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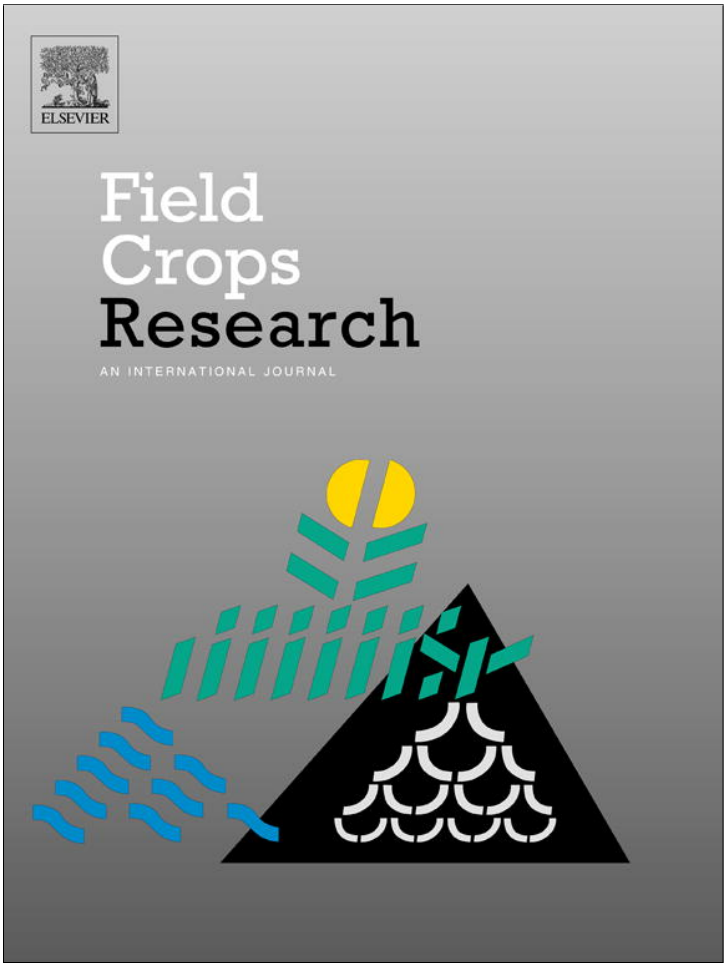
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Rapid determination of single-stalk and population lodging resistance strengths and an assessment of the stem lodging wind speeds for winter wheat

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ABSTRACT

Lodging is a major limiting factor on wheat production worldwide but due to experimental restrictions, there is little accurate information on wheat single-stalk lodging resistance strength, particularly at the population level. The single-stalk and population lodging resistance strength of 10 winter wheat varieties (*Triticum aestivum* L.) were measured in the field between 2010 and 2012 using a crop lodging resistance electronic measuring device and, based on the population lodging resistance strength, wind speed and wind pressure theory, the population stem lodging wind speed for each wheat variety was estimated. The single-stalk lodging resistance strength was 2.50–10.79 g-force stalk^{-1}; the population lodging resistance strength was 20.35–65.06 N m^{-1} and the population stem lodging wind speed was 11.93–24.69 m s^{-1} depending on variety and the growth stage. These results were consistent with general observations taken in the field and suggest that the method used in this study for population lodging resistance measurement and lodging wind speed evaluation may be suitable for the rapid identification of wheat variety lodging resistance in the field.

1. Introduction

Lodging, the permanent displacement of a cereal stalk from its natural upright position due to internal and external factors (Baker et al., 1998), is a major limiting factor on food production worldwide (Berry et al., 2003a). Lodging can be divided into stem lodging and root lodging. Stem lodging results from the bending or buckling of the lower stem internodes (Neenan and Spencer-Smith, 1975). Root lodging results from a failure in root soil integrity so that straight unbroken stalks lean or fall from the crown (Baker et al., 1998). The type of lodging that occurs is related to the wheat growing environment (Berry et al., 2003a), management regime (Easson et al., 1993; Stapper and Fischer, 1990; Berry et al., 2000), the growth and development period (Berry et al., 2000, 2003a,b) and the varieties grown (Easson et al., 1993; Crook and Ennos, 1994). The production survey results showed that wheat can happen lodging to result in a considerable reduction in production from booting stage (GS 41, using Zadoks Growth stages) (Zadoks et al., 1974) to milky stage (GS 85), of which is from 10% to 50%. In 1998, large area wheat lodging occurred in Anhui province, China, lead to lose 30% (Li et al., 2005). Stem lodging is an important factor leading to reduced wheat yields in China, so improving stem lodging resistance is seen as one of the most important breeding objectives (Tian and Yang, 2005). Many techniques have been described to evaluate wheat lodging resistance (Liu et al., 2007; Tian and Yang, 2005). They can be divided into two types according to their specific implementation mode and the research objects. Of which visual field evaluation for natural or artificially induced lodging is the most commonly used method. Various techniques have been used to artificially induce lodging, such as increased planting density, excessive application of nitrogen fertilizer and other cultivation and management techniques (Li et al., 2001; Liu et al., 2007; Tian and Yang, 2005). Harrington and Waywell (1950) induced lodging by exposing individual plots to strong wind produced by an airplane propeller whereas Bauer (1964) made use of wind tunnels to evaluate the level of lodging resistance in wheat. Briggs (1990), Kelbert et al. (2004) and Navabi et al. (2006) induced the complete flattening of a wheat experiment by dragging a weighted plywood board, mounted on 6 cm skids, across the length of each plot, and then determined the level of lodging by analyzing the number of wheat stalks that returned to upright growth. Using the physical characteristics of wheat stalk such as elasticity, bending strength and so on to identify the wheat lodging resistance is another important research method. The traditional visual evaluation method of lodging resistance is to bend the wheat stalks artificially in the field to an angle of 30°–45° against the ground to determine their lodging resistance. Murphy et al. (1958) proposed using a breakdown test to evaluate wheat stalk flexibility. Five stalks tied into a bundle were

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pushed to an angle of 45° vertically, and the lodging resistance of the tested cultivar was then calculated from the force required to move the stalks from the perpendicular to 45° and the time taken for the stalks to return to an upright position. Wang and Li (1997) introduced a method of measuring wheat stalk bending strength. It is of using the force required breaking the second internode of wheat stalk to evaluate wheat lodging resistance, and this force is called the stalk bending strength. Xiao et al. (2002) used a prostrate tester (DIK-7400, Daiki Rika Kogyo Co. Ltd., Tokyo, Japan) to study wheat stalk strength. This method saves time and is less damaging to the plants.

