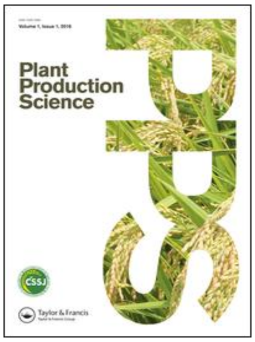

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Effect of planting density on lodging-related morphology, lodging rate, and yield of tartary buckwheat (*Fagopyrum tataricum*)

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ABSTRACT
Increase of planting density has been widely used to increase grain yield in crops. However, it may lead to higher risk of lodging hence causing significant yield loss of the crop. To investigate the effects of planting density on lodging-related morphology, lodging rate (LR), and yield of tartary buckwheat, an experiment was carried out with a split-plot randomized block design at the experimental farm of Chengdu University (Sichuan, China) in the 2012 and 2013 growing seasons. Results showed that plant density significantly affected characteristics of stem and root. In each season, with the increasing of planting density, light transmittance, main root length, number of first lateral root, root volume, internode number, and first internode diameter decreased, the plant height, first internode length, abortion rate and LR increased. Increasing density caused decreased grains number per plant, the dry matter weight and yield displayed an acceleration first and then deceleration. The correlation analysis indicated that the internode number, first internode diameter, number of first lateral roots, and root volume were significantly negatively correlated with LR, but positively correlated with stem breaking strength and lodging resistance index. The LR was significantly positively correlated with plant height and first internode length. In both years, the D2 (9×10^5 plant ha^{-1}) and D3 (12×10^5 plant ha^{-1}) yielded more grains than in other treatments, and the effects of density on two cultivars showed the same trend. The results suggested that planting density could alter lodging-related traits, lodging resistance, and yield of tartary buckwheat.

Abbreviations: PAR: photosynthetically active radiation; SBS: stem breaking strength; LR: lodging rate; LRI: lodging resistance index

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Buckwheat is an edible and medicinal crop which is distributed throughout the world, China, India, Russia, Japan, South Korea, France, Canada, America, Poland, Bhutan, Slovenia, Nepal etc. The buckwheat has two cultivated species, tartary buckwheat (*Fagopyrum tataricum* (L.) Gaertner; Polygonaceae) and common buckwheat (*Fagopyrum esculentum* Moench; Polygonaceae). The morphological traits of tartary buckwheat are similar to common buckwheat, but there are some differences. In general, tartary buckwheat is more robust, and the plant height of tartary buckwheat is up to 100–150 cm, while that of common buckwheat is 60–100 cm. Tartary buckwheat is one of the most complete and nutritional foods, being rich in minerals, vitamins, protein, dietary fiber, amino acids, trace elements, and various bioactive phytochemicals (Zhao et al., 2012). The seeds are widely consumed as buckwheat flour, noodles, bread, tea, vinegar, and the sprouts which are consumed as part of the daily diet and traditional medicine. Thus, interest in its use to benefit health is growing and farmers are eager to increase their total yields to meet the increasing market demands and their overall returns.

In production, the yield of tartary buckwheat is 1200–1500 kg ha^{-1} (Zhang et al., 2008). The important limiting factor is the inadequate agricultural strategies resulting in low and unstable grain yields. Enhancing biological production per unit area is an effective way to improve the yield potential of crops (Albrecht et al., 1986). In the field production of tartary buckwheat, increasing the planting density is an easy way to increase yield but often conflicts with lodging resistance, because the lodging happens easier under higher planting density (Hagiwara et al., 1999). Thus, preventing the occurrence of lodging

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in tartary buckwheat is of primary importance. One of the main goals in buckwheat cultivation is identifying the best planting density for the desired yield.

Lodging can be affected by many factors. Previous studies focused mainly on differences in lodging-related traits in varieties (e.g. rice, maize, and wheat), including correlations between lodging resistance and plant height; length and diameter of basal internodes; weight of basal internodes; and starch, cellulose, or lignin contents, as well as those between cultivation conditions and yield or lodging resistance (Esechie et al., 2004; Mobasser et al., 2009; Tripathi et al., 2004; Xiang et al., 2010; Zuber et al., 1999). The risk of lodging increases at high planting density. When lodging appeared, the normal canopy structure was altered with the photosynthetic capability and dry matter production declined (Hitaka & Kobayashi, 1961). Lodging prevents the movements of water, mineral nutrients, and assimilates through the xylem and phloem, and consequently reducing grain quality and quantity (Kashiwagi et al., 2005). Therefore, field producers should consider the number of plants per square unit to determine the proper planting distance and density (Yadi, 2012).

The results of prior studies have provided useful information on the morphological traits and physiological mechanisms of lodging resistance and yield in other crops. However, few analogous reports exist for tartary buckwheat. This study was conducted to evaluate the effects of planting density on lodging-related morphological characteristics, lodging rate (LR), and yield of tartary buckwheat, and to provide a theoretical basis for high-yielding and lodging-resistance cultivation techniques for this crop.

