Influence of Speed and Rainfall on Large-Scale Wheat Lodging from 2007 to 2014 in China

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Abstract

Strong wind and heavy rain remain the two most important causes of large acreage wheat (Triticum aestivum L.) lodging in China. For research the influence of wind speed and rainfall—separately as well as together—on the extent and degree of lodging, five levels of the severity of lodging were defined based on a combination of the lodging area and the degree of tilting. Detailed meteorological information was studied on 52 instances of large-scale lodging that occurred from 2007 to 2014. The results showed that strong wind’s lodging accounted for 8% of the instances studied, continuous rainfall’s lodging accounted for 19% and strong winds-heavy rainfall’s accounted for 73%. The minimum instantaneous wind speed that could cause large-scale lodging was closely related to rainfall. Without rainfall, the wind speed that resulted in lodging ranging in severity from slight to severe (Level 2 to Level 5) was 14.9 m/s, 19.3 m/s, 21.5 m/s, and 26.5 m/s, respectively; when accompanied by rainfall, the wind speed that resulted in lodging of the same severity decreased linearly with the increase of rainfall. These results will be particularly useful in preventing and alleviating wheat lodging as well screening wheat varieties with good lodging resistance.

Introduction

Lodging, or the permanent tilting or bending of stems from the vertical, is a major limiting factor to grain production worldwide [1]. China is the world’s largest producer of winter wheat (Triticum aestivum L.), and lodging, in severe cases, can lower the wheat production by as much as 80% [2] besides being a potential health risk in the form of fungal infection of grains and the subsequent development of mycotoxins [3–5]. Lastly, lodging also makes mechanical harvesting difficult [2, 5]. In China, food production lost due to lodging was estimated at more than 2 million tones annually [2]. Therefore, a detailed study of the influence of the wheat plant itself and of meteorological factors on lodging and its mechanism is essential to devise practical strategies to reduce crop losses due to lodging and to further our understanding of the theoretical aspects of lodging.
Recent years have seen many papers on lodging in wheat, which is generally related to a variety of factors, such as the environment [1], management practices, the period of growth and development [1,6–7], and varietal characteristics [6,8–9]. Among these, wind and rain are the two most important factors [1]. Because lodging occurs at random and cannot be simulated, besides being difficult to quantify and to observe systematically, little research has been conducted so far on the influence of wind speed and rainfall—separately as well as together—on the extent and severity of lodging. However, in recent years, the extensive telecommunication network and news coverage make it easier to collect information on instances of large-scale lodging. The present paper draws on such network news and meteorological data from 2007 to 2014 to study such relevant factors as wind speed, rainfall, and growth stages of wheat and the impact of these factors on the extent and severity of lodging to guide further theoretical research on lodging and for screening wheat varieties for resistance to lodging.

Research Methods
Lodging in wheat and historical weather data
Information about instances of large-scale lodging in wheat from 2007 to 2014 was collected from the public reports on the Internet, and indicated the specific source in the references. This information, in the form of text and images (including video clips), was refined by adding the exact location, date, and the severity of lodging by means of further searches, electronic maps, databases, and so on. The final list comprised 52 instances of lodging for each of which sufficient data were available, including the stage of the crop, wind speeds, and the intensity of rainfall. In particular, we consulted two large data sets, namely the ‘China terrestrial climate data daily value data sets’ [10] and the ‘China daily precipitation grid real-time analysis system (Version 1.0) data set’ [11], obtained from the China meteorological data sharing network (http://cdc.cma.gov.cn). All the data on rainfall and wind speed from the news reports and weather forecasts were checked and verified against these data sets. Whenever necessary, the data on wind speed and rainfall were either obtained from a China national benchmark meteorological observatory station nearest to the site of lodging or were interpolated from such data. To make it easier to compare the data, the wind speed used was the average maximum wind speed (instantaneous maximum wind speed) 10 m above the ground for 3 seconds recorded from 8 p.m. to 8 p.m. of the next day. The Beaufort scale by literature or the weather forecast took the median of its corresponding wind speed scale (m/s) as the maximum average wind speed for 10 minutes, then converted to the instantaneous maximum wind speed multiplied by 1.59; Rainfall was the daily rainfall recorded from 8 p.m. to 8 p.m. of the next day.

Growth stages of wheat
The entire growth period of wheat was divided into ten stages based on the Zadoks’ cereal development scale [12]. Because lodging occurs mainly from the anthesis stage to the maturity stage, the study was mainly confined to three of the ten growth stages (GS), namely anthesis, milk development, and maturity. The anthesis stage extends from the beginning of flowering to full flowering (GS 60–69); the grain filling stage extends from the beginning starch deposition in the grains to endosperm in the condensed form (GS 70–79); and the maturity stage extends from the point at which the grain begins to harden to the point at which it is too hard to be split with a thumbnail (GS 80–91).

Degree of severity of lodging
To facilitate computerized analysis of data, the severity of lodging was divided into five levels or degrees based essentially on China’s national agricultural industry standard NY/T1301-2007
Technical procedures for wheat variety regional trials [13] That standard was supplemented by including the extent (area) of lodging as a percentage of the area under wheat. The levels were as follows.