In recent years, papers have been published on the mechanisms and factors that affect wheat lodging (Easson et al., 1993; Baker et al., 1998; Berry et al., 2003a,b, 2004, 2007; Sterling et al., 2003). Baker et al. (1998) proposed a predictive model for wheat stem lodging; Berry et al. (2003a) conducted a field verification of the model, and Sterling et al. (2003) measured some parameters of the model using wind tunnel experiments which led to the model being amended. These lodging assessment methods and theoretical models have provided valuable insights into the evaluation of wheat lodging resistance. However, most of these methods are based on single-stalk lodging and so far there has been little research conducted on the determination method of wheat populations lodging resistance strength, and the assessment method of the population stem lodging wind speed based on the value of the wheat populations lodging resistance strength. We assume that the wheat population lodging resistance strength can directly reflect the actual lodging tolerance of different wheat varieties. Wind is the most important external factors that cause wheat population stalk lodging; the population stalk lodging results from the horizontal force exerted upon the population stalks by wind (wind load) more than the maximum bending moment that the population stalk is able to withstand at their base. The population stem lodging wind speed that the population stalk is able to withstand can be calculated by using the Bernoulli equation from their maximum horizontal force measured.

The purpose of this study was (1) to use a purpose built crop lodging resistance electronic measuring device to record the strength of a single stalk of wheat and the overall population lodging resistance; (2) to study the relationship between the population lodging resistance strength and the ear number per unit area, plant height, stalk bending strength and single-stalk lodging resistance strength; and (3) to establish an evaluation method to ascertain the population stem lodging wind speed of different wheat varieties. This research should provide the technical and theoretical basis for breeding high-yielding and lodge resistant wheat varieties.

2. Materials and methods

2.1. Plant materials

Ten wheat cultivars: Zhoumai 18, Aikang 58, Wenmai 6, Zhoumai 22, Zhengmai 9023, Pingan 6, Yumai 18, BH 001, Zamai 3 and Zamai 4 were selected for the field experiment. All the cultivars (or lines) came from the Wheat Center at the Henan Institute of Science and Technology. The experiment was conducted at the Henan Institute of Science and Technology (35°18′N, 113°52′E) experimental field between 2010 and 2012. The experiment was a randomized block design with three replications. Each plot was 10 rows wide, row spacing was 0.23 m and the plots were 4 m long. Nitrogen and phosphorus were applied at 170 kg ha^{-1} and 112.8 kg ha^{-1}, respectively. Of this, 100 kg ha^{-1} nitrogen and all the phosphorus was applied as a diammonium hydrogen phosphate ($(NH_4)_2PO_4$, 64%) base fertilizer. The remaining 70 kg ha^{-1} nitrogen was applied as urea ($CO(NH_2)_2$, N 46%) with irrigation at the stem elongation stage (GS 30). In order to objectively evaluate the lodging resistance of the different wheat varieties, all the wheat varieties were sown at the same seed rate (240 seeds m^{-2}). The first experiment was sown in 1 October 2010 and harvested in 6 June 2011. The measurement of single-stalk and population lodging resistance strength began at the anthesis stage (GS 65) (on 8 May) and continued until the wheat was fully mature (GS 93) on 5 June. It was undertaken once every seven days. The second experiment was sown in 20 October 2011 and harvested in 6 June 2012. The measurement of single-stalk and population lodging resistance strength began at the anthesis stage (GS 65) (on 6 May) and continued until the wheat was fully mature (GS 93) on 29 May. Twenty representative stalks were randomly sampled from the middle of the plot each time. Plant height, center of gravity height and internode length was all measured.

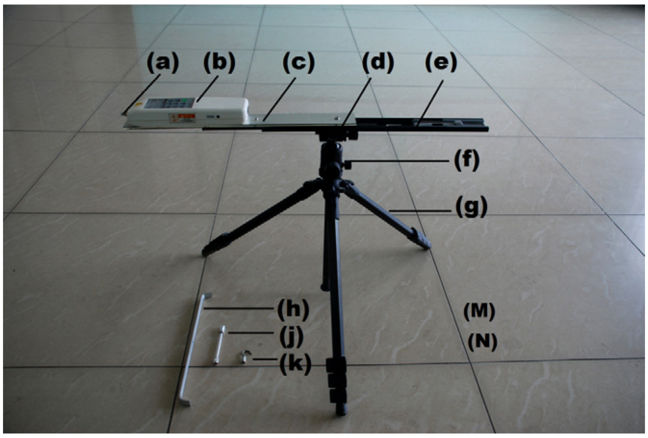

Fig. 1. The crop lodging resistance electronic measuring device. (a) Probe installation location, (b) force measurement unit, (c) dust and connection plate, (d) quick release plate, (e) ball guideway, (f) ball joints, (g) adjustable multi-functional tripod, (h) wheat population lodging resistant strength measurement probe, (j) "V" shape probe (stalks bending strength measurement probe), and (k) wheat sing stalk lodging resistant strength measurement probe.