1. Materials and methods

1.1. Plant material and treatments

Field experiments were conducted in the 2012 and 2013 growing seasons at the farm of Chengdu University (30°65′N and 104°19′E, 495 m altitude), Sichuan Province, China. During the 2012 and 2013 growth seasons, the mean temperature is 16.7 °C in 2012 and 16.2 °C in 2013. The cumulative temperatures above 10 °C are 1115.6 °C in 2012 and 1098.4 °C in 2013. The precipitation is 46.8 mm in 2012 and 56.4 mm in 2013. The total solar radiation is 480 and 495 MJ m^{-2} (Table 1). The annual frost-free period is 278–300 days and annual sunshine duration is 1042–1412 h. Two tartary buckwheat cultivars ChuanQiao-1 and XiQiao-1, obtained from the National Research and Development Center for coarse cereal processing at Chengdu University were used in this study. The soil of the fields is clay loam in texture and acidic (pH 7.82) with 51.0, 23.2, and 32.9 mg kg^{-1} available N, P, and K, respectively; 0.72, 0.49, and 15.9 g kg^{-1} total N, P, and K, respectively; and 11.7 g kg^{-1} organic matter. Soil tests were done on samples taken from the upper 20 cm of the soil.

The experiment had a split-plot block design with four replications. The factors were variety (ChuanQiao-1 and XiQiao-1) as main plot, and plant density (D1–D4: 6×10^5, 9×10^5, 12×10^5, and 15×10^5 plants ha^{-1}, respectively) as sub plot. The seeds were sown on 21 August 2012, and 24 August 2013, respectively, at a total of 32 unit plots of 4 × 2 m each. Healthy tartary buckwheat seeds were surface-sterilized for 5 min in 0.1% Potassium Permanganate solution followed by four 1-min deionized-H_2O rinses. Then, the seeds were soaked in sterilized water at 25 °C for 4 h and subsequently planted with a hill distance of 20 cm and row spacing of 25 cm. Seedlings were thinned to the final density (see above) 15 days after germination. Insects, diseases, and weeds were intensively controlled to avoid yield losses, and synthetic fertilizer (N:P:K = 15:15:15) was applied as basal fertilizer at the rate of 600 kg ha^{-1}. Other management was based on optimized standards of field production. Tartary buckwheat was harvested on 23 November 2012 and 27 November 2013, respectively.

1.2. Measurement techniques

1.2.1. Light transmittance of canopy

At the full-bloom stage, a light quantum gage (3415FSE, Spectrum Tech., Aurora, IL, USA) was used to investigate the photosynthetically active radiation (PAR) of the canopy. Measurements were done at 0 and 50 cm above the ground and at the top of canopy. Twenty points were sampled at each position in every plot, and light transmittance was calculated as: light transmittance = PAR at 0 or 50 cm above ground/PAR at top of canopy.

1.2.2. Plant characteristics

Fifteen plants per plot were sampled and measured at the seedling, beginning bloom, full-bloom, and mature stage. Basal stem diameter, plant height, internode length, main root length, number of first lateral roots, root volume, and main root diameter were measured. Root and shoot sections were oven-dried at 65 °C to constant weight

Table 1. The meteorological data in each growth seasons.

Year	Mean temperature (°C)	Precipitation (mm)	Total solar radiation (MJ m^{-2})	Cumulative temperatures above 10 °C (°C)
2012	16.7	46.8	480	1115.6
2013	16.2	56.4	495	1098.4

and then weighed. The root/shoot ratio was calculated as: root/shoot ratio = dry weight of roots/dry weight of shoots.

1.2.3. Lodging and stem lodging resistance index

The lodging occurred at stage of maturity, and the lodging percentage was recorded at 3 days before harvesting. Lodging plant number and total plant number of tartary buckwheat in each experiment plot was investigated, and lodging plants were those in which the stems were completely or partially broken or leaned 30° or more from the vertical. The LR and stem lodging resistance index (LRI) were calculated as:

$$\mathrm{LR}(\%) = \text{number of lodged plants in a plot}/\text{number of all plants in the plot} \times 100;$$

$$\mathrm{LRI} = \text{stem breaking strength}/\text{stem height of center of gravity}.$$

1.2.4. Stem breaking strength

Ten standing plants were selected randomly from one half of each plot, avoiding the outer three rows, to measure stem breaking strength (SBS) of the first internode. SBS was estimated at seedling stage and beginning bloom stage as previously described in sorghum (Esechie & Maranville, 1975). The instrument used for measuring SBS was a digital force tester (YYD-1, Zhejiang Top Instrument, China).

1.2.5. Dry matter, yield and its component

Fifteen plants were selected randomly from one half of each plot at the mature stage (at least 70% of grains mature), to measure grain number per plant and number of effective plants per m^2. The whole plant of tartary buckwheat were dried to a constant weight at 65 °C after exposure to 105 °C for 0.5 h, and the dry weight was measured as the trait of biomass. The grains were oven-dried at 65 °C for 48 h then weighed, and 1000-grain weight was measured. Seed setting rate (%) was calculated as number of seeds at maturity/all seeds of plant plus flowers × 100. Seed abortion rate (%) was calculated as number of flowers at maturity/all seeds of plant plus flowers × 100.

1.3. Statistical analysis

Microsoft Excel 2010 and Microsoft Office Publisher (Redmond, WA, USA) were used to process the data and draw figures, and SPSS Statistics 17.0 (IBM, Chicago, IL, USA) was employed for analysis of variance.

2. Results

2.1. Light transmittance of the canopy

The canopy light transmittance in tartary buckwheat differed with planting density in 2012 and 2013 (Figure 1). Light transmittance clearly declined with increased planting density at both 0 and 50 cm above the ground, and light transmittance was lower at the former than the latter. The light transmittance of D3 and D4 were lower than that of D1 and D2, and the denser canopies shaded more easily than those grown at lower densities. Both cultivars varied similarly in canopy light transmittance with planting density. However, values for ChuanQiao-1 were slightly lower than for XiQiao-1 at the same density and height.