Level 1: no lodging

Level 2: slight lodging. Lodging area less than 20% of the total area under wheat at the given site; stems tilted at an angle less than 30°

Level 3: medium lodging. Lodging in small, scattered patches; lodging area 20%–40% of the total area; tilt angle 30°–45°

Level 4: heavy lodging. Lodging in large but scattered patches, lodging area 40%–80% of the total area; tilt angle 45°–60°

Level 5: severe lodging. Lodging in large, contiguous areas; lodging area more than 80% of the total area; tilt angle more than 60°

Statistical analysis
All statistical analysis was carried out using SPSS ver. 13.0 (SPSS Inc., Chicago, IL, USA).

Results
Details of each of the 52 instances of lodging chosen for analysis are given in Table 1. The data include the location, date, and time; rainfall and maximum wind speed; the growth stage of wheat at which the crop was affected; the level of lodging (on a scale of 1, no lodging to 5, severe lodging); and one or more supporting references.

Lodging time and region distribution
The data in Table 1 show a more or less continual increase in the frequency of lodging: 2007 and 2008 saw two instances of lodging each; 2009 and 2011 saw three instances each; 2010, four; 2012, nine; and 2013, twenty-nine. The instances were distributed in the nine provinces or autonomous regions of Henan, Hebei, Shandong, Shanxi, Anhui, Jiangsu, Hubei, Xinjiang and Inner Mongolia.

Growth stages and lodging
Among the three stages during which lodging was observed, the instances were distributed as follows: anthesis, 2 instances; milk development, 35 instances; and maturity, 15 instances.

Meteorological factors and lodging types
The instances of lodging fell into three categories by cause, namely strong wind, continuous rain, and strong wind coupled with heavy rain.

Strong wind and lodging. Strong wind was taken as the cause of lodging in those instances where strong wind was the sole cause, that is when it was not accompanied by any rainfall or accompanied by only slight rainfall (< 10.0 mm). Among the 52 lodging events studied, only four (Fig 1a–1d) fell in this category: in 2007 in Tancheng county, Shandong; in 2012 in Lijin county, Shandong and in Lingbi county, Anhui; and in 2013 in Jingzhou city, Hubei. Strong winds could lead to lodging at all levels of severity over large areas. Wind at 14.1 m/s resulted in Level 2 lodging in Lijin; that at 18.3 m/s resulted in Level 3 lodging over 17 000 ha in Jingzhou; and that at 24.4 m/s resulted in Level 5 lodging over more than 600 ha in
## Table 1. Large-scale lodging in winter wheat in China: date, location, rainfall, wind speed, growth stage of crop, severity and area.