2.2. Measurement items and methods

2.2.1. Determination of single stalk and population lodging resistance strength

Single-stalk lodging resistance strength was measured using an adaptation of the method reported by Xiao et al. (2002). The device used was a purpose built the crop lodging resistance electronic measuring device (Fig. 1). The device consisted of a force measurement unit, a ball guideway, ball joints, an adjustable multi-functional tripod, quick release plate and special probes. The basic measurement principle was to use the force measurement unit to exert a force on the plant stalk so that it bent 45° from the perpendicular, and then record the force needed to achieve this. The larger the force, the stronger the crop stalk lodging resistance strength.

The test procedure for the single-stalk lodging resistance strength was as follows: (1) the device was installed 0.25–0.3 m in front of the tested cultivar. (2) The force measurement unit was pushed out horizontally along the ball guideway, the probe hooked onto the 2/3 part of the tested stalk height, and kept in a horizontal position. (3) The device was then pulled back slowly to make the stalk bend to 45° from the perpendicular. Twenty samples were measured for each wheat cultivar and a mean value calculated.

The method used to measure the population lodging resistance strength was similar to the single-stalk lodging resistance strength. The large "U" shape probe was connected at the front of the force measurement unit. The force measurement unit was aligned to the 2/3 part of the tested population stalks height. The measurement

Table 1
Basic stalk characteristics of the 10 wheat cultivars tested between 2010 and 2012.

Cultivar	2010–2011				2011–2012			
	Ear number (ears m^{-2})	Plant height (cm)	Center of gravity height (cm)	Stalk bending strength (N)	Ear number (ears m^{-2})	Plant height (cm)	Center of gravity height (cm)	Stalk bending strength (N)
Zhoumai 18	571	73.14 ± 2.03	35.35 ± 1.02	5.67 ± 1.10	468	69.48 ± 1.55	36.57 ± 1.95	6.28 ± 0.60
Aikang 58	600	65.02 ± 1.76	33.61 ± 1.11	5.32 ± 1.58	422	61.77 ± 0.57	30.05 ± 1.28	5.79 ± 0.68
Wenmai 6	628	76.80 ± 1.65	38.65 ± 1.06	4.84 ± 1.29	443	74.96 ± 3.34	35.18 ± 2.70	5.65 ± 0.29
Zhoumai 22	532	71.22 ± 1.40	42.45 ± 1.49	5.09 ± 1.39	554	67.66 ± 2.89	33.74 ± 2.29	5.81 ± 0.33
Zhengmai 9023	504	83.36 ± 1.87	34.44 ± 1.20	3.39 ± 0.56	383	79.19 ± 2.30	36.33 ± 2.49	6.61 ± 0.58
Pingan 6	587	77.29 ± 1.41	39.11 ± 1.69	5.23 ± 1.62	521	73.43 ± 5.17	35.11 ± 4.70	7.03 ± 0.47
Yumai 18	539	77.31 ± 1.44	39.95 ± 1.50	3.57 ± 0.89	418	73.44 ± 1.10	35.46 ± 3.00	6.70 ± 0.23
BH 001	575	78.56 ± 1.97	39.39 ± 1.99	5.18 ± 0.94	503	74.63 ± 1.04	37.71 ± 1.78	7.87 ± 0.25
Zamai 4	532	71.55 ± 3.63	39.56 ± 2.37	5.44 ± 2.06	462	65.97 ± 4.3	40.22 ± 5.35	7.29 ± 1.03
Zamai 3	543	81.58 ± 4.05	45.10 ± 1.94	5.28 ± 1.77	425	76.50 ± 6.56	45.52 ± 1.89	8.25 ± 1.34
Mean	561	75.58 ± 5.43	38.76 ± 3.55	4.90 ± 0.78	434	71.70 ± 1.97	36.59 ± 2.79	7.02 ± 0.81

(1) To verify the accuracy of the measurement results of the experimental method in the article as well as variation of wheat single stems and population lodging strength, the experiment lasted two years, the paper provides two years' data from 2010 to 2012. (2) Except the ear number per square meter, other values are means ± SD (n = 20).

unit was extended horizontally along the ball guideway to make the stalks in front of the tested population bend 45° from the perpendicular. Ten samples were measured for each wheat cultivars and a mean value calculated.

2.2.2. Determination of the stalk bending strength

Stalk bending strength (or stalk strength) was measured using an adaptation of the method reported by Wang and Li (1997). The crop lodging resistance measuring device was placed on a table, and the rotating ball joint was placed vertically downward. The "V"-shaped probe was vertically aligned to the middle of the internode laid flat on a 50 cm high plate grooved at 5 cm intervals and slowly pressed downwards until the internode broke. The value displayed was the stalk bending strength in N stalk^{-1}. Twenty stalks per wheat cultivar were measured and the mean calculated.

Plant height and center of gravity height were measured based on the methods reported by Wang and Li (1997). The center of gravity height refers to the distance from the stalk (with ear, leaf, and sheath) base to the balance fulcrum. Plant height and internode length were measured using a 100 cm ruler.

2.3. The wind speed distribution in the later growth stages of wheat

The wind speed distribution data in the later growth stages of wheat at Zhengzhou Station, China's National Weather Station from 2000 to 2009 came from China's Meteorological Data Sharing Service System (http://cdc.cma.gov.cn/home.do).

2.4. Statistical analysis

All experimental data reported in this paper were the means of 20 individual measurements except the population lodging resistance strength which were the means of 10 measurements. The correlation coefficient between the experimental data, significance analysis and multiple linear regressions were carried out using SPSS 13.0 statistical software.

3. Results

3.1. Basic stalk characteristics of the tested wheat cultivars

The basic stalk characteristics of the 10 wheat cultivars used between 2010 and 2012 are shown in Table 1. The data listed in the table were measured on 20–21 May and used to study the relationship between the single stalks, the population lodging resistance strength and the indicators are shown in Table 1.

