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RESEARCH ARTICLE

EVALUATING QUINOA LODGING RISK AND YIELD UNDER DIFFERENT IRRIGATION THRESHOLDS, NITROGEN RATES AND PLANTING DENSITIES IN NORTH-WESTERN CHINA

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KEYWORDS

lodging index, orthogonal design, soil matric potential, stem strength

HIGHLIGHTS

- A moderate irrigation threshold of −25 kPa gave the greatest actual yield.
- Nitrogen rates of 80–160 $kg \cdot ha^{-1}$ reduced lodging risk without yield decrease.
- Planting density of 30 $plants \cdot m^{-2}$ provided both high yield and lodging resistance.
- A lower-stem lodging index was best for prediction of quinoa lodging risk.

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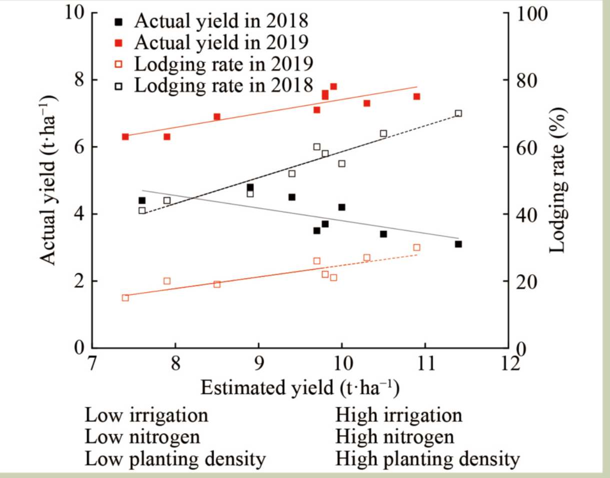
GRAPHICAL ABSTRACT



ABSTRACT

Lodging is a major yield-limiting factor of quinoa production. In 2018 and 2019, the orthogonal field experiments were conducted to investigate the responses of quinoa lodging risk and yield to irrigation threshold (soil matric potential of −15, −25 and −55 kPa), nitrogen rate (80, 160 and 240 $kg \cdot ha^{-1}$) and planting density (20, 30 and 40 plants m^{-2}). Results showed that high irrigation thresholds and nitrogen rates significantly ($P < 0.05$) increased plant height and fresh weight per plant, and high planting densities reduced stem diameter and strength, all of those led to significantly ($P < 0.05$) high lodging risks. The −15 and −55 kPa treatments gave the lowest actual yield ($P < 0.05$) in 2018 and 2019, respectively. Higher lodging rate with a nitrogen rate of 240 $kg \cdot ha^{-1}$ resulted in a lower actual yield than 80 and 160 $kg \cdot ha^{-1}$ in both years. Planting density of 30 plants m^{-2} gave a significantly ($P < 0.05$) greater estimated yield than 20 plants m^{-2} and had a lower lodging rate than 40 plants m^{-2}, resulting in the maximum actual yield among planting densities. In conclusion, a moderate irrigation threshold of −25 kPa, a nitrogen rate of 80–160 kg·ha^{-1} and an intermediate planting density of 30 plants m^{-2} were determined to be best for quinoa cultivation in North-western China. In addition, the lower-stem lodging index (quarter plant height) could evaluate lodging risk more accurately than middle-stem (half plant height) or upper-stem (three quarters plant height) lodging indexes.

1 INTRODUCTION

Quinoa (*Chenopodium quinoa*) is a nutritious crop with high protein content and balanced essential amino acids, and its yield potential has been continuously achieved under suitable agronomic measures to meet increasing global demand[1,2]. North-western China, with its high altitude and abundance of sunshine, is the largest quinoa production region in China[3]. However, the local farmers often use excessive irrigation, fertilizer and planting density based on their past experience, resulting in serious wastage of water, deep drainage, nitrogen leaching and low photosynthetic efficiency[4–6]. Also, this unsuitable production management can induce severe lodging of quinoa[7–10] leading to substantial yield losses[11,12]. Lodging occurs due to the interactions between plant, wind, rain and soil. Wind exerts a force which bends and breaks the stem base (stem lodging) or rain wets the soil and reduces the soil strength, resulting in the failure of the soil-root anchorage system (root lodging). In North-western China, quinoa lodging is mainly in the form of stem lodging because the farmers tend to grow tall cultivars (1.6–2.0 m) and large spike for great yield[13–15]. Therefore, more appropriate irrigation, nitrogen fertilizer application and planting density practices are urgently required to concurrently improve yield and stem lodging resistance.

Irrigation is beneficial to the development of the stem and leaf, and improves yield[2,16]. However, greater plant height[17], canopy growth[18] and length of the basal internodes[19] with higher irrigation lead to an increase in crop lodging risk[12]. Thus, an optimal irrigation scheduling should focus on concurrently increasing yield and lodging resistance in the production of quinoa. The soil matric potential is recommended as a criterion to schedule irrigation in arid and semiarid areas[20]. However, the quinoa yield and lodging risk under soil matric potential-based irrigation management have not been adequately studied. Generally, increasing nitrogen rate can increase in quinoa yield[2,7,21] but associated increase of plant height and center of gravity under high nitrogen rates can also result in severe lodging risk[22,23]. In Germany, the quinoa lodging rate has been reported to increase from 5% to 20% as nitrogen application rate was increased from 0 to 120 kg·ha^{-1}[7] but a detailed investigation of how nitrogen fertilizer affects the lodging resistance in quinoa has not been undertaken. Increasing planting density remains one of the most effective agronomic means to improve quinoa yield[24,25] but severe lodging under dense planting conditions have been frequently reported in wheat[26] and maize[27,28]. High lodging risk is associated with low strength and diameter of the basal internodes under high planting density[29] whereas the relationships between lodging risk, yield and planting density in quinoa has received little attention. Although early research[2] revealed the effects of soil matric potential-based irrigation criteria, nitrogen application rate and planting density on quinoa growth, seed quality, water use efficiency and estimated yield, yield losses caused by lodging have not been specifically analyzed.

Evaluating crop lodging risk quantitatively is a prerequisite to preventing yield loss caused by lodging[30–32]. Lodging index takes plant height (or center of gravity height), fresh weight per plant and stem strength into account and it has been widely applied as an indicator to represent crop lodging risk[33–35]. Basal stem strength was often used to calculate the lodging index[34,35] because the basal stem sustained a greater bending moment than the higher position, which was considered to be more susceptible to bend or break[36]. However, whether the stem lodging mainly occurs at the stem base is unclear because the basal stem also has the greatest stem strength along the stem[29,37]. Therefore, the determination of an optimal position along the stem to calculate the lodging index for evaluating crop lodging risk is worthy of investigation.

The purposes of this study were (1) to explore the responses of lodging resistance and actual yield of quinoa to irrigation threshold, nitrogen rate and planting density, and (2) to determine an optimal position along the stem to calculate lodging index for evaluating and assessing quinoa lodging risk.