| No. | Date        | Location and province               | Rainfall (mm) | Wind speed (m/s) | Growth stage | Lodging level, area and data sources |
|-----|-------------|--------------------------------------|---------------|------------------|--------------|--------------------------------------|
| 1   | 05/22/2007 | Qufu county, Shandong                | 66.4<sup>a</sup> | 10.8–13.3        | GFS          | Level 4, lodging mostly along the wind direction, 80,667 ha [14] |
| 2   | 05/28/2007 | Tanching county, Shandong            | <1.0          | 24.4             | GFS          | Level 5, 533 ha [15]                 |
| 3   | 06/04/2008 | Yinan county, Shandong               | 58.5<sup>a</sup> | 17.2             | MS           | Level 4, large area, irregular lodging [16] |
| 4   | 05/17/2008 | Weishi county, Henan                 | 52.4          | 26.5             | GFS          | Level 5, lodging along the wind direction, 12,000 ha [17] |
| 5   | 06/12/2009 | Huocheng county, Xinjiang Uygur Autonomous Region | 21.3 | 17.2 | GFS | Level 4, lodging along the wind direction, 1,300 ha [18] |
| 6   | 06/06/2009 | Luyi county, Henan                   | 50.0          | 22.6             | MS           | Level 5, complete lodging along wind direction, 1,300 ha [19] |
| 7   | 06/03/2009 | Xiaying and Yongcheng counties, Henan | 23.2 | 29.1 | MS | Level 5, complete lodging roughly in one direction, 200,000 ha [20] |
| 8   | 06/08/2010 | Suzhou city, Anhui                   | 72.5          | 16.2             | MS           | Level 4, complete lodging in one direction, 121,000 ha [21] |
| 9   | 06/22/2010 | Kuitun city, Xinjiang Uygur Autonomous Region | 30.0 | 30.1 | GFS | Level 5, complete lodging in one direction, 1000 ha [22] |
| 10  | 06/18/2010 | Heze City, Shandong                  | 20.0          | 17.7             | MS           | Level 5, large-scale lodging in one direction [23] |
| 11  | 05/30/2010 | Longxi county and Si county, Anhui   | 34.4          | 26.5             | MS           | Level 5, large-scale lodging only in one direction, 40,000 ha [24–25] |
| 12  | 06/06/2011 | Jize county, Hebei                   | 23.9          | 19.9             | MS           | Level 4, large-scale lodging in one direction [26] |
| 13  | 06/06/2011 | Neiqui county, Luquan city in Hebei  | 23.2          | 30.6             | MS           | Level 5, incomplete lodging in one direction, 2,200 ha [27] |
| 14  | 04/12/2012 | Jingzhou, Jiangling and Gong'an county, Hubei | 22.0–46.0 | 15.4             | AS           | Level 3, lodging area 30,000 ha [28] |
| 15  | 05/16/2012 | Lingxi county, Anhui                 | 0.9           | 26.5             | GFS          | Level 5, large-scale irregular lodging [29] |
| 16  | 06/10/2012 | Jiyang county, Shandong              | 54            | 22.6             | MS           | Level 5, lodging area 5,300 ha [30] |
| 17  | 05/07/2012 | Langxi county, Anhui                 | 82.2          | 9.1              | GFS          | Level 2, lodging in one direction but in strips [31] |
| 18  | 07/02/2011 | Altay city, Xinjiang Uygur Autonomous Region | 28.1 | 14.9 | GFS | Level 4, large-scale lodging along the wind direction, 50 ha [32] |
| 19  | 06/02/2012 | Shouguang city, Shandong             | 30.0          | 17.2             | MS           | Level 5, complete lodging along the wind direction [33–34] |
| 20  | 06/26/2012 | Wulatezhongqi, Inner Mongolia Autonomous Region | 80.2–171.0 | 11.9–17.2 | GFS | Level 5, large-scale lodging over a contiguous area, 8,500 ha [35] |
| 21  | 05/25/2012 | Lijin county, Shandong               | 4.3           | 14.1             | GFS          | Level 2, stems tilted in one direction to less than 30° [36] |
| 22  | 06/07/2012 | Linyi county, Shandong               | 34.4          | 19.0             | MS           | Level 5, complete lodging along the wind direction, 2,000 ha [37] |
| 23  | 06/06/2012 | Yutian county, Hebei                 | 15.3          | 14.4             | GFS          | Level 2, small area, irregular lodging, 2,000 ha [38] |
| 24  | 05/25/2013 | Weihai county, Shandong              | 48.7          | 16.3             | GFS          | Level 3, patchy lodging, 6,600 ha [39] |
| 25  | 05/24/2013 | Boxing county, Shandong              | 25–50         | 10.6             | GFS          | Level 2, patchy lodging in a radiating pattern [40–41] |
| 26  | 05/27/2013 | Dong'e county, Shandong              | 20.0          | 26.5             | GFS          | Level 5, large-scale lodging in one direction [42–43] |
| 27  | 05/25/2013 | Liaocheng city, Shandong             | 114.3         | 11.8             | GFS          | Level 4, large-scale lodging in one direction, 23,000 ha [44] |
| 28  | 05/26/2013 | Huantai county, Shandong             | 30.0          | 11.1             | GFS          | Level 3, lodging partly along the sowing direction [45] |
| 29  | 05/25/2013 | Chingping county, Shandong           | 46.7          | 19.0             | GFS          | Level 4, large-scale lodging in one direction(Wu, 2013)[46] |
| 30  | 05/25/2013 | Qufu city, Shandong                  | 109.0         | 10.9             | GFS          | Level 5, large-scale lodging along the wind direction [47–48] |
| 31  | 07/15/2013 | Nenjiang county, Heilongjiang        | 54.7          | 18.9             | AS           | Level 5, large-scale and complete lodging [49] |
| 32  | 05/25/2013 | Shanghai county, Shandong            | 44.2<sup>a</sup> | 14.9 | GFS | Level 2, point, patchy lodging [50] |
| 33  | 05/25/2013 | Yinan county, Shandong               | 101.3<sup>a</sup> | 15.3 | GFS | Level 4, large-scale lodging in one direction [51] |

(Continued)
Tangcheng. One obvious characteristic of such lodging was that stems of all the plants had tilted in the same direction, namely along the direction of wind.

Continuous rainfall and lodging. Continuous rainfall in the present context refers to rains lasting from several hours to several days at a time and a high rainfall intensity but not accompanied by strong winds. Of the 52 lodging events, 10 fell into this category including, for example, the lodgings that occurred in Jining city, Shandong, in 2007 (Fig 2a); Langxi county, Anhui, in 2012 (Fig 2b); Xinxiang city, Henan, in 2013 (Fig 2c); and Zaozhuang city, Shandong, in 2013 (Fig 2d). The most important features of lodging due to rainfall were that (1) the lodging was messy, the plants lodging randomly in different directions and (2) more often, the plants had lodged from the root plate. The severity of lodging varied from slight to severe.