The ear number range per unit area of the 10 cultivars was 418–628 ears m^{-2}, with an average of 507 ears m^{-2}, which was similar to what was expected given the seed and fertilizer rates used in this experiment. Plant heights ranged from 59.02 to 83.36 cm, with an average of 72.79 cm. The center of gravity height for the plants tested ranged from 30.05 to 45.52 cm, with an average of 37.68 cm, which was about 50% of the average plant height of the wheat cultivars tested. Stalk bending strengths were 3.39–7.87 N stalk^{-1}, with an average of 5.96 N stalk^{-1} at the anthesis stage (GS 65). As the sowing date in the second experiment was later 20 days than that of the first experiment, the plant height and ear number were smaller than those of the first experiment, while the stalk bending strength was greater than that of the first experiment.

3.2. The single-stalk lodging resistance strength at different stages of growth

The single-stalk lodging resistance strength of the 10 wheat cultivars tested between 2010 and 2012 is shown in Table 2.

The results obtained from 2010 to 2011 show that the single-stalk lodging resistance strength of the cultivars exhibited the basic similar trends. The strength is highest at the anthesis stage (GS 65), and then gradually decreases until it is grain dough stage (GS 83), after which there is a slight increase. The strength ranged from 5.33 to 9.47 g-force stalk^{-1}, with an average of 7.87 ± 1.72 g-force stalk^{-1} on 8 May, 2.50 to 5.07 g-force stalk^{-1}, with an average of 4.10 ± 0.86 g-force stalk^{-1} on 30 May, and ranged from 2.63 to 5.70 g-force stalk^{-1}, with an average of 4.35 ± 0.96 g-force stalk^{-1} on 5 June. However, due to the difference of cultivars growth period, the maximum lodging resistant strength of most cultivars appear on 8 May, and a few cultivars are on 15 May. In 2011–2012, owing to the later wheat sown and higher air temperature, the lodging resistant strength was only measured four times. But the trend of the 10 cultivars lodging strength was basically similar to that in the 2010–2011 experiment.

3.3. The population lodging resistance strength at different stages of growth

The population lodging resistance strength of the 10 cultivars used between 2010 and 2012 is shown in Table 3.

Table 3 shows that there is a significant difference in the population lodging resistance strength between the cultivars ($p < 0.001$). The strength for most cultivars exhibited similar trends, which was relatively weak at the anthesis stage (GS 65) and reached a maximum at the early grain milk stage (GS 73), after which it decreased and reached a minimum at full maturity (GS 93). Some cultivars,

Table 2
The single-stalk lodging resistance strength of the 10 wheat cultivars tested at the different growth stages between 2010 and 2012 (unit: g-force stalk^{-1}).

Cultivar	2010–2011						2011–2012				
	8 May	15 May	22 May	30 May	2 June	Mean	6 May	13 May	20 May	29 May	Mean
Zhoumai 18	8.04 ± 2.12	6.92 ± 1.75	4.24 ± 1.10	4.59 ± 1.85	4.88 ± 1.26	5.73 ± 1.66ab	6.96 ± 3.76	7.13 ± 2.65	7.12 ± 1.59	5.48 ± 2.78	6.67 ± 2.69ab
Aikang 58	9.42 ± 2.66	7.85 ± 1.91	6.40 ± 1.46	5.07 ± 1.07	5.70 ± 1.23	6.61 ± 1.95a	9.56 ± 2.82	9.59 ± 2.14	6.87 ± 2.18	6.93 ± 1.84	8.24 ± 2.24a
Wenmai 6	5.38 ± 1.66	6.01 ± 1.77	4.31 ± 0.76	3.59 ± 0.88	3.29 ± 0.56	4.52 ± 1.28ab	7.01 ± 2.31	7.11 ± 1.24	5.68 ± 2.17	5.25 ± 2.63	6.26 ± 2.09ab
Zhoumai 22	9.43 ± 1.66	6.31 ± 1.66	4.15 ± 0.98	3.75 ± 0.41	4.22 ± 1.24	5.57 ± 2.38ab	10.79 ± 3.37	8.00 ± 2.48	5.64 ± 1.55	6.62 ± 2.70	7.76 ± 2.53a
Zhengmai 9023	5.79 ± 1.17	5.77 ± 1.60	3.07 ± 0.65	2.50 ± 0.39	2.63 ± 0.71	3.95 ± 1.58b	5.08 ± 1.21	5.23 ± 1.72	4.03 ± 1.19	4.44 ± 0.45	4.70 ± 1.14b
Pingan 6	9.47 ± 2.01	7.76 ± 1.66	5.02 ± 1.39	4.51 ± 1.37	4.66 ± 1.40	6.28 ± 2.22ab	10.94 ± 1.43	5.92 ± 1.86	5.39 ± 2.22	4.08 ± 1.10	6.58 ± 1.65ab
Yumai 18	5.33 ± 1.35	5.30 ± 0.84	4.06 ± 0.95	2.96 ± 0.45	3.38 ± 0.74	4.21 ± 1.09b	5.42 ± 0.96	6.46 ± 1.40	4.78 ± 1.15	3.69 ± 1.20	5.09 ± 1.18b
BH 001	8.27 ± 1.77	6.21 ± 1.32	4.79 ± 1.12	4.42 ± 0.76	4.61 ± 1.14	5.66 ± 1.62ab	6.91 ± 1.65	3.64 ± 0.83	4.76 ± 1.66	3.56 ± 1.08	4.72 ± 1.30b
Zamai 4	8.45 ± 2.07	8.82 ± 2.99	5.81 ± 2.21	4.81 ± 1.19	4.93 ± 1.49	6.56 ± 1.94ab	5.12 ± 1.86	9.34 ± 2.98	5.34 ± 1.59	4.26 ± 0.65	6.08 ± 1.91ab
Zamai 3	9.16 ± 2.42	6.37 ± 1.73	4.08 ± 0.61	4.77 ± 1.47	5.18 ± 1.17	5.91 ± 2.00ab	5.38 ± 2.43	3.78 ± 0.66	3.69 ± 0.98	4.26 ± 1.43	4.21 ± 1.23b
Mean	7.87 ± 1.72	6.73 ± 1.10	4.59 ± 0.96	4.10 ± 0.86	4.35 ± 0.96	5.53 ± 0.98ab	7.32 ± 2.18	6.62 ± 1.80	5.33 ± 1.63	4.86 ± 1.58	6.03 ± 1.80ab

(1) Duncan test, subset for alpha = 0.05. (2) To verify the accuracy of the measurement results of the experimental method in the article as well as variation of wheat single stems and population lodging strength, the experiment lasted two years, the paper provides two years' data from 2010 to 2012. (3) Values are means ± SD (n = 20).