2 MATERIALS AND METHODS

2.1 Experimental site

Field traits were conducted in 2018 and 2019 at Shiyanghe Experimental Station of China Agricultural University, which was located in Wuwei City, Gansu Province, China (102°50′ E, 37°52′ N, 1581 m asl). This region has a typical continental temperate climate with a mean annual precipitation of 164 mm and the pan evaporation of over 2000 mm. The rainfall and wind speed during quinoa growing seasons in 2018 and 2019 are shown in Fig. 1. The experimental site has sandy loam soil. The soil bulk density was 1.5 g·cm^{-3} both in 2018 and 2019. The field capacities were 0.31 and 0.30 cm^3·cm^{-3} in 2018 and 2019, respectively. The total nitrogen, phosphorus and potassium of the soil were 0.066%, 0.075% and 1.81% in 2018 and 0.060%, 0.076% and 1.92% in 2019.

2.2 Experimental design and treatments

Irrigation threshold levels were designed as previously described[20], regarding soil matric potential of −15, −25 and −55 kPa as the high, intermediate and low irrigation thresholds, respectively. Base on earlier research[7,24,38], the nitrogen application rates of 80, 160, and 240 kg·ha^{-1} were used. Planting densities (20, 30, and 40 plants m^{-2}) were determined to explore the possible greater yield under a higher planting density compared to some local field experiments[39,40]. The experiment was designed in an orthogonal design with three replicates and laid out as shown in Table 1.

2.3 Agronomic practices and irrigation scheduling

Agronomic practices and irrigation scheduling were as previously described[2]. The quinoa cv. Longli No.1 was used

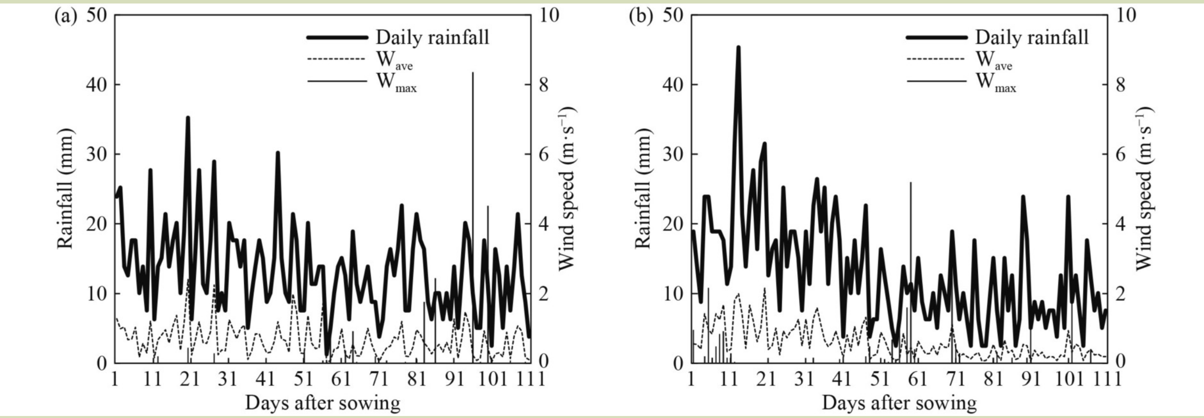


Fig. 1 Rainfall and average wind speed and maximum wind speed during quinoa growing seasons in 2018 (a) and 2019 (b). W_{ave}, average wind speed; W_{max}, maximum wind speed.

Table 1 Experimental layout using orthogonal design L_9 (3^3)

Experiment	Irrigation threshold (kPa)	Nitrogen rate (kg·ha^{-1})	Planting density (plants m^{-2})
1	−15	80	20
2	−15	160	30
3	−15	240	40
4	−25	80	30
5	−25	160	40
6	−25	240	20
7	−55	80	40
8	−55	160	20
9	−55	240	30

because it is a tall local cultivar with disease resistance, salt tolerance and of high yield potential and nutrition[39].

2.4 Measurements

2.4.1 Lodging related traits and lodging index

On 8 August 2018 and 10 August 2019, six plants per treatment were collected and the lateral branches were removed. The following measurements were made within 1 h of sampling: plant height, center of gravity height, fresh weight (main stem with ear) per plant, stem diameter and stem strength at quarter, half and three quarters of the plant height from the stem base. Fresh weight was measured on an electronic balance to 0.01 g. The center of gravity height was determined by balancing the stem on a ruler[34]. Plant height and center of gravity height were measured from the soil line of the stem. Stem diameter was measured using digital calipers to 0.001 mm, and D_L, D_M, and D_U represented the stem diameters at quarter, half and three quarters of the plant height from the stem base, respectively. The stem strength was measured by the YYD-1 stem strength analyzer (Top Instrument, Zhejiang, China). The sample was put on the groove of support pillars 10 cm apart. The analyzer was set perpendicular to the stem, loading gradually on the stem and stem strength (N) was recorded once the stem was broken.

The lodging index (LI) was calculated using the following equation[33]:

$$LI = (CGH \times FW)/SS \quad (1)$$

where LI is the lodging index (cm·g·N^{-1}), CGH is the center of gravity height (cm), FW is the fresh weight (main stem and ear) (g), and SS is the stem strength (N). Higher LI means greater lodging risk. The SS_L, SS_M, and SS_U represented the stem strengths at quarter, half and three quarters of the plant height from the stem base, respectively, and the lodging indexes for the corresponding positions were LI_L, LI_M and LI_U.

2.4.2 Observed lodging rate

Lodging occurred on 2 August 2018 and 7–8 August 2019. The observed lodging rate (LR_{ob}, %) was recorded 2–3 days after the occurrence of lodging, and it was calculated by dividing the number of observed lodging plants by the total number of plants. The lodging given is stem lodging from our field observations, thus the lodging rate refers to stem lodging rate.

2.4.3 Estimated yield and actual yield

To obtain the estimated seed yield, 15 plants were harvested on 18 August 2018 and 2019 (a previously described[2]). The actual yield was calculated as follows:

$$Y_{ac} = Y_{es} - Y_{es} \times LR_{ob}/100 \quad (2)$$

where, Y_{ac} is the actual yield (t·ha^{-1}), Y_{es} is the estimated yield (t·ha^{-1}), LR_{ob} is the observed lodging rate (%).

2.4.4 Meteorological data

Meteorological data were continuously recorded by a standard automatic weather station (Hobo, Onset Computer Co., Cape Cod, MA, USA), which is located near the experimental field.

2.5 Statistical analysis

The effects of the irrigation threshold, nitrogen rate, planting density, year as well as their interactions on plant height, center of gravity height, stem diameters, stem strengths, lodging indexes, actual yield, estimated yield and the observed lodging rate were analyzed statistically by the multivariate ANOVA. The post-hoc multiple comparisons were analyzed by least significant difference. The multivariate ANOVA, post-hoc tests and Pearson correlation were calculated via SPSS 19.0 version (IBM, Armonk, NY USA). All reported statistical differences were significant at $P \leqslant 0.05$.