Strong winds accompanying heavy rainfall and lodging. The most common cause of lodging—observed in 73% of the lodging events that constituted the present study—was a combination of strong winds and heavy rainfall. Depending on the wind speed and the intensity of rainfall, the severity of lodging ranged from Level 3 to Level 5.

| No. | Date       | Location and province                  | Rainfall (mm)a | Wind speed (m/s)b | Growth stagec | Lodging level, area and data sources                                                                 |
|-----|------------|---------------------------------------|----------------|------------------|---------------|---------------------------------------------------------------------------------------------------|
| 34  | 05/27/2013 | Zaozhuang city, Shandong              | 109.4          | 12.3             | GFS           | Level 5, large-scale continuous lodging [52–53]                                                   |
| 35  | 05/22/2013 | Yuncheng city, Shanxi                 | 40.7           | 23.3             | GFS           | Level 5, large-scale lodging in one direction, 1,100 ha [54]                                    |
| 36  | 05/26/2013 | Dezhou city and NingJin county,       | 25.2–62.9      | 25.2             | GFS           | Level 4, large-scale lodging [55–56]                                                             |
| 37  | 05/25-26/  | Ningyang county, Shandong             | 104.0          | 14.9             | GFS           | Level 4, large-scale lodging in one direction [57]                                                |
| 38  | 05/25-26/  | Yancheng city, Jiangsu                | 30.0           | 19.7             | GFS           | Level 4, large-scale lodging in one direction [58]                                                |
| 39  | 05/26/2013 | Daifeng city, Jiangsu                 | 40.0           | 16.6             | GFS           | Level 4, large-scale, irregular lodging [59]                                                       |
| 40  | 05/25/2013 | Pizhou county, Suining county, Jiangsu| 100.0c         | 15.5             | GFS           | Level 4, patchy lodging, 16,000 ha [60–61]                                                       |
| 41  | 06/02/2013 | Daming county, Hebei                  | 23.3           | 19.0             | MS            | Level 5, large-scale lodging in one direction, 4,000 ha [62–63]                                 |
| 42  | 06/25/2013 | Botou city, Hebei                     | 40.0c          | 14.9             | MS            | Level 4, large-scale, irregular lodging [64]                                                      |
| 43  | 05/25/2013 | Jingxi county, Hebei                  | 32.0           | 17.2             | GFS           | Level 3, patchy, incomplete lodging in one direction [65]                                         |
| 44  | 05/26/2013 | Wuqiao county, Hebei                  | 32.0           | 17.2             | GFS           | Level 4, lodging along the planting direction, 1,000 ha [66]                                      |
| 45  | 06/07/2013 | Zhengding county, Hebei               | 76.5           | 17.2             | MS            | Level 4, lodging area 6,600 ha [67–68]                                                           |
| 46  | 06/09/2013 | Longyao county, Hebei                 | 35.3           | 19.0             | MS            | Level 4, 80% lodging in one direction [69–70]                                                     |
| 47  | 05/24/2013 | Wuyang city, Henan                    | 77.0           | 13.8             | GFS           | Level 5, large-scale lodging in one direction [71–72]                                            |
| 48  | 05/25/2013 | Xinxiang city, Henan                  | 66.5c          | 12.6             | GFS           | Level 3, patchy, incomplete lodging in one direction [73]                                         |
| 49  | 04/05/2013 | Jingzhou city, Hubei                  | 7.8            | 18.3             | AS            | Level 3, patchy lodging, 17,000 ha [74]                                                          |
| 50  | 05/22/2013 | Yongji city and Jishan county, Shanxi  | 21.2           | 21.3             | GFS           | Level 4, lodging in strips in one direction, 11,550 ha [75–76]                                  |
| 51  | 05/26/2013 | Heze city, Shandong                   | 86.4           | 16.4             | GFS           | Level 4, large-scale lodging in one direction, 6,600 ha [77]                                    |
| 52  | 05/26/2013 | Weifang city, Shandong                | 11.7           | 15.3             | GFS           | Level 3, large-scale lodging in one direction [78]                                                |

a Rainfall (mm): the daily rainfall between 8 p.m. to 8 p.m. of the next day.

b Wind speed (m/s): the average maximum wind speed on the same day at 10 m from the ground and prevailing for at least 3 seconds.

c Rainfall type: the continuous rainfall.

d Growth stage: AS = Anthesis stage; MS = Mature stage; GFS = Grain filling stage.

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Effect Wind Speed, Rainfall on Large-Scale Wheat Lodging in China, 2007-2014

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The most important feature of lodging due to a combination of strong winds and heavy rain was that the lodging occurred in the downwind direction. Depending on whether the wind direction and the planting direction were at right angles to each other or parallel, the lodging was divided into two typical types. When the two directions were at right angles to each other, the lodging was extensive and along the direction of the wind, which is illustrated by the lodging in Chiping county, Shandong, in 2013 (Fig 3a) and that in Weishi county, Henan, in 2008 (Fig 3b). When the wind direction was parallel to the planting direction, the lodging occurred in surges, or waves, which is illustrated by the lodging in Shouguang city, Shandong (Fig 3c) and in Wulatezhongqi in Inner Mongolia. Both in 2012 (Fig 3d).