Table 3
The population lodging resistance strength of the 10 wheat cultivars tested at the different growth stages between 2010 and 2012 (unit: N m^{-1}).

Cultivar	2010–2011						2011–2012				
	8 May	15 May	22 May	30 May	5 June	Mean	6 May	13 May	20 May	29 May	Mean
Zhoumai 18	30.23 ± 0.70	30.76 ± 1.82	43.74 ± 3.04	45.03 ± 2.15	32.88 ± 1.94	36.53 ± 1.75bc	38.51 ± 7.67	64.59 ± 16.92	50.25 ± 11.73	43.55 ± 1.31	51.72 ± 9.41ab
Aikang 58	58.58 ± 3.19	64.83 ± 1.79	55.03 ± 4.32	54.29 ± 3.90	37.40 ± 2.86	54.02 ± 3.18a	50.15 ± 7.84	65.06 ± 6.09	55.82 ± 8.33	50.27 ± 2.71	55.33 ± 6.24a
Wenmai 6	38.46 ± 2.01	55.02 ± 2.41	41.17 ± 4.06	33.24 ± 3.00	24.98 ± 1.55	38.57 ± 3.30bc	39.49 ± 5.43	56.14 ± 6.50	41.44 ± 1.48	40.86 ± 4.99	46.73 ± 4.60abc
Zhoumai 22	39.74 ± 0.66	38.44 ± 2.15	42.32 ± 1.46	42.49 ± 3.11	34.75 ± 2.49	39.55 ± 0.86b	48.07 ± 7.14	52.09 ± 6.74	51.71 ± 13.15	52.59 ± 4.30	51.12 ± 7.83a
Zhengmai 9023	35.38 ± 2.20	35.07 ± 1.16	30.85 ± 1.97	29.28 ± 3.88	30.78 ± 2.79	32.27 ± 0.74bc	31.72 ± 1.89	36.56 ± 5.72	31.83 ± 5.13	43.18 ± 4.66	33.32 ± 4.35c
Pingan 6	38.97 ± 0.61	43.65 ± 1.53	43.33 ± 2.40	40.94 ± 2.82	29.54 ± 1.90	39.28 ± 1.55b	47.94 ± 7.02	65.55 ± 9.74	49.90 ± 2.89	46.26 ± 7.15	52.41 ± 6.70a
Yumai 18	37.28 ± 1.01	28.39 ± 1.99	33.75 ± 1.92	24.15 ± 1.74	20.35 ± 1.24	28.78 ± 1.85c	29.06 ± 13.88	45.77 ± 10.13	31.30 ± 9.33	35.96 ± 5.11	35.52 ± 9.61c
BH 001	34.05 ± 1.75	48.00 ± 1.85	42.98 ± 1.49	30.36 ± 1.18	35.14 ± 1.19	38.11 ± 1.30bc	38.74 ± 3.28	57.95 ± 5.23	49.20 ± 2.76	49.80 ± 4.39	43.57 ± 3.92ab
Zamai 4	35.18 ± 1.61	46.85 ± 2.58	48.87 ± 2.96	40.48 ± 2.41	31.62 ± 1.92	40.60 ± 1.98b	33.64 ± 7.36	49.30 ± 6.26	55.72 ± 3.71	51.65 ± 5.72	47.58 ± 5.76abc
Zamai 3	47.42 ± 2.58	37.68 ± 1.59	36.15 ± 2.76	28.13 ± 1.59	33.80 ± 2.46	36.64 ± 1.89bc	26.33 ± 3.94	49.85 ± 10.70	33.89 ± 2.32	36.11 ± 2.88	36.55 ± 4.96bc
Mean	39.53 ± 8.06	42.87 ± 11.24	41.82 ± 7.07	36.84 ± 9.33	31.12 ± 5.12	38.44 ± 6.56bc	38.37 ± 6.55	54.28 ± 8.40	45.11 ± 6.08	45.02 ± 4.32	45.38 ± 6.34abc

(1) Duncan test, subset for alpha = 0.05. (2) To verify the accuracy of the measurement results of the experimental method in the article as well as variation of wheat single stems and population lodging strength, the experiment lasted two years, the paper provides two years' data from 2010 to 2012. (3) Values are means ± SD (n = 20).

however, such as BH001 and Zhengmai 9023, showed an increase in strength after grain dough stage (GS 83).

The population lodging resistance strength (y) depends on the size of wheat population (x_1), plant height (x_2), single-stalk lodging resistance strength (x_3) and stalk bending strength (x_4) and is modeled by the following equation:

$$\hat{y} = 44.189 + 0.014x_1 - 0.481x_2 + 3.462x_3 + 2.130x_4$$
$$(F = 40.839,\ R^2 = 0.970,\ p = 0.001)$$

The model explains well the relationship between the population lodging resistance strength and the above mentioned factors. The relationship between the population lodging resistance strength and the four factors used in the model is shown in Table 4.

3.4. The wind speed distribution in the later growth stages of wheat

To understand the wind speed distribution (April 20–June 10) in the later growth stages of wheat, wind speed data observed at Zhengzhou station, China's national weather station, between 2000 and 2009 were analyzed (Fig. 2).