3 RESULTS

3.1 Plant height, center of gravity height and fresh weight per plant

Irrigation threshold, nitrogen rate and planting density had significant effects on plant height whereas year did not. Center of gravity height was significantly ($P < 0.01$) affected by irrigation threshold and nitrogen rate. Besides, the interaction effects of irrigation threshold × planting density and nitrogen rate × planting density on plant height and center of gravity height were significant (Table 2). A −55 kPa irrigation threshold gave significantly ($P < 0.05$) lower plant height and center of gravity height than with −25 and −15 kPa irrigation thresholds in both years (Fig. 2). A nitrogen rate of 240 kg·ha^{-1} gave the greatest ($P < 0.05$) plant height and center of gravity height in both 2018 and 2019, followed by nitrogen rates of 160 and 80 kg·ha^{-1} (Fig. 2). Plant height with 20 plants m^{-2} was significantly ($P < 0.05$) higher than with 40 plants m^{-2} in 2018 but not in 2019 ($P > 0.05$) (Fig. 2). There was no significant ($P > 0.05$) difference in center of gravity height among planting density treatments in either year.

Irrigation threshold, nitrogen rate, planting density, irrigation

Table 2 F-values for multivariate ANOVA of irrigation threshold, nitrogen rate, planting density, year and their interactions on lodging-related traits, lodging indexes, observed lodging rate, estimated yield and actual yield

Items	PH	CGH	D_L	D_M	D_U	SS_L	SS_M	SS_U	FW	LI_L	LI_M	LI_U	LR_{ob}	Y_{es}	Y_{ac}
I	37.8^{**}	5.9^{**}	55.8^{**}	3.7^{*}	3.6^{*}	3.9^{*}	7.7^{**}	3.8^{*}	8.7^{**}	12.1^{**}	28.3^{**}	24.6^{**}	34.8^{**}	45.6^{**}	3.5^{*}
N	112.4^{**}	15.5^{**}	24.5^{**}	38.9^{**}	21.6^{**}	66.5^{**}	15.2^{**}	10.9^{**}	20.9^{**}	0.5^{ns}	12.2^{**}	14.2^{**}	6.8^{**}	6.1^{**}	1.6^{ns}
D	4.1^{*}	1.2^{ns}	121.9^{**}	100.2^{**}	57.0^{**}	231.5^{**}	129.7^{**}	40.0^{**}	82.6^{**}	4.0^{*}	0.1^{ns}	4.5^{*}	11.2^{**}	24.6^{**}	3.0^{ns}
Y	0.18^{ns}	4.3^{*}	7.1^{**}	1.6^{ns}	45.9^{**}	0.1^{ns}	2.5^{ns}	10.2^{**}	3.5^{ns}	1.2^{ns}	11.5^{**}	33.2^{**}	221.0^{**}	0.2^{ns}	167.0^{**}
I × N	2.1^{ns}	82.1^{ns}	61.6^{**}	50.4^{**}	29.2^{**}	116.5^{**}	65.2^{**}	20.1^{**}	41.6^{**}	2.0^{ns}	0.3^{ns}	2.3^{ns}	5.6^{**}	12.5^{**}	1.6^{ns}
I × D	56.3^{**}	7.8^{**}	12.9^{**}	19.8^{**}	7.6^{**}	34.0^{**}	8.0^{**}	5.5^{**}	10.7^{**}	0.3^{ns}	6.3^{**}	7.1^{**}	3.4^{**}	3.3^{*}	0.9^{ns}
I × Y	2.9^{ns}	0.6^{ns}	2.1^{ns}	1.9^{ns}	9.9^{**}	0.2^{ns}	1.0^{ns}	0.2^{ns}	0.2^{ns}	0.3^{ns}	0.5^{ns}	0.5^{ns}	3.0^{ns}	0.8^{ns}	10.0^{**}
N × D	19.0^{**}	3.0^{*}	28.6^{**}	2.1^{ns}	2.5^{*}	2.6^{*}	4.2^{**}	1.9^{ns}	4.6^{**}	6.1^{**}	14.4^{**}	12.4^{**}	17.4^{**}	23.0^{**}	1.9^{ns}
N × Y	1.7^{ns}	0.1^{ns}	0.7^{ns}	4.0^{*}	0.4^{ns}	6.1^{**}	1.9^{ns}	0.04^{ns}	0.4^{ns}	0.4^{ns}	0.9^{ns}	0.3^{ns}	2.3^{ns}	0.4^{ns}	6.7^{**}
D × Y	0.8^{ns}	0.1^{ns}	5.9^{**}	0.4^{ns}	2.8^{ns}	0.3^{ns}	0.1^{ns}	1.2^{ns}	0.6^{ns}	0.2^{ns}	0.2^{ns}	0.4^{ns}	4.2^{*}	0.03^{ns}	6.5^{**}
I × N × Y	0.9^{ns}	0.1^{ns}	4.5^{**}	2.0^{ns}	2.7*	0.17^{ns}	0.2^{ns}	1.3^{ns}	0.3^{ns}	0.1^{ns}	0.4^{ns}	0.6^{ns}	2.2^{ns}	0.5^{ns}	3.3^{*}
I × D × Y	1.4^{ns}	0.1^{ns}	1.9^{ns}	3.8^{**}	1.5^{ns}	3.0^{*}	1.1^{ns}	0.7^{ns}	0.2^{ns}	0.2^{ns}	0.7^{ns}	0.6^{ns}	1.2^{ns}	0.7^{ns}	3.4^{*}
N × D × Y	2.0^{ns}	0.3^{ns}	2.6^{*}	2.8^{*}	6.2^{**}	0.1^{ns}	0.7^{ns}	0.8^{ns}	0.1^{ns}	0.2^{ns}	0.5^{ns}	0.7^{ns}	1.6^{ns}	0.9^{ns}	5.1^{**}

Note: I, N, D and Y, irrigation threshold, nitrogen rate, planting density and year, respectively; PH, plant height; CGH, center of gravity height; D_L, D_M and D_U, stem diameter at 1/4, 1/2 and 3/4 plant height, respectively; SS_L, SS_M and SS_U, stem strength at 1/4, 1/2 and 3/4 plant height, respectively; FW, fresh weight per plant; LI_L, LI_M, and LI_U, lodging index at 1/4, 1/2 and 3/4 plant height, respectively; LR_{ob}, observed lodging rate; Y_{es}, estimated yield; Y_{ac}, actual yield; * and **, significant at $P < 0.05$ and $P < 0.01$, respectively; ns, no significant, $P > 0.05$. According to multivariate statistical analysis for orthogonal design in this study, the I × N × D and I × N × D × Y cannot be calculated.

threshold × nitrogen rate, irrigation threshold × planting density and nitrogen rate × planting density all had highly significant ($P < 0.01$) effects on fresh weight per plant whereas year did not (Table 2). With irrigation threshold increasing from −55, −25 to −15 kPa, the fresh weight per plant increased from 361, 406 to 412 g per plant in 2018 and from 327, 389 to 393 g per plant in 2019 (Fig. 2). In 2018, the fresh weight per plant with a nitrogen rate of 240 kg·ha^{-1} was 438 g per plant, which was significantly ($P < 0.05$) higher than that with a nitrogen rate of 80 kg·ha^{-1} (347 g per plant) (Fig. 2). In 2019, the fresh weight per plant significantly ($P < 0.05$) increased from 317, 362 to 429 g per plant with nitrogen rate increasing from 80, 160 to 240 kg·ha^{-1}, respectively (Fig. 2). A planting density of 20 plants m^{-2} gave significantly ($P < 0.05$) greater fresh weight per plant than 30 and 40 plants m^{-2} in both years (Fig. 2).

