiration water consumption of aboveground parts, the growth of aboveground parts was restricted more than that of root systems, so the RSR increased in turn from two plants to five plants in the cluster densities treatment (Bai *et al*., 2010).

Grain yield

The effect of the three factors on grain yield (GY) was significant (P<0.01). In addition to the interaction term of plant arrangements and cluster densities, all other interaction terms were significant (P<0.05) (Table 4; Figure 8). In the tillage treatments, the GY

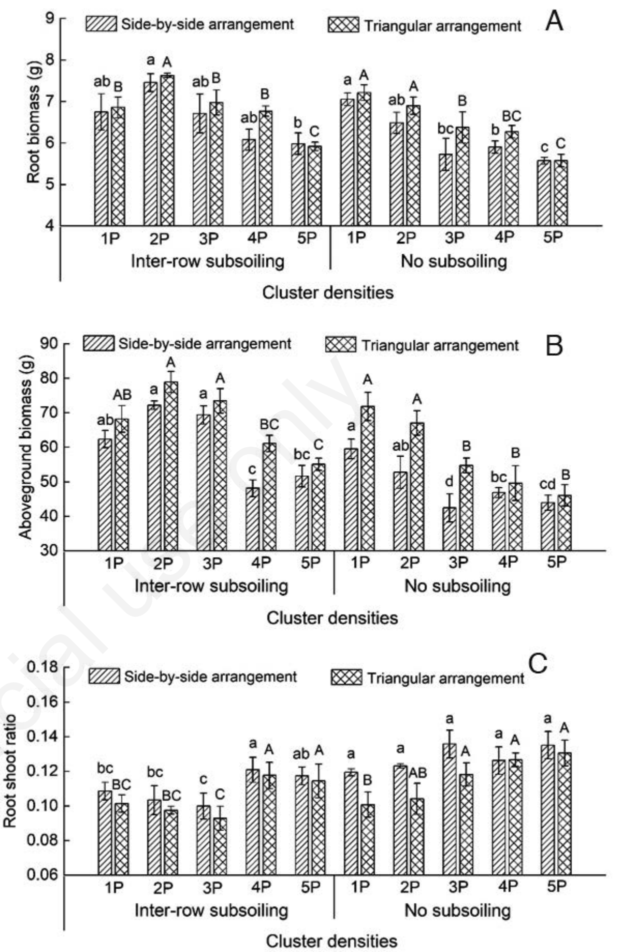

Figure 7. Effect of plant arrangements and cluster densities on biomass accumulation and allocation under different tillage treatments. A) Root biomass (RB); B) aboveground biomass (AB); C) root shoot ratio (RSR). Means followed by different lowercase letters or uppercase letters are significantly different (P<0.05); error bars are standard deviations.

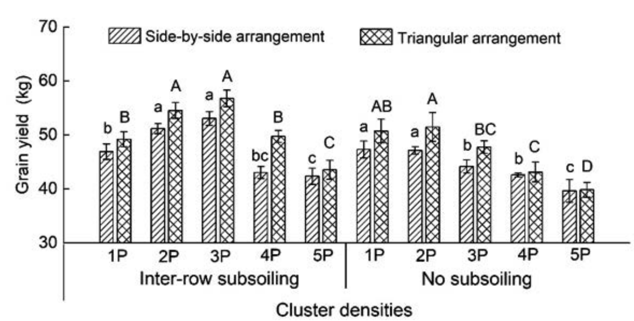

Figure 8. Effect of plant arrangements and cluster densities on grain yield under different tillage treatments. Means followed by different lowercase letters or uppercase letters are significantly different (P<0.05); error bars are standard deviations.

in the inter-row subsoiling treatment (49.02 g) was 8.04% higher than that in the no subsoiling treatment (45.37 g) (Table 4; Figure 8). The reason was that compared with the no subsoiling treatment, the inter-row subsoiling treatment resulted in earlier emergence time, a higher percentage of emergence, and more biomass accumulation, which contributed to the high grain yield (Silva *et al*., 2012).

In the plant arrangements, the GYs were 45.63 g and 48.76 g in the side-by-side and triangular arrangements, respectively (Table 4; Figure 8). Obviously, the GY in the triangular arrangement was higher than that in the side-by-side arrangement. The reason was that the triangular arrangement provided a reasonable growth environment for soybean plants, which promoted the growth of root systems and aboveground parts. The biomass accumulation was directly related to soybean grain yield (Chao *et al*., 2014).

In the cluster densities, the two plants treatment resulted in the largest GY, and the five plants treatment resulted in the smallest GY (Table 4). As expected, with the increase of cluster densities, the GY first increased and then decreased (Figure 8). The reason was that when the cluster density was at a low level, the grain yield increased with the increase of cluster densities. However, when the cluster density increased to the critical value (two or three plants), the intensified competition among plants decreased grain yield (Prusinski and Nowicki, 2020; Xu *et al*., 2021).

Conclusions

We have concluded that the performance of inter-row subsoiling treatment was much better than that of no subsoiling treatment in northern China. Different plant arrangements had no significant effect on the seedling emergence, but in terms of biomass accumulation and grain yield, the triangular arrangement was more advantageous than the side-by-side arrangement. Among all blocks, the optimal cluster density was two plants for biomass accumulation and grain yield. This study provided a reference for the innovative design of the twin-row planter with subsoiling and the optimisation of soybean agronomy.

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