The daily maximum wind speed (maximum mean wind speed over 10-min) was recorded as a strong breeze once (10.8–13.8 m s^{-1}), 29 times as a fresh breeze (8.0–10.7 m s^{-1}) and 203 times as a moderate breeze (5.5–7.9 m $^{-1}$). The maximum wind speed (maximum instantaneous wind speed for 3 s) was recorded as a strong gale (20.8–24.4 m s^{-1}) once, 7 times as a fresh gale (17.2–20.7 m s^{-1}), 27 times as a moderate gale (13.9–17.1 m s^{-1}) and 78 times as a strong breeze (10.8–13.8 m s^{-1}).

4. Discussion

4.1. Single-stalk and population lodging resistance strength at different stages of growth

The results obtained for the single-stalk lodging resistance strength of the 10 wheat cultivars tested showed a similar tendency to the results reported by Xiao et al. (2002) but there was a reduction in stalk strength. Both the single-stalk and population lodging resistance strength showed similar trends, but the maximum strength for population lodging resistance strength occurred relatively late in the season. The single-stalk lodging resistance strength reached a maximum at the anthesis stage (GS 65), while the population lodging resistance strength reached a maximum at the early grain milk stage (GS 73).

In this study, the single-stalk and population lodging resistance strength was measured in the field at different growth stages using the crop lodging resistance electronic measuring device. In order to reduce the impact of the interaction between the different stalks when measuring the resistance strength of a single stalk, the strength measurement used one stalk every time (or two stalks and the mean calculated for some cultivars). The actual lodging resistance strength is a comprehensive index, dependent on plant height, ear number per unit area, ear weight, stalk bending strength, single-stalk lodging resistance strength, growth and development stage and so on. Therefore, single stalk lodging resistant strength is not able to completely reflect the actual wheat lodging resistant ability, and in contrast the population lodging resistant strength may be more similar to the wheat actual lodging resistant ability. Plant height has a significant negative correlation with single-stalk and population lodging resistance strength (Table 4). In order to objectively assess the overall lodging resistance of the wheat cultivars and to facilitate direct comparison between cultivars, single-stalk and population lodging resistance strength was measured at 2/3 of plant height (relative height) rather than at a specific height.

Compared to the artificially induced wheat lodging methods and the stalks physical characteristics evaluation methods in the existing literatures, this method has obvious improvements in three aspects mainly. Firstly, the device is to measure the horizontal pushing force or pull force by using the digital force gauge exerted upon wheat single stalks or population stalks, and with the help of the multi-function tripod and the ball guideway, the digital force gauge always maintains a level height during measurement process. The results are more accurate than those obtained through other methods. Secondly, the device can use different probe to measure respectively the single stalk and the population lodging resistant strength in normal growth state of wheat in the field. The data obtained can directly reflect the actual lodging tolerance of different wheat cultivars. Thirdly, the method is convenient and instant, in terms of 10–15 samples should be tested for each cultivar and 1 min for each sample on average, the single stalk or the population lodging resistant evaluation last only 10–15 min.

4.2. Assessment of the maximum wind resistance speed for each variety tested

4.2.1. Wind speed, wind pressure conversion theory and related assumptions

Wind pressure is the force exerted upon a plane by wind perpendicular to its flow direction; the unit is the kilo Newton/m (kN m^{-1}). It is called "wind load" in the construction industry. Wind load is one of the main natural loads that wheat is subjected to. Berry et al. (2003a) thought that the stalk lodging results from the base bending moment of the stalk(s) more than the failure moment of the stalk base. According to the Bernoulli equation, standard wind pressure corresponding to a certain wind speed can be calculated from the following equation (Zhu, 1975):

$$W_0 = \frac{r \times v^2}{2g} \tag{1}$$

where W_0 is the standard wind pressure (kN m^{-2}), r is the air density (kN m^{-3}), v is the wind speed (m s^{-1}), and g is the acceleration due to gravity (m s^{-2}). To take the standard state where pressure 1013 hPa at 15 °C, the air density r = 0.01225 kN m^{-3}, the sea at latitude 45° and g = 9.80 (m s^{-2}), then

$$W_0 = \frac{r \times v^2}{2g} = \frac{0.01225 \times v^2}{2 \times 9.80} = \frac{v^2}{1600} \tag{2}$$

As there are differences in air pressure, temperature, humidity, latitude and other conditions for different places, W_0 calculated from Eq. (2) needs to be revised according to the corresponding conditions found at the experiment site. At present, the anemometer height at most weather stations in China is 10 m height above the ground. Wind speed at different heights can be calculated from the following equation (Zhu, 1975).

$$\frac{V_z}{V_1} = \frac{\log\ z - \log\ z_0}{\log\ z_1 - \log\ z_0} \tag{3}$$

where V_z is the wind speeds at height Z (m), V_1 is the wind speed at height Z_1 (m), and Z_0 is the roughness of the ground. Z_0 changes with the environmental conditions. If it is assumed that V_z is the wind speed measured at a meteorological station (Z = 10 m height); V_1 is the wind speed that directly causes wheat lodging in the field. Baker et al. (1998) reported that the wind at 2 m height above the ground or at 1 m above crop canopy can penetrate the canopy (wheat plant height used in Baker et al.'s experiment was 1 m). In this experiment, the average height is at 0.65–0.83 m, and according to the actual calculations, it is assumed here that wind speed at

Table 4
The relationship between the population lodging resistance strength and single-stalk lodging resistance strength and other factors.

	Ear number (m^2) (x_1)	Plant height (x_2)	Single-stalk lodging resistance strength (x_3)	Stalk bending strength (x_4)	Population lodging resistance strength (x_5)
Ear number (m^2) (x_1)	1	−0.330	0.452	0.452	0.512
Plant height (x_2)		1	−0.771**	−0.518	−0.876**
Single-stalk lodging resistance strength (x_3)			1	0.608*	0.929**
Stalk bending strength (x_4)				1	0.744*
Population lodging resistance strength (x_5)					1

* Correlation is significant at the 0.05 level (2-tailed).
** Correlation is significant at the 0.01 level (2-tailed).