3.2 Stem diameter and stem strength

Except for the D_M and D_U in 2018, increasing irrigation threshold gave a significant ($P < 0.05$) increase in D_L, D_M and D_U for both years (Fig. 3). A nitrogen rate of 240 kg·ha^{-1} gave significantly ($P < 0.05$) greater stem diameters (D_L, D_M, and D_U) than with a nitrogen rate of 80 kg·ha^{-1} in 2018 and 2019 (Fig. 3). The stem diameters (D_L, D_M, and D_U) with a planting density of 20 plants m^{-2} were significantly ($P < 0.05$) greater than with planting densities of 30 and 40 plants m^{-2} in both years (Fig. 3).

Stem strengths (SS_L, SS_M and SS_U) tended to decrease with increasing irrigation threshold in both years (Fig. 4). In 2018 and 2019, a nitrogen rate of 80 kg·ha^{-1} gave significantly ($P < 0.05$) lower stem strengths (SS_L, SS_M and SS_U) than with 240 kg·ha^{-1} (Fig. 4). Increasing planting density led to a decrease in stem strengths (SS_U, SS_M and SS_L), and the differences in stem strengths were all significant ($P < 0.05$) between planting densities (Fig. 4).

3.3 Lodging index and observed lodging rate

In 2018 and 2019, the irrigation threshold of −55 kPa gave significantly ($P < 0.05$) smaller lodging indexes (LI_U, LI_M and LI_L) than those with −15 kPa and −25 kPa treatments, while the difference between −15 kPa or −25 kPa treatments was not significant (Table 3). The 240 kg·ha^{-1} nitrogen rate treatment gave significantly ($P < 0.05$) greater LI_U, LI_M and LI_L than those with a nitrogen rate of 80 kg·ha^{-1} treatment (Table 3) in 2018 and 2019. Planting density of 20 plants m^{-2} treatment gave the lowest ($P < 0.05$) LI_L of the planting densities, whereas the LI_U decreased with increasing planting density in both years (Table 3). The LI_M was not significantly ($P > 0.05$) affected by planting density in either year (Table 3).

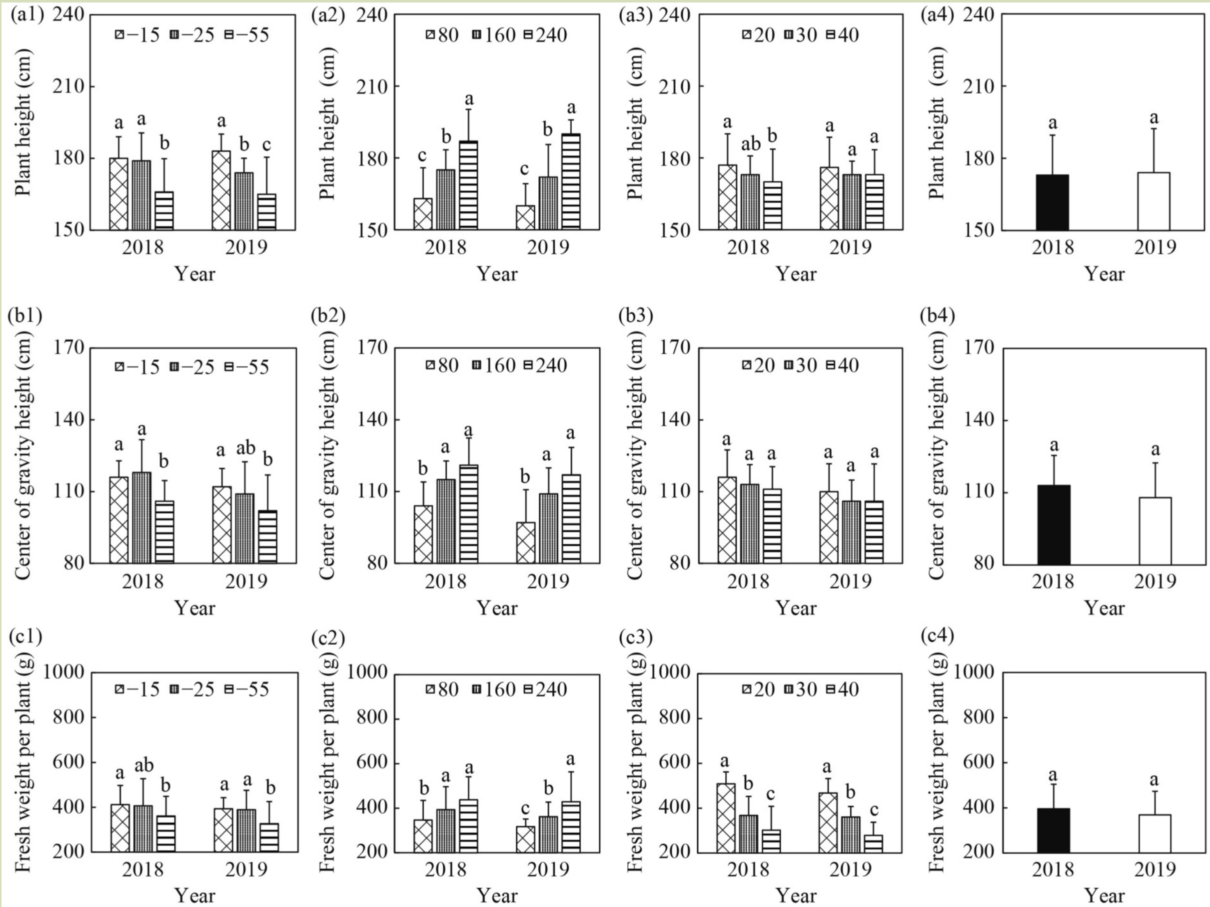


Fig. 2 The effects of irrigation threshold (kPa) nitrogen rate (kg·ha^{-1}), planting density (plants m^{-2}) and year on plant height (a1–a4), center of gravity height (b1–b4) and fresh weight per plant (c1–c4) in 2018 and 2019. Values followed by the same letter with a year at different levels in the same treatment are not significantly different (P < 0.05) by post-hoc multiple comparison; values followed the same letters between years are significantly different by one-way ANOVA (P > 0.05).