2.2. Agronomic traits

The agronomic traits of tartary buckwheat differed significantly with cultivar and planting density, and the patterns were similar in 2012 and 2013 (Table 2). As density increased, plant height and first internode length increased

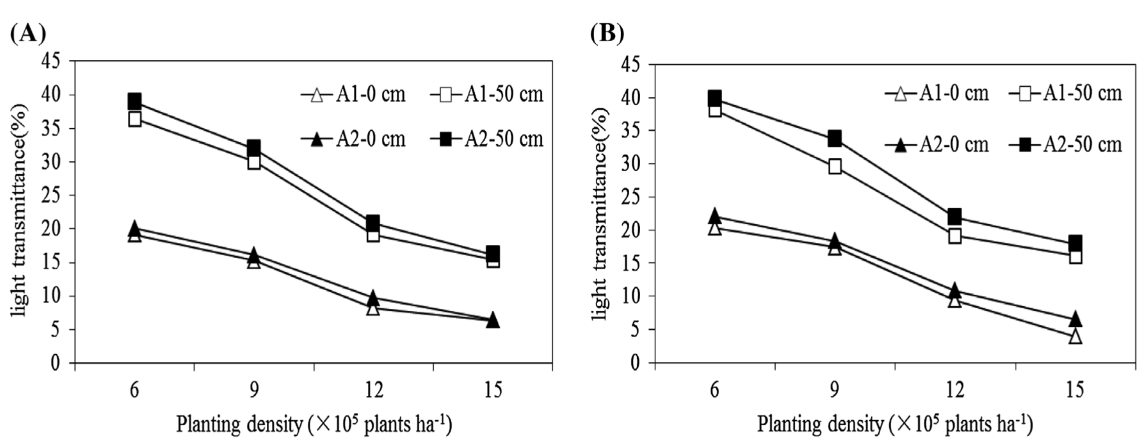

Figure 1. Effect of planting density on canopy light transmittance of tartary buckwheat in the 2012 (A) and 2013 (B) growing seasons.
Notes. A1-0 and A1-50 cm represent light transmittance at 0 and 50 cm above the ground in the ChuanQiao-1 cultivar, respectively. A2-0 and A2-50 cm represent light transmittance 0 and 50 cm above the ground in the XiQiao-1 cultivar, respectively. Values are means (n = 20).

Table 2. Effect of planting density on agronomic traits of two tartary buckwheat cultivars in 2012 and 2013.

Year	Cultivar	Planting density ($\times 10^5$ plant ha^{-1})	Plant height (cm)	Internode number	First internode length (cm)	First internode diameter (mm)
2012	ChuanQiao-1	6	95.2e	15.3	4.11c	5.08
		9	97.6de	14.8	4.24c	4.47
		12	99.4d	14.1	4.55b	4.23
		15	105.7c	13.7	4.69ab	4.11
	XiQiao-1	6	105.4c	17.7	3.69d	5.12
		9	108.4bc	16.9	4.15c	4.49
		12	109.3b	16.4	4.24c	4.21
		15	115.2a	16.0	4.65a	4.18
	ChuanQiao-1		99.5b	14.5b	4.40a	4.47a
	XiQiao-1		109.6a	16.8a	4.18a	4.50a
		6	100.3d	16.5a	3.90d	5.10a
		9	103.0c	15.8b	4.19c	4.48b
		12	104.4b	15.3c	4.40b	4.22c
		15	110.5a	14.9d	4.67a	4.15d
F-value	A		1363.58**	890.79**	5.95^{ns}	1.74^{ns}
	B		245.89**	90.59**	13.38*	547.79**
	A × B		4.72*	0.24^{ns}	4.07*	0.22^{ns}
2013	ChuanQiao-1	6	95.1e	15.6	4.18c	5.17
		9	96.3e	14.7	4.21c	4.46
		12	99.7d	14.2	4.58b	4.19
		15	107.3c	13.9	4.59b	4.08
	XiQiao-1	6	107.4c	18.2	3.59d	5.25
		9	108.7b	16.9	4.21c	4.52
		12	108.8b	16.6	4.26c	4.20
		15	118.9a	15.9	4.72a	4.11
	ChuanQiao-1		99.6b	14.6b	4.39a	4.48a
	XiQiao-1		111.0a	16.9a	4.20a	4.52a
		6	101.3d	16.9a	3.89d	5.21a
		9	102.5c	15.8b	4.21c	4.49b
		12	104.3b	15.4c	4.42b	4.20c
		15	113.1a	14.9d	4.66a	4.10d
F-value	A		221.60**	402.96**	1.40^{ns}	8.31^{ns}
	B		49.20**	55.55**	14.07*	1121.65**
	A × B		3.73*	0.87^{ns}	4.67*	0.26^{ns}

Notes. Means within a column followed by different letters are significantly different ($p < 0.05$) according to Duncan's multiple range test.
*Significant at 0.05 probability levels; **Significant at 0.01 probability levels.
^{ns}Represent non-significant at 0.05 probability level.
A represent cultivar; B represent planting density; A × B represent the interaction between cultivar and planting density.

significantly, but internode number and first internode diameter reduced significantly. ChuanQiao-1 and XiQiao-1 differed significantly in plant height and internode number at the same planting density, but no obvious differences in first internode length and first internode diameter were seen. The main root length, number of first lateral roots, root volume, and main root diameter were decreased with the increase of planting density (Table 3). Compared with D1, the D4 significantly decreased the main root length, number of first lateral roots, root volume, and main root diameter by 9.70–13.09, 7.11–16.61, 21.34–25.12, and 8.09–15.47%, respectively.