2.0 m height above the ground (Z_1 = 2.0 m) can penetrate the canopy and cause lodging.

Assuming the population lodging resistance strength (the maximum horizontal pushing force) bearing on unit cross-sectional area of wheat population is equal to the maximum wind load that the population can withstand, according to Eq. (4), the population lodging resistance strength can be transformed into the maximum wind load using Eq. (4).

$$W_0 = W_p = \frac{P}{L \times (H - Z_0) \times 1000} \quad (4)$$

where W_p is the maximum horizontal force bearing on the unit cross-sectional area of a wheat population (kN m^{-2}), P is the population lodging resistance strength measured (N m^{-1}), L is the width of the tested population cross-section (1.0 m), H is the tested population height and Z_0 as explained in Eq. (3).

4.2.2. Assessment of the population stem lodging wind speed

If it is assumed that W_p is the maximum wind load on a unit cross-section of a wheat population, then the population stem lodging wind speed (m s^{-1}) can be calculated according to the following procedure:

(1) The population lodging resistance strength (P) and plant height (h) is substituted into Eq. (4) to calculate the W_p value.
(2) W_p values are substituted into Eq. (2) to calculate V_1 (the maximum horizontal wind speed at crop canopy height).
(3) V_1 is substituted into Eq. (3) to calculate the standard wind speed V_z (wind speed observed at the weather station).

The population stem lodging wind speed of the 10 wheat varieties tested is shown in Table 5.

The population stem lodging wind speed that the 10 wheat cultivars can withstand was significantly different ($p < 0.05$). The population stem lodging wind speed for the most wheat cultivars tested was greatest at the early grain milk stage, followed by the anthesis stage, and the minimum wind resistance speed was at full maturity. However, the population stem lodging wind speed for individual cultivars slightly increased at full maturity. The average population stem lodging wind speeds that the 10 wheat cultivars could withstand were between 11.93 and 24.69 m s^{-1}, depending on growth stage, which is 6 (10.8–13.8 m s^{-1}) to 9 (20.8–24.4 m s^{-1}) on the Beaufort scale (Wikipedia). The calculated results are consistent with field observations. Using the fast clustering method, the 10 wheat cultivars can be divided into high lodging resistance, medium lodging resistance, low lodging resistance and no lodging resistance, according to their population stem lodging wind speed at different growth stages (Fig. 3).

Aikang 58 is one of the best cultivars of lodging resistance planted in China, with 2.7 million hectares planted annually. Since 2006, when the variety began to be cultivated, lodging had not occurred (Yao and Zi, 2011). Zhoumai 18, Zhoumai 22 and Pingan 6 are the cultivars most resistant to lodging. Yumai 18 and Wenmai 6 were used as control cultivars in the experiments. The population stem lodging wind speed of Wenmai 6 is significantly greater than that of Yumai 18. Although the results obtained from two years' experiments had some differences, but the basic trend was the same, which resulted mainly from the different growth period.

Sterling et al. (2003) used a wind tunnel to study the process of wheat stem lodging. They found that stem lodging occurs instantaneously when the stem base bending moment exceeds the stem strength. Therefore, for wheat cultivars to be considered to show good lodging resistance in Huanghuai Region of China, the speed analyzed result (Fig. 2) suggests, that they should be able to

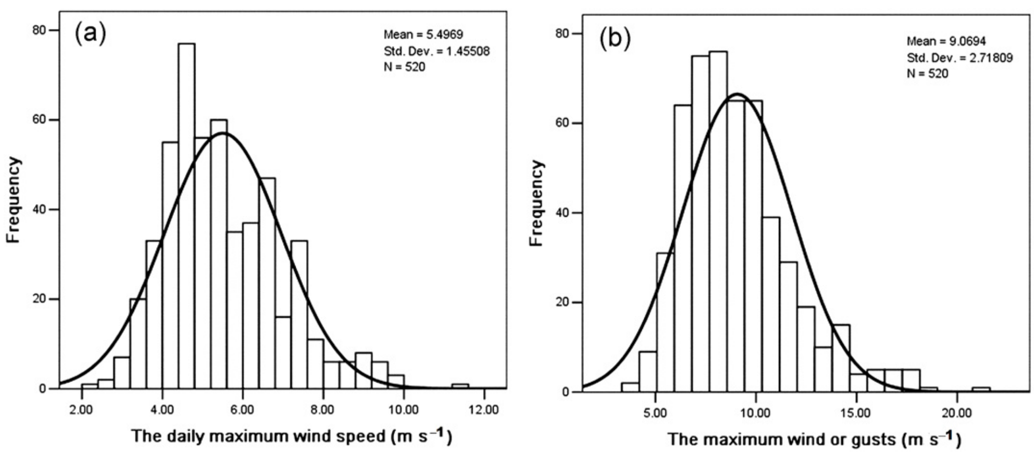

Fig. 2. The wind speed frequency distribution in the wheat growth late (April 20–June 10) at Zhengzhou station, China's national weather station from 2000 to 2009. (a) The daily maximum wind speed (maximum mean wind speed for 10-min). (b) The maximum wind or gusts (maximum instantaneous wind speed for 3 s).

Table 5
The population stem lodging wind speed of the 10 wheat cultivars tested at the different growth stages between 2010 and 2012 ($m\,s^{-1}$).