The lodging rate was significantly (P < 0.01) affected by irrigation threshold, nitrogen rate, planting density and year (Table 2). The lodging rate increased from 41%, 52% to 70% and from 15%, 22% to 30% with irrigation threshold increasing from −55, −25 to −15 kPa in 2018 and 2019, respectively (Table 3). The observed lodging rate significantly (P < 0.05) increased with the increase of nitrogen rate, reaching 46%, 58% and 60%, and 19%, 22% and 26% with nitrogen rates of 80, 160 and 240 kg·ha^{-1} treatments in 2018 and 2019, respectively. In 2018, the observed lodging rate was 64% and 55% with planting densities of 40 and 30 plants m^{-2}, respectively, which were both significantly (P < 0.05) higher than that with a planting density of 20 plants m^{-2} (44%). Similarly, in 2019, the observed lodging rate with a planting density of 40 plants m^{-2} was 27%, which was 7% and 6% greater than those with planting densities of 20 and 30 plants m^{-2}, respectively (Table 3).

3.4 Estimated yield and actual yield

Year had no significant (P > 0.05) effect on estimated yield whereas irrigation threshold, nitrogen rate and planting density significantly (P < 0.01) affected estimated yield (Table 2). In 2018, the estimated yield with a −15 kPa irrigation threshold was 11.4 t·ha^{-1}, which was significantly (P < 0.05) higher than that with a −55 kPa irrigation threshold (7.6 t·ha^{-1}) (Table 3). Similarly, the estimated yield with a −15 kPa irrigation threshold was 10.9 t·ha^{-1}, which was 3.5 t·ha^{-1} higher than that with a −55 kPa irrigation threshold (P < 0.05) in 2019 (Table 3). Estimated yield increased as the nitrogen rate increased from 80 to 160 kg·ha^{-1} (the difference was significant in 2019, P < 0.05) whereas it did not increase (P > 0.05) further when the nitrogen rate was 240 kg·ha^{-1} in either year (Table 3). The 20 plants m^{-2} planting density treatment gave the lowest (P < 0.05) estimated yield of planting densities in both years whereas there was no significant difference in estimated yield

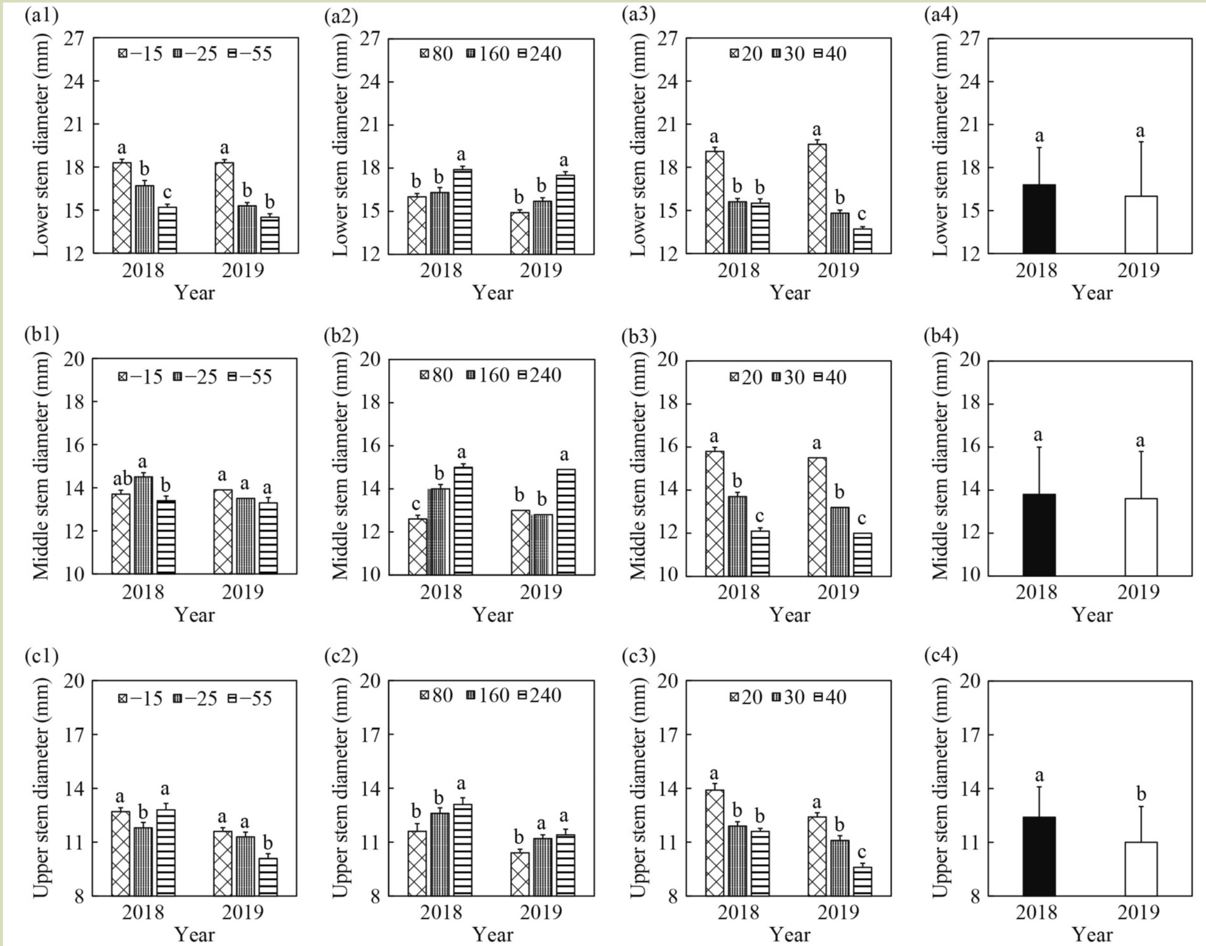


Fig. 3 The effects of irrigation threshold (kPa), nitrogen rate (kg·ha^{-1}), planting density (plants m^{-2}) and year on lower (a1–a4), middle (b1–b4), upper stem diameters (c1–c4) in 2018 and 2019. Lower, middle and upper, 1/4, 1/2 and 3/4 plant height, respectively; values followed by the same letter with a year at different levels in the same treatment are not significantly different (P < 0.05) by post-hoc multiple comparison; and values followed by the different same letter between years are not significantly different by one-way ANOVA (P > 0.05).

with 30 and 40 plants m^{-2} in either year (Table 3).