2.3. Root:shoot ratio

The root:shoot ratio of both cultivars increased at first and then decreased with growth stage at D1, D2, and D3 (Figure 2). The root:shoot ratio of D4 were generally lowest among all planting densities in the whole growing season, except at the stage of maturity. The root:shoot ratio of D1 at the beginning bloom stage was highest among all density treatments, with values of 0.118 for ChuanQiao-1 and 0.122 for XiQiao-1.

2.4. Lodging rate

The two-year study indicated that the LR was affected by planting density and cultivar in tartary buckwheat (Figure 3). The LR increased significantly with planting density from D2 to D4. The rates across all densities were 22.1–59.8% in 2012 and 18.2–58.3% in 2013 for XiQiao-1, and 34.2–71.0 and 32.2–69.4% for ChuanQiao-1, respectively. The two cultivars also differed in LR, with higher LR of ChuanQiao-1 at the same density compared with XiQiao-1.

2.5. SBS and LRI

Cultivar, planting density, and cultivar × plant density interactions significantly affected SBS and LRI (Table 4). The lowest SBS at the seedling stage (60.4 g in 2012, 78.9 g in 2013) and beginning bloom (433.3 and 440.7 g,

Table 3. Effect of planting density on agronomic traits of root in two tartary buckwheat cultivars in 2012 and 2013.

Year	Cultivar	Planting density	Main root length (cm)	Number of first lateral roots	Root volume (mL)	Main root diameter (mm)
2012	ChuanQiao-1	6	7.11	24.44d	1.64	4.08b
		9	7.04	23.09e	1.55	3.89b
		12	6.85	21.46f	1.33	3.84bc
		15	6.42	20.38g	1.29	3.75c
	XiQiao-1	6	7.43	26.13a	1.93	4.63a
		9	7.33	25.73b	1.67	4.64a
		12	7.23	24.73c	1.53b	4.64a
		15	6.95	24.27d	1.50	4.07b
	ChuanQiao-1		6.86b	22.34b	1.45b	3.89b
	XiQiao-1		7.24a	25.22a	1.66a	4.50a
		6	7.27a	25.29a	1.79a	4.36a
		9	7.19b	24.41ab	1.61b	4.27ab
		12	7.04c	23.10bc	1.43c	4.24b
		15	6.69d	22.33c	1.40c	3.91c
F-value	A		50.67**	37.43**	34.78**	30.65*
	B		23.37*	7.93^{ns}	26.8*	3.17^{ns}
	A × B		1.23^{ns}	43.31**	0.59^{ns}	9.27**
2013	ChuanQiao-1	6	7.56	25.14cd	2.15	4.72
		9	7.33	24.01e	2.09	4.62
		12	7.04	23.69f	1.76	4.33
		15	6.57	21.08g	1.61	3.99
	XiQiao-1	6	8.01	28.55a	2.48	5.32
		9	7.89	26.45b	2.15	5.14
		12	7.76	25.22cd	2.04	4.98
		15	6.99	24.68d	1.87	4.65
	ChuanQiao-1		7.13b	23.48b	1.90b	4.42b
	XiQiao-1		7.66a	26.23a	2.14a	5.02a
		6	7.79a	26.85a	2.32a	5.02a
		9	7.61b	25.23b	2.12b	4.88b
		12	7.40c	24.46c	1.90c	4.66c
		15	6.78d	22.88d	1.74d	4.32d
F-value	A		62.72**	32.97*	15.34*	360.79**
	B		41.72**	11.90*	17.96*	91.18**
	A × B		1.24^{ns}	130.40**	1.05^{ns}	0.13^{ns}

Notes. Means within a column followed by different letters are significantly different ($p < 0.05$) according to Duncan's multiple range test.
*Significant at 0.05 probability levels; **Significant at 0.01 probability levels.
^{ns}Represent non-significant at 0.05 probability level.
A represent cultivar; B represent planting density; A × B represent the interaction between cultivar and planting density.

respectively) occurred in ChuanQiao-1 at D4 (Table 4). XiQiao-1 had significantly higher SBS than ChuanQiao-1 at the same density in both years. Additionally, the patterns of variation in LRI and SBS with density were similar in the two cultivars, but with different magnitudes.

2.6. Seed setting rate and abortion rate

The seed setting rate and abortion rate of tartary buckwheat depended on planting density (Table 5). Higher planting densities reduced the seed setting rate and increased the abortion rate. Compared with D1, the seed setting rate for ChuanQiao-1 decreased by about 9.8–20.1% in 2012 and 9.3–20.0% in 2013 with other density treatments, while abortion rate was increased significantly by about 22.8–69.8% (2012) and 22.1–73.3% (2013). For XiQiao-1, the differences in seed setting rate and abortion rate with planting density were similar as ChuanQiao-1. The two cultivars did not differ significantly in seed setting rate and abortion rate at the same planting density.

2.7. Dry matter weight

As shown in Table 6, dry matter weight was affected significantly by planting density in 2012 and 2013. D3 and D4 produced more dry matter than D1 and D2, 28.0–34.3% (2012) and 19.7–37.0% (2013) for ChuanQiao-1 and 14.8–33.6% (2012) and 11.8–38.2% (2013) for XiQiao-1, respectively. The dry matter weight of D3 was the highest among all planting density treatments, which were significantly higher than D1 and D2. Two cultivars showed the similar trend in 2012 and 2013.