Discussion

Analysis of meteorological factors

Wind speed, rainfall, and severity of lodging. To study the effect of instantaneous maximum wind speed, singly or together with rainfall, on the degree of severity of lodging, the data were analyzed using the method of least significant difference (Table 2).

As can be seen in Table 2, the severity of lodging and the instantaneous maximum wind speed and/or daily rainfall was positively correlated. Except for level 3 lodging, the instantaneous maximum wind speed in other different degrees of lodging had significant differences ($P<0.05$), but no significant differences in daily rainfall ($P>0.05$).
The most common cause of lodging was the combined action of wind and rain. The two varied a great deal and yet led to the same degree of lodging (Fig 4a and 4b), which makes it difficult to isolate the contribution of each. Therefore, we plotted the mean values of wind speed and rainfall against the level of severity of lodging and developed appropriate linear equations (Fig 4c and 4d). The statistics showed that sample instantaneous maximum wind speed and sample average instantaneous maximum wind speed and the severity of lodging were significantly positively correlated, correlation coefficient $r$ were 0.624 ($P<0.01$, $R^2 = 0.389$) (Fig 4a) and 0.980 ($P<0.05$, $R^2 = 0.960$) (Fig 4d), respectively; and sample daily rainfall and sample average daily rainfall and the severity of lodging were not correlated, correlation coefficient were 0.132 ($P = 0.349 > 0.05$, $R^2 = 0.017$) (Fig 4b) and 0.694 ($P = 0.306 > 0.05$, $R^2 = 0.481$) (Fig 4d). Wind speed was the dominant factor in lodging whereas rainfall was the auxiliary factor. The combined effect, which was significant (although the effect of wind speed was greater), of instantaneous maximum wind speed and daily rainfall on the degree of lodging can be expressed by the following regression equation:

$$y = 0.146x_1 + 0.013x_2 + 0.146$$

Where $x_1$ is the wind speed, $x_2$ is the daily rainfall, $y$ is the degree or severity of lodging, $F = 32.509$, and $P = 0.000 < 0.01$. 

![Fig 2. Lodging due to continuous rainfall. a. Jining city, Shandong (05/22/2007). b. Langxi county, Anhui (05/08/2012). c. Xinxiang city, Henan (05/26/2013). d. Zaozhuang city, Shandong (05/26/2013). doi:10.1371/journal.pone.0157677.g002](image-url)
Rainfall and lodging. At present, it is generally believed that lodging in wheat is caused more by the bending moment induced by wind at the stem base or on the root plate than by the failure moment of the base stem or the root plate [1]. Although rainfall was not the main cause of large-scale lodging, rainfall significantly affected the severity of lodging by two ways: (1) rainfall can increase the weight of wheat plants to reduce the failure moment of the stem base and indirectly reduce the critical wind speed of wheat lodging; (2) rainfall can reduce the root anchoring effect makes wheat more susceptible to strong wind and root lodging. For example, wheat in soils saturated with water suffered heavy lodging at 9.8–12.3 m/s wind.

Table 2. Wind speed, rainfall, and severity of lodging in wheat.

| Severity of lodging (Level) | No. of instances(n = 52) | Instantaneous maximum wind speed (m/s) | Daily rainfall (mm) |
|----------------------------|--------------------------|----------------------------------------|---------------------|
|                            |                          | Minimum | Maximum | Mean±SD | Minimum | Maximum | Mean±SD |
| 2                          | 4                        | 9.1     | 14.4    | 12.1 ± 2.3a* | 4.3   | 80.0    | 34.3 ± 29.0a |
| 3                          | 8                        | 11.1    | 18.3    | 14.8 ± 2.7ab | 7.8   | 59.0    | 33.4 ± 16.4a |
| 4                          | 20                       | 11.8    | 21.3    | 16.8 ± 2.3b | 21.3  | 114.3   | 57.6 ± 29.0a |
| 5                          | 20                       | 12.3    | 30.6    | 22.0 ± 5.2c | 0.0   | 125.6   | 45.6 ± 34.2a |

*LSD test; p = 0.05

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speeds, as seen in Tancheng county, Shandong, in 2007 and in Zaozhuang city, Shandong and Bayinnaoer city of the Inner Mongolia Autonomous Region in 2013.