Year had a highly significant (P < 0.01) effect on actual yield (Table 2). A −15 kPa irrigation threshold gave a significantly (P < 0.05) lower actual yield than with a −25 kPa irrigation threshold in 2018. In 2019, −55 kPa irrigation threshold treatment gave a significantly (P < 0.05) lower actual yield (6.3 t·ha^{-1}), which was 1.2 and 1.3 t·ha^{-1} lower than with −15 and −25 kPa irrigation thresholds, respectively (Table 3). In 2018, 80 kg·ha^{-1} nitrogen rate treatment gave the highest (P < 0.05) actual yield among nitrogen rate treatments (Table 3). In 2019, there was no significant effect of nitrogen rate on actual yield (Table 3). In 2018, planting density of 40 plants m^{-2} treatment gave the significantly (P < 0.05) lower actual yield than that with a planting density of 20 plants m^{-2} whereas no significant (P > 0.05) difference in actual yield was found between planting densities of 20 or 30 plants m^{-2} (Table 3). In 2019, planting density of 30 plants m^{-2} treatment gave an actual yield of 7.8 t·ha^{-1}, which was 1.5 t·ha^{-1} higher than that with a planting density of 20 plants m^{-2} treatment (Table 3).

3.5 Correlation analysis

The observed lodging rate was significantly (P < 0.01) and positively correlated with estimated yield (R = 0.85, correlation coefficient) (Fig. 5). The correlations between plant height and observed lodging rate were highly significant (R = 0.61, P < 0.01) (Fig. 5). Strong correlations were found between stem diameter and corresponding strengths in 2018 and 2019 (Fig. 5). Fresh weight per plant correlated well with stem diameters and strengths. The R for LI_L, LI_M, LI_U and LR_{ob} decreased from 0.78 (P < 0.01), 0.64 (P < 0.01) to 0.44 (P > 0.05) (Fig. 5).

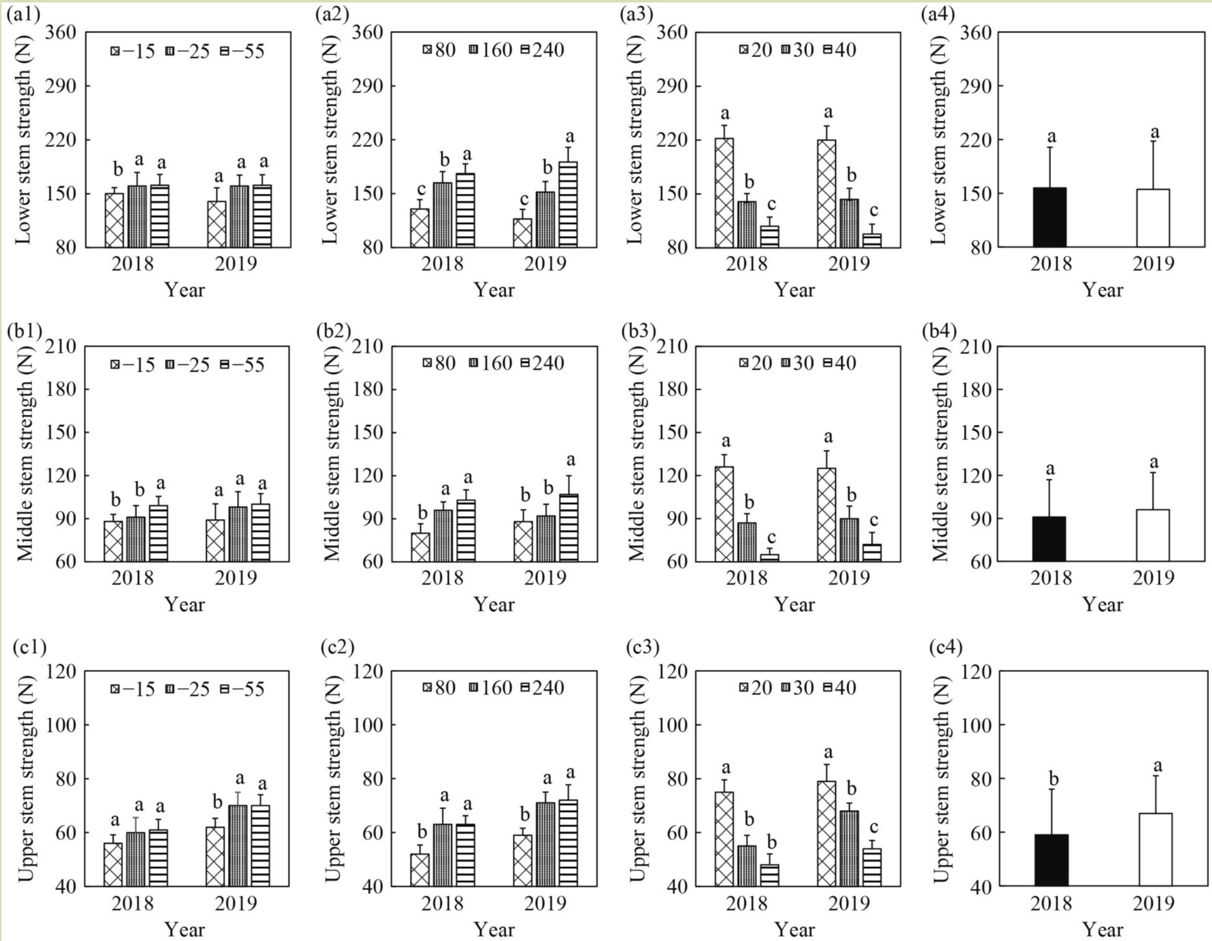


Fig. 4 The effects of irrigation threshold (kPa), nitrogen rate (kg·ha^{-1}), planting density (plants m^{-2}) and year on stem strength of lower (a1–a4), middle (b1–b4) and upper stem (c1–c4) in 2018 and 2019. Lower, middle, and upper, 1/4, 1/2 and 3/4 plant height, respectively; values followed by the same letter within a year at different levels in the same treatment are not significantly different (P < 0.05) by post-hoc multiple comparison; and values followed by the same letters between years are not significantly different by one-way ANOVA (P > 0.05).

4 DISCUSSION

A −55 kPa irrigation threshold can cause severe crop water stress throughout the growing seasons, resulting in negative effects on plant growth, leaf gas exchange efficiency and biomass formation[2]. As a result, the −55 kPa irrigation threshold treatment gave lower plant height, center of gravity height, stem diameter, fresh weight per plant and estimated yield than −15 and −25 kPa irrigation threshold treatment in this study (Figs. 2–4; Table 3). Despite obtaining the highest estimated yield (same as −25 kPa, statistically), the highest (P < 0.05) observed lodging rate also occurred with a −15 kPa irrigation threshold in 2018, resulting in lower actual yield than that with a −25 kPa irrigation threshold (Table 3). Thus, a moderate irrigation threshold of −25 kPa should be adopted to secure a stable actual yield and satisfying lodging resistance in quinoa cultivation.