2.8. Yield and its component

As shown in Figure 4, yield was affected by planting density and cultivar in 2012 and 2013. The D2 and D3 treatments yielded more grains than D1 and D2, about 10.4–15.4% (2012) and 11.2–15.3% (2013) for XiQiao-1 and 15.8–16.2% (2012) and 9.3–21.1% (2013) for ChuanQiao-1, respectively. The yield of XiQiao-1 was, on average, more than 226.9 kg ha^{-1} (18.5%) higher than that of ChuanQiao-1,

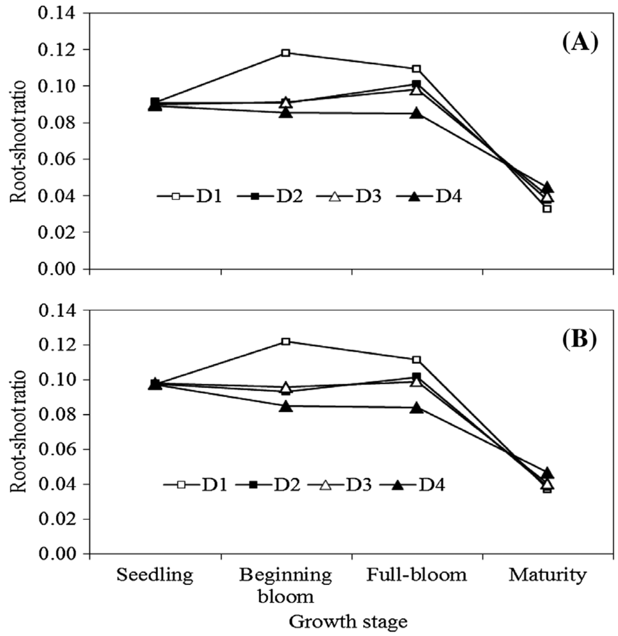

Figure 2. Effect of planting density on the root:shoot ratio of two tartary buckwheat cultivars (A: ChuanQiao-1; B: XiQiao-1).
Notes. Values are means (n = 4) in 2012 and 2013. D1, D2, D3, and D4 represent the planting densities 6×10^5, 9×10^5, 12×10^5, and 15×10^5 plant ha^{-1}, respectively.

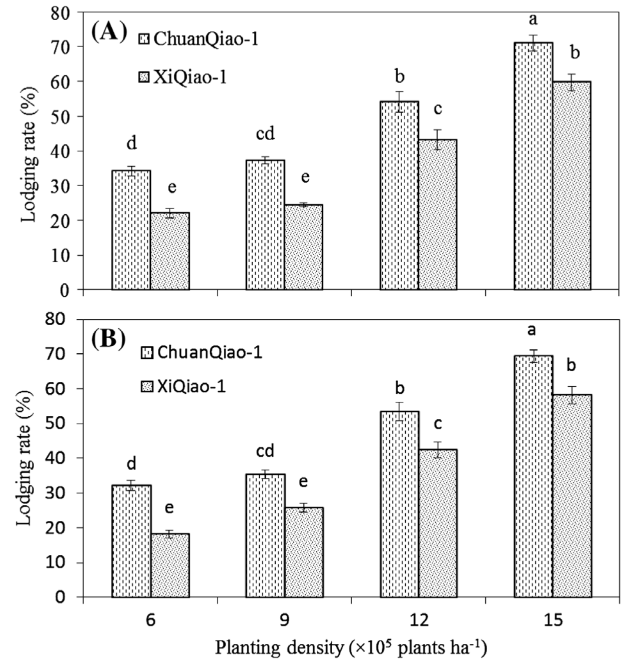

Figure 3. Effect of planting density on the LR of two tartary buckwheat cultivars in the 2012 (A) and 2013 (B) growing seasons.
Notes. Values are means ± SE (n = 4). Vertical lines at the tops of the bars show SE. The interaction effect of cultivar and planting density was significant (F_{2012} = 4.06*, F_{2013} = 32.92**). Bars with different letters are significantly different at $p < 0.05$ according to Duncan's multiple range test.*Significant at 0.05 probability levels; **Significant at 0.01 probability levels.

and the differences were significant at all four planting densities.

The grains number per plant of two tartary buckwheat cultivars decreased significantly with increasing the planting density in 2012 and 2013 (Table 6). The ChuanQiao-1 and XiQiao-1 differed significantly in grain number per plant at the same planting density (except D4 in 2012). The effective plants per m^2 of both cultivars increased significantly with the increasing the planting density in 2012 and 2013, while no significance between the two cultivars at the same planting density. The 1000-grain weight of both tartary buckwheat cultivars was not significantly different at the different planting density in 2012 and 2013.

2.9. Correlation and regression analysis

LR was positively correlated with both plant height and first internode length. Correlation analysis also demonstrated that the LR was significantly and negatively correlated with SBS, LRI, internode number, first internode diameter, number of first lateral roots, and root volume. But LR was not correlated with root:shoot ratio and main root length, as well as diameter of main root (Table 7).

Regression analysis indicated that the LR and plant height were significantly and positively correlated with planting density. The SBS, LRI, Internode number, first internode length, first internode diameter, main root length, number of first lateral roots, root volume were significantly and negatively correlated with planting density (Table 8).

3. Discussion

In the present study, the light transmittance had a great decrease with increased density (Figure 1). Thus, at high density, intense intraspecific competition decreases the amount of light available to coexisting plants, leading to taller plants, smaller main-stem diameters, elongated lower internodes, fewer internodes, less number of first lateral root, and smaller volume (Tables 2 and 3). These agronomic traits are often considered as the key characteristics affecting lodging incidence in case of lentil (Ball et al., 2005). In this study, the plant height, internode number, first internode length, first internode diameter, number of first lateral root, and root volume were significantly correlated with LR (Table 7). Therefore, increasing the light transmittance by planting at low or moderate densities also would enhance lodging resistance in tartary buckwheat. However, more studies are needed to test this hypothesis.