For quantitative research on the interaction between rainfall and instantaneous maximum wind speed as it affected lodging, the rainfall was categorized as follows: light (0–9.9 mm/day), moderate (10.0–24.9 mm/day), heavy (25.0–49.5 mm/day), torrential (50.0–99.0 mm/day), and heavy storm (above 100.0 mm/day). The average rainfall was then plotted against instantaneous maximum wind speed (Fig 5a–5d). Statistical results showed that there was a significantly negative relationship between the instantaneous maximum wind speed and average rainfall for the level 2–5 lodging, the correlation coefficient $r$ was -0.935, -0.911, -0.958 and -0.964, respectively; the regression equation’s $R^2$ was 0.8745, 0.829, 0.9178 and 0.929 (Fig 5a–5d), respectively. Using linear extrapolation and introducing different intensities of rainfall into the equations, the critical wind speed that would result in a given severity of lodging was calculated without rainfall or with varying intensities of rainfall. Without rainfall, instantaneous maximum wind speeds of 14.9 m/s, 19.3 m/s, 21.5 m/s, and 26.5 m/s, or maximum wind speeds of 9.4 m/s, 12.1 m/s, 13.5 m/s, and 16.7 m/s (equivalent to Force 5, 5–6, 6, and 7, respectively, on the Beaufort scale) resulted in severity levels of 2, 3, 4, and 5, respectively; with rainfall, similar levels of severity of lodging were reached at lower wind speeds: for example, the severity of lodging without rain at a given wind speed was the same as that at 95% of that wind speed when combined with light rain. The corresponding decrease in wind speed, which followed a linear pattern, that resulted in lodging of given severity, was as follows: 87% with moderate rain, 75% with heavy rain, and 49% with torrential rain.

Weather and lodging. Strong winds, continuous rain, and the two combined accounted for 8%, 19%, and 73% of the total instances of lodging examined in the present study, respectively. Apart from a few instances involving continuous rain, strong convectional weather was the most important type of weather to cause large-scale lodging; of the 52 instances examined, lodging caused by strong winds and by strong wind combined with heavy rain accounted for 42 times, or 81%, of the total.

The time at which the lodging occurred also followed a clear pattern. Of the 52 instances of lodging, 42 times, or 81%, occurred in the afternoon or the evening. The duration required for lodging depended on the weather. Lodging due to strong winds and that due to a combination of strong winds and heavy rainfall occurred quickly, within about 10 minutes to 2 hours. For example, heavy rains (52.4 mm) for half an hour with at least 10 minutes of Force 7–8 winds (instantaneous maximum wind speed of 28.3 m/s) resulted in lodging over more than 12 000 ha in Weishi county, Henan, on 17 May 2008, of which in nearly 6 667 ha the severity of lodging was Level 4 or higher; on 6 June 2009, heavy rain (50 mm), maximum wind speed of 16.2 m/s, and a hailstorm for 10 minutes led to lodging in nearly 540 ha in Luyi county, Henan. The duration of continuous rainfall that led to lodging, when not accompanied by strong winds, was usually longer, ranging from several hours to several days. These results indicate that strong convectional weather was the main type of weather for large-scale lodging in wheat.

Type and distribution of lodging

To study a recent instance of lodging in wheat, the authors conducted a field investigation in the area around Xinxiang city, Henan, from May to June 2014. The area had suffered two instances of larger-scale lodging, on 1 May and 15 June. The field survey showed that the major type continued to be stem lodging (Fig 6a and 6b): strong winds coupled with heavy rainfall mostly result in stem lodging, whereas continuous rains alone mostly lead to root lodging. These findings helped in elucidating the phenomenon of lodging in greater detail.
At present, except for a few instances of wheat lodging, large-scale lodging in wheat occurs mainly in the Huanghuai basin of China’s main wheat-producing region. The distribution of the 52 instances of wheat lodging, by province, was as follows: Shandong, 22 instances; Hebei, 9; Henan, 5; Anhui, 4; Jiangsu and the Xinjiang Uyghur Autonomous Region, 3 each; Hubei and Shanxi, 2 each; and Heilongjiang and the Inner Mongolia Autonomous Region, 1 each.

The wind and rain, especially the wind speed is the most important external factors that cause the population lodging; the 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[1,7]. The research on large-scale wheat lodging critical wind speed, rainfall and their interaction could provide the basis for the establishment of wheat breeding objectives and breeding strategies.

Lodging is closely related to wheat plant own factors (for example stalk strength) and rainfall, wind speed and other external factors. Under the condition of the same wind and rain, the degree of the lodging is significantly negative related to the stalk strength. The stalk strength has close relationship with plant high, stem thickness, elastic, planting pattern, population density, but because a lot of research on these have been done [1–9], no longer discussed in this paper. Therefore, it is necessary to comprehensively consider both the wind, rain outside factors and internal factors such as plant stem strength on lodging effects in wheat breeding and production practice.

Fig 4. Effect of instantaneous maximum wind speed and rainfall on the severity of lodging in wheat. a. Effect of sample instantaneous maximum wind speed. b. Effect of sample rainfall. c. Effect of sample average instantaneous maximum wind speed. d. Effect of sample average rainfall.

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Conclusions

Currently, large-scale lodging in China has three causes: strong winds, continuous rainfall, and strong winds combined with heavy rainfall; the last accounted for 73% of the 52 instances of large-scale lodging studied in the present paper. Strong convectional weather was the main type of weather that led to large-scale lodging. Wind speed was the dominant factor and rainfall

Fig 5. Interaction between daily rainfall and instantaneous maximum wind speed as it affected the level of severity of lodging. Sample values (○). Sample average values (●). a. Level 2. b. Level 3. c. Level 4. d. Level 5.

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Fig 6. Lodging in Xinxiang city, Henan, in June 2014. a. A spot showing many affected plants. b. Close-up of a few plants.