High nitrogen rate gave significant (P < 0.05) increase in plant height, center of gravity height, stem diameters, stem strength and fresh weight per plant in our experiments (Figs. 2–4), consistent with some early reports[41,42]. However, with the increased plant height, center of gravity height and fresh weight per plant, lodging risk can increase[43]. Also, great stem diameter and strength can reduce crop lodging[29]. Our results demonstrated that the observed lodging rate significantly (P < 0.05) increased with increasing nitrogen rate, increasing by 30% to 37% as nitrogen rate increased from 80 to 240 kg·ha^{-1}, respectively (Table 3). Estimated yield increased as the nitrogen rate increased from 80 to 160 kg·ha^{-1} but it did not further increase with nitrogen rate of 240 kg·ha^{-1} in either year, suggesting that an excessive nitrogen fertilization might have a

Table 3 Lodging indexes, observed lodging rate, estimated yield and actual yield in 2018 and 2019

Year	Treatment		LI_L ($cm\cdot g\cdot N^{-1}$)	LI_M ($cm\cdot g\cdot N^{-1}$)	LI_U ($cm\cdot g\cdot N^{-1}$)	Observed lodging rate (%)	Estimated yield ($t\cdot ha^{-1}$)	Actual yield ($t\cdot ha^{-1}$)
2018	Irrigation threshold(kPa)	−15	319 ± 40a	570 ± 55a	848 ± 69a	70 ± 9a	11.4 ± 2.3a	3.1 ± 1.4b
		−25	309 ± 68a	542 ± 71a	795 ± 80a	52 ± 7b	9.4 ± 2.2b	4.5 ± 1.5a
		−55	246 ± 38b	380 ± 40b	621 ± 51b	41 ± 7c	7.6 ± 1.9c	4.4 ± 1.6a
	Nitrogen rate ($kg\cdot ha^{-1}$)	80	279 ± 31b	448 ± 52b	699 ± 67b	46 ± 8b	8.9 ± 1.6a	4.8 ± 1.3a
		160	288 ± 56ab	489 ± 50b	720 ± 75b	58 ± 5a	9.8 ± 2.5a	3.7 ± 1.5b
		240	308 ± 60a	555 ± 63a	845 ± 58a	60 ± 10a	9.7 ± 2.3a	3.5 ± 1.6b
	Planting density (plants m^{-2})	20	268 ± 45b	493 ± 60a	797 ± 57a	44 ± 9b	7.9 ± 2.5b	4.4 ± 1.4ab
		30	299 ± 43a	486 ± 60a	761 ± 91a	55 ± 8a	10.0 ± 2.1a	4.2 ± 1.6a
		40	309 ± 58a	512 ± 45a	706 ± 52a	64 ± 6a	10.5 ± 1.8a	3.4 ± 1.4b
	Average		291 ± 57a	497 ± 115a	754 ± 164a	54 ± 18a	9.5 ± 2.2a	4.0 ± 1.2b
2019	Irrigation threshold (kPa)	−15	320 ± 14a	501 ± 36a	717 ± 35a	30 ± 4a	10.9 ± 1.2a	7.5 ± 2.4a
		−25	281 ± 52a	436 ± 46a	599 ± 53b	22 ± 4b	9.8 ± 2.0a	7.6 ± 1.6a
		−55	216 ± 29b	331 ± 35b	472 ± 49c	15 ± 2c	7.4 ± 1.4b	6.3 ± 1.3b
	Nitrogen rate ($kg\cdot ha^{-1}$)	80	263 ± 30a	343 ± 25b	514 ± 35b	19 ± 3b	8.5 ± 1.5b	6.9 ± 1.9a
		160	277 ± 42a	444 ± 50a	566 ± 49b	22 ± 4ab	9.8 ± 1.4a	7.5 ± 2.0a
		240	279 ± 58a	481 ± 42a	709 ± 53a	26 ± 3a	9.7 ± 2.0a	7.1 ± 1.5a
	Planting density (plants m^{-2})	20	234 ± 43b	413 ± 52a	661 ± 82a	20 ± 5a	7.9 ± 2.0b	6.3 ± 1.7b
		30	277 ± 22ab	433 ± 17a	567 ± 21b	21 ± 2a	9.9 ± 1.6a	7.8 ± 2.0a
		40	301 ± 64a	421 ± 48a	561 ± 34b	27 ± 4a	10.3 ± 1.0a	7.3 ± 1.7ab
	Average		275 ± 77a	428 ± 126b	595 ± 169b	22 ± 9b	9.3 ± 2.1a	7.1 ± 1.2a

Note: LI_L, LI_M, and LI_U, lodging index at 1/4, 1/2 and 3/4 plant height, respectively; values followed by the same letter within a year at different levels in the same treatment are not significantly different ($P > 0.05$) by post-hoc multiple comparison (least significant difference); and values followed by the letter between years are not significantly different by one-way ANOVA ($P > 0.05$).

limited effect on improving quinoa yield potential, consistent with an earlier report[24]. As to actual yield, nitrogen rate of 80 and 160 $kg\cdot ha^{-1}$ gave the significantly ($P < 0.05$) greatest actual yield of the nitrogen rates in 2018 and 2019, respectively (Table 3). In conclusion, a high nitrogen rate of 240 $kg\cdot ha^{-1}$ did not promote actual yield but increase lodging risk, and a nitrogen rate ranging from 80 to 160 $kg\cdot ha^{-1}$ would be better for quinoa production in this region.

In this study, stem diameters, fresh weight per plant and stem strengths all significantly ($P < 0.05$) increased with decreasing planting density, consistent with earlier reports[25,44]. This might be caused by the fact that high planting density can lead to strong competition for light, water and nutrients as well as population shading, limiting the growth of stem and canopy of individual plants[37]. Greater fresh weight per plant would increase crop lodging whereas greater stem diameter and strength would reduce lodging risk[29,36]. Overall, the observed lodging rate significantly ($P < 0.05$) increased by 35% to 45% with increasing planting density from 20 to 40 plants m^{-2} in our experiments (Table 3). A similar trend of higher lodging rate under greater planting density has been reported in wheat[36,45] and maize[46], highlighting the challenge of optimizing yield performance by controlling crop lodging under optimal planting density. Estimated yield significantly ($P < 0.05$) increased by 2.1 $t\cdot ha^{-1}$ as planting density increased from 20 to 30 plants m^{-2} whereas there was no significant difference in estimated yield between planting densities of 30 or 40 plants m^{-2} ($P > 0.05$) (Table 3). Our results showed that an intermediate planting density of 30 plants m^{-2} gave the greatest actual yield over two consecutive years, which is recommended for quinoa cultivation in this region to reduce lodging risk and achieve a relatively great yield.