The root:shoot ratio is usually given as the ratio of the weights of the roots and the top of a plant (Richard, 1992). The reduction in the root:shoot ratio caused by cultural practice is commonly thought to be had detrimental effects on plants. Hébert et al. (2001) and Ma et al. (2009)

Table 4. Effect of planting density on the SBS and LRI in two tartary buckwheat cultivars.

Year	Cultivar	Planting density ($\times 10^5$ plant ha^{-1})	SBS (g) Seedling stage	SBS (g) Beginning bloom	LRI Seedling stage	LRI Beginning bloom
2012	ChuanQiao-1	6	145.1	620.8b	11.61	28.64a
		9	119.1	514.8c	8.96	22.06c
		12	117.1	498.4c	8.89	21.12c
		15	60.4	433.3d	4.58	20.37c
	XiQiao-1	6	214.7	680.5a	15.06	29.74a
		9	173.5	650.5ab	12.10	25.37b
		12	170.5	638.5b	11.92	23.91bc
		15	119.0	446.7d	7.18	14.44d
	ChuanQiao-1		110.4b	516.8b	8.51b	23.05a
	XiQiao-1		169.4a	604.1a	11.57a	23.37a
		6	179.9a	650.7a	13.34a	29.19a
		9	146.3b	582.7b	10.53b	23.72b
		12	143.8b	568.5b	10.41b	22.52b
		15	89.7c	440.0c	5.88c	17.41c
F-value	A		252.54**	18.05*	301.96**	0.02^{ns}
	B		101.09**	18.18*	307.75**	15.13*
	A × B		1.06^{ns}	14.98**	0.38^{ns}	4.67*
2013	ChuanQiao-1	6	152.7	680.5b	13.52	30.15a
		9	122.4	527.6c	9.84	24.33b
		12	119.8	509.1c	8.99	22.65b
		15	78.9	440.7d	5.01	20.56c
	XiQiao-1	6	224.6	714.1a	17.14	32.75a
		9	192.1	672.3b	14.32	26.41b
		12	180.4	660.8b	12.35	24.39bc
		15	126.7	452.6d	8.41	15.98d
	ChuanQiao-1		118.5b	539.5b	9.34b	24.42a
	XiQiao-1		181.0a	625.0a	13.06a	24.88a
		6	188.7a	697.3a	15.33a	31.45a
		9	157.3b	600.0b	12.08b	25.37b
		12	150.1b	585.0b	10.67c	23.52b
		15	102.8c	446.7c	6.71d	18.27c
F-value	A		130.24**	16.18*	202.09**	0.07^{ns}
	B		41.94**	18.81*	186.81**	10.37*
	A × B		0.72^{ns}	49.52**	0.41^{ns}	4.06*

Notes. Means within a column followed by different letters are significantly different ($p < 0.05$) according to Duncan's multiple range test.
*Significant at 0.05 probability levels;
**Significant at 0.01 probability levels.
^{ns}Represent non-significant at 0.05 probability level.
A represent cultivar; B represent planting density; A × B represent the interaction between cultivar and planting density.

Table 5. Effect of planting density on the seed setting rate and abortion rate in two tartary buckwheat cultivars.

Cultivars	Planting density ($\times 10^5$ plant ha^{-1})	2012 Seed setting rate (%)	2012 Abortion rate (%)	2013 Seed setting rate (%)	2013 Abortion rate (%)
ChuanQiao-1	6	60.2	23.2	61.4	21.7
	9	54.3	28.5	55.7	26.5
	12	53.1	33.2	55.2	31.2
	15	48.1	39.4	49.1	37.6
XiQiao-1	6	62.0	21.4	63.5	20.7
	9	57.8	25.8	57.9	25.4
	12	53.6	31.7	55.6	30.2
	15	50.4	35.4	51.2	34.8
ChuanQiao-1		53.9a	31.1a	55.4a	29.3a
XiQiao-1		56.0a	28.6a	57.1a	27.8a
	6	61.1a	22.3d	62.5a	21.2d
	9	56.1b	27.2c	56.8b	26.0c
	12	53.4b	32.5b	55.4b	30.7b
	15	49.3c	37.4a	50.2c	36.2a
F-value	A	8.32^{ns}	7.84^{ns}	5.34^{ns}	8.12^{ns}
	B	62.60**	135.51**	135.69**	211.16**
	A × B	0.30^{ns}	0.22^{ns}	0.11^{ns}	0.12^{ns}

Notes. Means within a column followed by different letters are significantly different ($p < 0.05$) according to Duncan's multiple range test.
**Significant at 0.01 probability levels. ^{ns}Represent non-significant at 0.05 probability level.
A represent cultivar; B represent planting density; A × B represent the interaction between cultivar and planting density.

Table 6. Effect of planting density on dry matter weight and yield component of two tartary buckwheat cultivars.