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was the auxiliary factor. The minimum wind speed that could cause large-scale lodging was closely related to rainfall. Without rainfall, the instantaneous minimum wind speed that resulted in lodging ranging in severity from slight to severe (Level 2 to Level 5) was 14.9 m/s, 19.3 m/s, 21.5 m/s, and 26.5 m/s, respectively (the corresponding maximum wind speeds being 9.4 m/s, 12.1 m/s, 13.5 m/s, and 16.7 m/s, equivalent to Force 5, 5–6, and 6–7 on the Beaufort scale); when accompanied by rainfall, the instantaneous minimum wind speed that resulted in lodging of the same severity decreased linearly with rainfall: with light rain, the wind speed was 95% of that which resulted in the same severity of lodging in the absence of rain, the corresponding decrease with moderate rain being 87%; with heavy rain, 75%; and with torrential rain, 49%. Shandong was the province that was most prone to lodging (in terms of both the extent and the severity of lodging), followed in that order by Hebei and Anhui. In breeding wheat for resistance to lodging, breeders should focus on strong winds together with heavy rainfall; such resistant varieties, to be worthwhile, should be able to withstand strong winds (equivalent to Force 6 or above on the Beaufort scale).

Supporting Information

S1 Table. No. of instances, Instantaneous maximum wind speed (m/s), Daily rainfall (mm) and Severity of lodging. Meteorological data in the table were obtained from two sources: (1) the China Meteorological Data Sharing Network [http://cdc.cma.gov.cn/]; (2) Huayun Information Technology Engineering Limited company (paid service). (DOC)

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Author Contributions

Conceived and designed the experiments: LYN. Performed the experiments: LYN SWF WHD GL. Analyzed the data: LYN SWF WHD GL. Wrote the paper: LYN.

References

1. Berry PM, Sterling M, Baker CJ, Sparkes DL (2003) A calibrated model of wheat lodging compared with field measurements. Agric. For. Meteorol. 119: 167–180.
2. Liu HP, Cheng DG, Wu E, Cao XY (2012) Analysis on wheat lodging causes and countermeasures in huanghuai area. Shandong Agricultural Sciences 44: 55–56.
3. Baker CJ, Berry PM, Spink JH, Sylvester-Bradley R, Griffin JM, Scott RK, et al. (1998) A method for the assessment of the risk of wheat lodging. J. Theor. Biol. 194: 587–603. PMID: 9790832
4. Foulkes MJ, Slafer GA, Davies WJ, Berry MP, Sylvester-Bradley R, Martre P, et al. (2011) Raising yield potential of wheat. III. Optimizing partitioning to grain while maintaining lodging resistance. J. Exp. Bot. 62: 469–486. doi: 10.1093/jxb/erq300 PMID: 20952627
5. Zhu XK, Wang XG, Guo KQ, Guo WS, Feng CN, Peng YX (2006) Stem characteristics of wheat with stem lodging and effects of lodging on grain yield and quality. Journal of Triticeae Crops 26 (1): 87–92.
6. Berry PM, Spink JH, Foulkes MJ, Wade A (2003) Quantifying the contributions and losses of dry matter from non-surviving shoots in four cultivars of winter wheat. Field Crop. Res. 80: 111–121.
7. Niu LY, Feng SW, Ru ZG, Li G, Zhang ZP, Wang ZW (2012) Rapid determination of single-stalk and population lodging resistance strengths and an assessment of the stem lodging wind speeds for winter wheat. Field Crop. Res. 139: 1–8.
8. Crook MJ, Ennos AR (1994) Stem and root characteristics associated with lodging resistance in four winter wheat genotypes. J. Agric. Sci. Camb. 123: 167–174.
9. Easson DL, White EM, Pickles SL (1993) The effects of weather, seed rate and genotype on lodging and yield in winter wheat. J. Agric. Sci. Camb. 121: 145–156.

10. Shen Y, Feng MN (2013) China daily precipitation grid real-time analysis system (version 1.0) data sets. The China national meteorological information center web site. http://cdc.cma.gov.cn/choiceStation.do.

11. Zou FL, Zhu YJ (2013) China land climate data log data sets. The China national meteorological information center. http://cdc.cma.gov.cn/choiceStation.do.

12. Zadoks JC, Chang TT, Konzak CF (1974) A decimal code for the growth stages of cereals. Weed Research 14:415–421.

13. China national agricultural industry standard NY/T1301-2007. Technical procedures for wheat variety regional trials.

14. Zhang HL, Zhang FW, Song J, Zong XH (2007) Continuous rainfall and strong wind caused 81,000 hectares wheat lodging in Jining city of Shandong. [Website].

15. Zou FL, Zhu YJ (2013) China land climate data log data sets. The China national meteorological information center. http://cdc.cma.gov.cn/choiceStation.do.