Correlation analysis in our experiments found a strong positive relationship between estimated yield and lodging rate (R = 0.85, $P < 0.01$), verifying the great lodging risks under high-yield conditions[47]. Plant height (R = 0.61) and stem strengths (R = 0.47 – 0.62) were significantly associated with observed

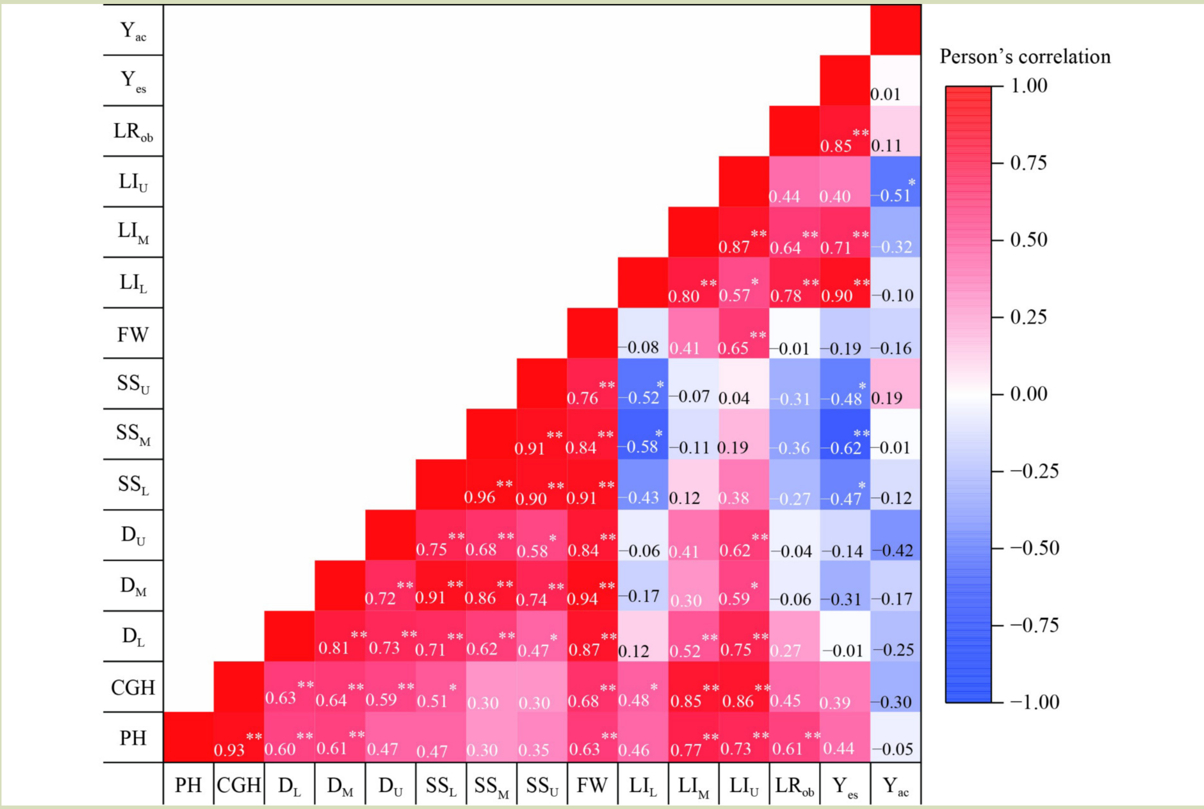


Fig. 5 Pearson' correlation between lodging-related traits, lodging indexes, observed lodging rate, estimated yield and actual yield for two years. PH, plant height; CGH, center of gravity height; D_L, D_M and D_U, stem diameter at 1/4, 1/2 and 3/4 plant height, respectively; SS_L, SS_M and SS_U, stem strength at 1/4, 1/2 and 3/4 plant height, respectively; FW, fresh weight per plant; LI_L, LI_M, and LI_U, lodging index at 1/4, 1/2 and 3/4 plant height, respectively; LR_{ob}, observed lodging rate; Y_{es}, estimated yield; Y_{ac}, actual yield; * and **, significant at $P < 0.05$ and $P < 0.01$, respectively.

lodging rate (Fig. 5), consistent with previous studies[30,31,34,48]. However, increasing nitrogen rate increased stem strength but planting density did not affect plant height ($P > 0.05$) (Fig. 2 and Fig. 4), which is inconsistent with the trends in of lodging rate under varying nitrogen rates and planting densities (Table 3), revealing the limitation of individual parameters in predicting crop lodging resistance. Comparing plant height and stem strengths, the lower-stem lodging index had a stronger correlation ($R = 0.78$, $P < 0.01$) with lodging rate. Also, it was higher than the middle-stem ($R = 0.64$) and upper-stem ($R = 0.44$) lodging indexes. Therefore, the lower-stem lodging index was more reliable for predicting quinoa lodging risk than plant height, stem strength as well as middle- and upper-stem lodging indexes under different agronomic practices in this region.

The interannual variation of lodging rate was highly significant ($P < 0.01$) in our experiments (54% in 2018 and 22% in 2019) (Table 2 and Table 3), which was mainly caused by the great differences in the weather between years (Fig. 1). Therefore, it is important that there was a greater reduction of yield due to lodging in 2018 than that in 2019 resulting in differences in the correlation between estimated yield and actual yield between years. In a year with severe lodging (such as 2018), the greater estimated yield with higher lodging risk was associated with lower actual yield whereas there was higher actual yield in the year with less lodging (such as 2019). Although the lodging index is a scientific indicator to evaluate crop lodging resistance, it is difficult to predict difference in lodging severity caused by particular weather events. Therefore, further studies should give attention to the interaction between crop lodging resistance and environmental factors (wind and rain) to predict and prevent lodging[11,45].

Quinoa cv. Longli No.1, used in this study, is a typical cultivar in north-western China with tall plants, high yield and good nutritional qualities. However, our study found that the high lodging risk of this cultivar could restrict its future use. This study aimed to reduce the lodging risk by optimizing some agronomic practices. However, breeding of cultivars with strong lodging resistance would also be an effective method to improve yield potential[49]. Therefore, the reduction of quinoa lodging risk should be achieved through multiple coordinated approach.

5 CONCLUSIONS

Increasing irrigation threshold can increase estimated yield, but it also led to an increase in lodging risk. An irrigation threshold of −25 kPa gave the highest actual yield both in 2018 and 2019. The lodging rate increased with a higher nitrogen rate. The estimated yield increased with nitrogen rate increasing from 80 to 160 kg·ha^{-1} but not at 240 kg·ha^{-1} in either year. Increasing planting density can increase lodging rate and estimated yield, but the difference in estimated yield was not significant between 30 or 40 plants m^{-2}. From the above results, it is reasonable to conclude that a suitable yield and lodging resistance can be realized by appropriate irrigation with a threshold of −25 kPa, applying nitrogen at 80–160 kg·ha^{-1} and sowing at 30 plants m^{-2} for quinoa production in this region of China.

The lower-stem lodging index is recommended for predicting lodging risk under different agronomic practices rather than plant height, stem strength, or the middle- and upper-stem lodging indexes.

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Compliance with ethics guidelines

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