Year	Cultivar	Planting density($\times 10^5$ plant ha^{-1})	Dry matter weight per m^2 (g)	Grains number per plant	1000-grain weight (g)	Effective plants per m^2
2012	ChuanQiao-1	6	290.1	102.2b	2.1	53.7
		9	320.1	89.9d	2.11	78.5
		12	401.3	85.2e	2.06	99.3
		15	396.8	78.7f	2.04	129.1
	XiQiao-1	6	322.0	119.0a	2.16	54.2
		9	367.9	100.1b	2.09	81.3
		12	430.1	95.7c	2.06	100.7
		15	422.5	82.1ef	2.01	132.3
	ChuanQiao-1		352.1b	89.0b	2.09a	90.2a
	XiQiao-1		385.6a	99.2a	2.08a	92.1a
		6	306.1c	110.6a	2.15a	54.0d
		9	344.0b	95.0b	2.10a	79.9c
		12	415.7a	90.5c	2.06a	100.0b
		15	409.7a	80.4d	2.03a	130.7a
F-value	A		46.15**	13.92*	1.03^{ns}	0.94^{ns}
	B		115.26**	20.98*	7.22^{ns}	745.44**
	A × B		0.69^{ns}	9.23**	0.098^{ns}	1.67^{ns}
2013	ChuanQiao-1	6	303.9	108.9b	2.15	54.1
		9	335.6	91.0e	2.13	79.7
		12	416.3	86.87f	2.10	100.5
		15	401.8	80.53g	2.06	131.9
	XiQiao-1	6	342.1	123.2a	2.14	55.71
		9	417.5	102.2c	2.09	83.8
		12	472.8	97.5d	2.08	107.1
		15	466.7	84.87f	2.03	133.7
	ChuanQiao-1		364.4b	91.8b	2.11a	91.6a
	XiQiao-1		424.8a	101.9a	2.09a	95.1a
		6	323.0c	116.1a	2.15a	54.9d
		9	376.6b	96.6b	2.11a	81.8c
		12	444.6a	92.2c	2.09a	103.8b
		15	434.3a	82.7d	2.05a	132.8a
F-value	A		44.35**	23.53*	5.46^{ns}	9.08^{ns}
	B		38.55**	45.29**	6.68^{ns}	243.80**
	A × B		2.53^{ns}	6.02**	0.032^{ns}	2.53^{ns}

Notes. Means within a column followed by different letters are significantly different ($p < 0.05$) according to Duncan's multiple range test.
*Significant at 0.05 probability levels; **Significant at 0.01 probability levels.
^{ns}Represent non-significant at 0.05 probability level.
A represent cultivar; B represent planting density; A × B represent the interaction between cultivar and planting density.

found that increasing the sowing density reduced the root:shoot ratio and resulted in more frequent lodging in maize. Similarly, the lower root:shoot ratios also proved that high-density conditions are not beneficial for the growth of tartary buckwheat. In this study, we found that the root:shoot ratios of two cultivars in high-density conditions were less than at lower densities throughout growth, except at seedling and maturity (Figure 2). It might be the high-density conditions increased the intraspecific competition of tartary buckwheat, and resulted in weaker growth of root and shoot, which might affect the lodging resistance. However, the root:shoot ratio was not correlated with LR in this study (Table 7). At this point, the root:shoot ratio could reflect the growth of tartary buckwheat, but we have found no evidence directly connecting root:shoot ratio to lodging. So, based on these results, further study is needed to illustrate the relationship between LR and root:shoot ratio. The LR of the two tartary buckwheat cultivars increased with planting density (Figure 3). However, both SBS and LRI decreased significantly from low-density (6×10^5 plant ha^{-1}) to high-density (15×10^5 plant ha^{-1}) plantings in 2012 and 2013 (Table 4). SBS and LRI are keys to lodging resistance in sunflower and soybean (Antonio et al., 2010; Xiang et al., 2010). The study also found that the SBS and LRI were closely and inversely related to lodging (Table 7). Duan et al. (2004) also concluded that SBS and LRI were the key index to lodging, which were negative correlated with LR. However, further studies are needed to understand how higher densities can be effectively integrated into lodging-resistant cultivation and to understand their correlations.

Blossoming, fruiting, and grain filling are dependent on suitable environmental condition at the reproductive growth stage. It seems that producing reproductive units is reduced due to thickened density and limited light (Figure 1) and finally most flowers would fade at early stages. In this case, the denser population decreased the seed setting rate, but significantly increased seed abortion rate for tartary buckwheat (Table 5). Thickened density caused to increasing effective plants per m^2 in tartary buckwheat (Table 6), resulting in little photosynthetic matters that are available for blossoming and fruiting, grain

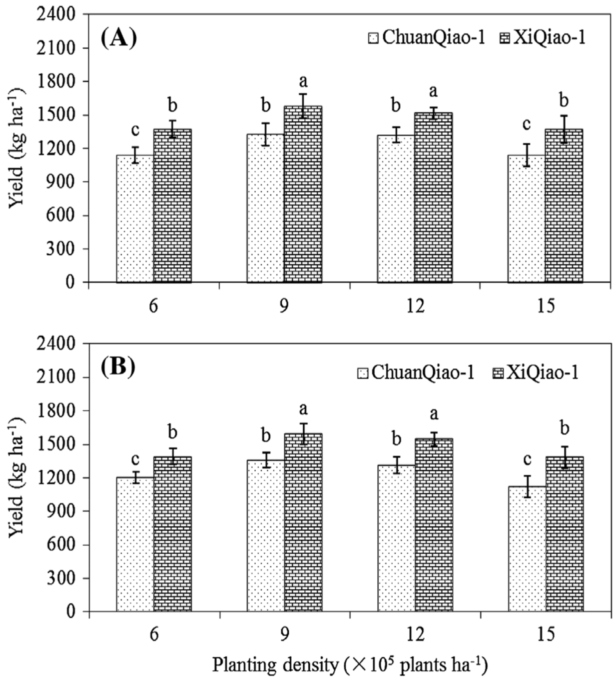

Figure 4. Effect of planting density on the yields of two tartary buckwheat cultivars in the 2012 (A) and 2013 (B) growing seasons.