Cultivar	2010–2011						2011–2012				
	8 May	15 May	22 May	30 May	5 June	Mean	8 May	15 May	22 May	30 May	Mean
Zhoumai 18	15.06	15.19	18.12	18.38	15.71	16.49bc	17.52	22.68	20.01	18.62	19.80bc
Aikang 58	22.64	23.82	21.94	21.79	18.09	21.66a	21.68	24.69	22.87	21.70	22.77a
Wenmai 6	16.47	19.70	17.04	15.31	13.27	16.36bc	16.95	20.21	17.36	17.24	17.99cd
Zhoumai 22	17.57	17.28	18.13	18.17	16.43	17.51b	19.98	20.79	20.72	20.89	20.60b
Zhengmai 9023	15.01	14.94	14.02	13.65	14.00	14.32c	15.03	16.14	15.06	17.54	15.98e
Pingan 6	16.51	17.48	17.41	16.93	14.38	16.54bc	18.92	22.12	19.30	18.59	19.78bc
Yumai 18	16.15	14.58	15.37	13.00	11.93	14.20c	14.73	18.49	15.29	16.39	16.29cd
BH 001	15.28	18.14	17.17	14.43	15.52	16.11bc	16.83	20.59	18.97	19.09	18.92bc
Zamai 4	16.48	19.02	19.42	17.68	15.62	17.64b	16.99	20.57	21.87	21.05	20.21bc
Zamai 3	17.61	15.70	15.38	13.56	14.87	15.42bc	13.66	18.80	15.50	16.00	16.10e
Mean	17.22	17.98	17.72	16.63	15.28	16.97bc	17.23	20.51	18.69	18.71	18.84bc

(1) Duncan test, subset for alpha = 0.05. (2) To verify the accuracy of the measurement results of the experimental method in the article as well as variation of wheat single stems and population lodging strength, the experiment lasted two years, the paper provides two years' data from 2010 to 2012.

withstand a daily maximum wind speed of at least a strong breeze and a maximum wind speed of at least a fresh gale.

Wheat lodging resistance depends on plant height, center of gravity height and stalk bending strength. If the plant height remains the same, the population lodging resistance strength changes with center of gravity height and stalk bending strength. At flowering and early grain filling, due to greater stalk bending strength (Wang and Li, 1997; Xie et al., 2009) and lower center of gravity height (the reduced weight of the smaller ears) (Crook and Ennos, 1994; Xie et al., 2009), the strength of the population lodging resistance is greater and there is a reduction in lodging. At the milky ripe stage, the increasing weight of the ears (leading to an increase in the center of gravity height) (Crook and Ennos, 1994), is sustained by the outward transport of material stored in the stalk leading to a reduction in the stalk bending strength (Xie et al., 2009) which, in turn, leads to a lower wind resistance speed. A slight recorded increase in wind resistance speed for a few cultivars were mainly caused by grain dryness and a lower center of gravity height at full maturity.

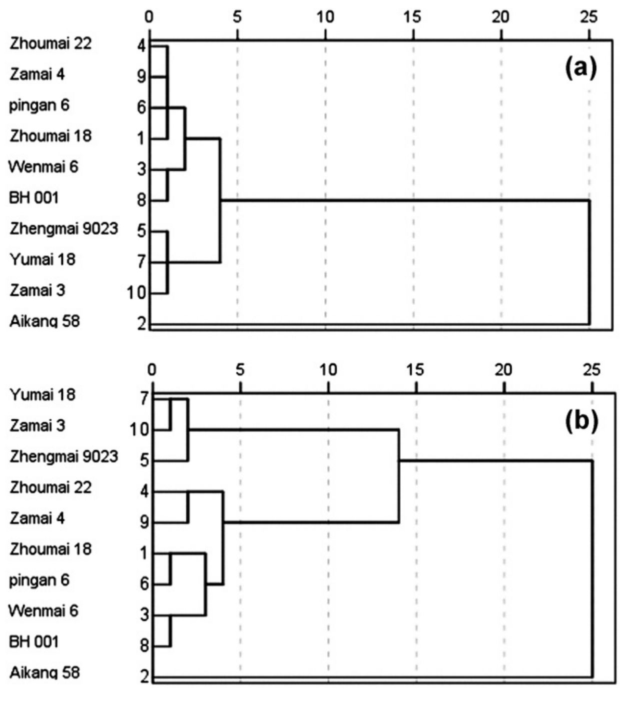

Fig. 3. Cluster analysis diagram of the population stem lodging wind speed of the 10 wheat varieties tested. The clustering used is fast clustering method. (a) 2010–2011 and (b) 2011–2012.

In this study, we only measured the single-stalk and population lodging resistance strength of wheat under dry soil conditions. The population stem lodging wind speed was evaluated based on the population lodging resistance strengths measured in the field. Soil moisture and rainfall have an important impact on the single-stalk and population lodging resistance strength. Thus, the changes in the lodging resistance strength needs further study under different soil moisture and rainfall conditions. Z_0, H, V_1 (the wind speed directly causes wheat lodging in the field) and the population lodging resistance strength were the four critical parameters involved in the calculation of the population stem lodging wind speed. In this article, to facilitate to compare effect of plant height on the population stem lodging wind speed, Z_0 valued 0.16 m (the ground roughness of the generally open fields), V_1 valued 2.0 m (data reported in the literature), and the accurate values of Z_0 and V_1 also need further research.

5. Conclusions

In this study, the single-stalk and population lodging resistance strength were measured using a purpose built crop lodging resistance electronic measuring device and the population stem lodging wind speed that 10 wheat cultivars could withstand was evaluated based on their population lodging resistance strengths measured in the field. The evaluation results consistent with field observations. These results showed that the population lodging resistance strength, as a composite indicator, objectively reflected the actual lodging resistance of the 10 wheat cultivars tested. The novel assessment method for the wheat lodging resistance strength determines directly the wheat population lodging resistance strength using the crop lodging resistance electronic measuring device, and directly in the wheat population level predict the population stem lodging wind speed. This method not only greatly simplifies the determination of the program, and the results may be more accurate. Therefore, these methods of the measurement and assessment of the population lodging resistance strength have an important application value in the rapid identification of wheat lodging resistance in breeding and production programs.

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