Notes. Values are means ± SE (n = 4). Vertical lines at the tops of the bars show SE. The interaction effect of cultivar and planting density was significant (F2012 = 5.94**, F2013 = 16.11**). Letters above bars indicate significant difference at p < 0.05 according to Duncan's multiple range test. **Significant at 0.01 probability levels.

Table 7. Correlation coefficients among plant trait, LR and lodging resistance of tartary buckwheat.

	LR	SBS (beginning bloom)	LRI (beginning bloom)
LR		−0.8879**	−0.8201**
Plant height	0.7373**	−0.1716 ^{NS}	−0.4892 ^{NS}
Internode number	−0.7471**	0.7788**	0.5117*
First internode length	0.9034**	−0.8537**	−0.8856**
First internode diameter	−0.7862**	0.7285**	0.864**
Main root length	−0.4688^{NS}	0.4913^{NS}	0.3202^{NS}
Number of first lateral root	−0.8303**	0.8108**	0.6069*
Root volume	−0.666**	0.6550**	0.7600**
Main root diameter	−0.4804^{NS}	0.3323^{NS}	0.3572^{NS}
Root:shoot ratio	−0.2062^{NS}	−0.3294^{NS}	−0.1421^{NS}

*Significant at 0.05 probability levels; **Significant at 0.01 probability levels. ^{NS}No-significant at 0.05 probability levels; LR is lodging rate.

filling. Finally, the seed setting rate would be reduced due to increasing plants per m^2. However, the increasing plant density caused to increase the total grains per m^2. Correspondingly, the yield of tartary buckwheat did not show a sustained downward tendency with the increasing of planting density (Figure 4). It seems that seed setting rate and abortion rate were not main reasons for grain yield difference in different density levels, because there may be differences in yield component due to thickening

Table 8. Regression of lodging-related traits on planting density.

	Planting density (x_1)
Plant height	$y_1 = 92.16 + 1.20 \times 10^{-4} x_1$ ($R^2 = 0.3274$*)
Internode number	$y_2 = 17.77 - 1.99 \times 10^{-5} x_1$ ($R^2 = 0.2498$*)
First internode length	$y_3 = 3.42 - 8.38 \times 10^{-6} x_1$ ($R^2 = 0.7672$**)
First internode diameter	$y_4 = 5.68 - 1.13 \times 10^{-5} x_1$ ($R^2 = 0.6847$**)
Main root length	$y_5 = 8.21 - 9.29 \times 10^{-6} x_1$ ($R^2 = 0.4916$**)
Number of first lateral root	$y_6 = 28.32 - 3.81 \times 10^{-6} x_1$ ($R^2 = 0.3976$**)
Root volume	$y_7 = 2.36 - 5.49 \times 10^{-6} x_1$ ($R^2 = 0.3281$*)
LR	$y_{10} = -3.44 + 4.38 \times 10^{-4} x_1$ ($R^2 = 0.8215$**)
SBS(Beginning bloom)	$y_{11} = 818.62 - 2.36 \times 10^{-2} x_1$ ($R^2 = 0.6413$**)
LRI(Beginning bloom)	$y_{12} = 37.57 - 1.30 \times 10^{-4} x_1$ ($R^2 = 0.8180$**)

*Significant at 0.05 probability levels; **Significant at 0.01 probability levels. ^{NS}No-significant at 0.05 probability levels; SBS is stem breaking strength; LR is lodging rate; LRI is lodging resistance index.

density. The grains number per plant decreased significantly with the increasing of planting density, whereas a contrary trend was observed for effective plants per m^2. The 1000-grain weight remained unchanged when cultivar and planting density changed (Table 6). Our results showed that the dry matter weight per m^2 increased at first and then decreased with the increasing of tartary buckwheat density. Obviously, given the effective plants per m^2, the high-density condition was not beneficial for dry matter weight per plant and grain number per plant. Thus, all of these were the crucial factors influencing yield of tartary buckwheat, changing plant density caused main change in yield.

In our study, 9×10^5 and 15×10^5 plant ha^{-1} densities yielded highest and lowest yield of the two tartary buckwheat cultivars, but XiQiao-1 yielded more grain than ChuanQiao-1 in both years. Many researchers have also reported lower grain yields at higher planting densities, and proper density could obtain the higher yield (Duran et al., 2013; Garcia et al., 1988; Rahim et al., 2012). In addition, increasing soybean density caused decreased grain yields (Larry et al., 2002). Generally, the higher planting density easily leads to lodging and then reduces yield. The time of lodging is also important for crops. Many studies have indicated that the time of lodging plays a significant role in yield; the earlier the onset of lodging, the greater influence to yield and yield component (Carter & Hudelson, 1988). In this study, lodging occurred at maturity stage, therefore the effect of lodging on growth and yield formation was of no significance. However, if the lodging happened at the earlier stage (such as full-blooming and grain filling), there would be the greater effect on yield and yield component. Thus, the yield and yield component of tartary buckwheat will be different from this study, but more experimental data are required.

In conclusion, our study found that planting density significantly affected the agronomic traits, lodging resistance, and yield of tartary buckwheat. The plant height, internode number, first internode length, first internode diameter, number of first lateral root, and root volume are considered as the key characteristics affecting lodging incidence of tartary buckwheat. Growing tartary buckwheat at the density of 9×10^5 plant ha^{-1} was most beneficial to its growth and yield in southwest China. The yield of XiQiao-1 was higher than that of ChuanQiao-1. Therefore, XiQiao-1, planted at 9×10^5 plant ha^{-1} was recommended to produce the desired yield in these regions.

Disclosure statement

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