16. Shandong news (2008) Heavy wind caused wheat lodging in Yinan county of Shandong. [Website].

17. He W, Yang GY (2008) Weishi county, Nearly 13,000 hectares wheat lodging. [Website].

18. Chen YD, Zhang Y (2009) Zhao Yazhong went to 63 regiment to inspect the disaster. [Website].

19. Liu HP (2009) Storm and hail hit Luyi county, large area wheat lodging. [Website].

20. He T (2009) Takes measures to deal with wheat lodging. [Website].

21. Qi S (2010) Heavy rain caused wheat lodging in Suzhou. [Website].

22. Liu Y (2010) Gale and heavy rain disasters hit 131 regiment. [Website].

23. Xinhua news agency (2010) Thunderstorm, strong wind and hail attack, Heze city wheat lodging. [Website].

24. He XF (2011) Disaster weather hit Suzhou of Anhui, hundreds of people affected by nearly 300 million yuan loss. [Website].

25. Wu M (2011) Agricultural machinery department actively ready to harvest the lodging wheat. [Website].

26. Hei P (2011) Dragon Boat Festival rainstorm caused lodging of wheat to be harvested. [Website].

27. Bai HB (2011) Storm caused 2,200 hectares of wheat lodging. [Website].

28. Agricultural bureau of Jingzhou district (2012) Large-scale wheat lodging’s causes and management countermeasures in Jingzhou district. [Website].

29. Meteorological bureau of Lingbi county (2012) Strong convective weather hit Lingbi county. [Website].

30. Wu YG (2012) Storm caused Jiayang 5,300 hectares wheat lodging, civil servants to help with harvest. [Website].

31. Lang Xi BBS (2012) Wheat and rape lodging at Shiwu village of LangXi. [Website].

32. Guan JJ (2012) Heavy rain rushed down Aweitai town’s wheat. [Website].

33. Liu W (2012) Hail, such as jujube, caused wheat lodging, and hundreds of greenhouse damaged. [Website].

34. Youku video (2012) Storm led to some villagers’ wheat lodging in Shouguang city of Shandong. [Website].

35. Han JW (2012) Heavy rain in 50 years hit "granary" beyond Great Wall, agricultural production in Hetao suffered heavy losses. [Website].
36. Ai D (2012) Strong convective weather caused part wheat lodging of Lijin county last night. http://bbs.iqilu.com/thread-9021127-1-1.html.2012-5-26

37. Hu B (2012) The hail cause flaky wheat lodging in Deping county of Linyi. http://roll.sohu.com/20120611/n345269868.shtml.2012-5-26

38. Wu M (2012) Seize time to reduce losses of wheat lodging. http://www.farmers.org.cn/Article/ShowArticle.asp?ArticleID=181956.

39. Zhao PP, Yu QP (2013) Wind and rain led to 6600 hectares wheat lodging, experts remind to strengthen prevention and control of plant diseases and insect pests. http://www.whnews.cn/2013news/2013-05/29/content_5700080.htm.

40. Lu TC (2013) Stormy raided, wheat lodging. http://pic.gmw.cn/cameramanplay/538939/638841/1021322.html

41. Wang JC Liu ZW, Liu YS (2013) Days of rain, Binzhou city’s 11,000 hectares wheat lodging. http://binzhou.dzwww.com/bzhxw/201305/t20130528_8431462.htm

42. Wang YN (2013) Bad weather hit Liaocheng, nearly 700 hectares wheat even failed completely. http://news.sdchina.com/minsheng/5557.html.

43. Zhang HL (2013) After hail, Dong’e county’s 650 hectares wheat lodging. http://v.iqilu.com/2013/05/25/3901049.shtml.

44. Feng WY (2013) Heavy rain caused 20,000 hectares wheat lodging in Liaoacheng. http://news.xinhuanet.com/local/2013-05/29/c_124779100.htm.

45. Han K (2013) Heavy rain and wind attacked Huantai and Gaoqing county, large-scale wheat lodging. http://news.lznews.cn/2013/0528/695413.html.

46. Wu W (2013) Large-scale wheat lodging. http://tieba.baidu.com/p/2353984350.

47. Hou YX (2013) Qufu rainstorm emergency services and disaster investigation. http://roll.sohu.com/20130528/n377296561.shtml.

48. Li HC (2013) Heavy rains caused Jining county’s wheat lodging. http://www.jnnews.tv/news/2013-05/27/cms347501article.shtml.

49. Wu M (2013) Fifth farm suffered windstorm disaster, large area wheat lodging. http://www.sinograinbf.com/news/2013-7-17/9438.htm.

50. Qilu P (2013) One-third of wheat lodging in Shanghe. http://bbs.iqilu.com/thread-11689624-1-1.html.

51. Langya news (2013) Storm caused large-scale wheat lodging in Dazhuang town of Yinan. http://www.hj0539.com/news/local/1992850.html.

52. Hua X (2013) Storms hit parts of China, wheat production reduced due to lodging. http://news.xinhuanet.com/photo/2013-05/27/cms347501article.shtml.

53. Mei Y (2013) Heavy rain led to Suqian city’ 67000 hectares wheat lodging. http://jsnews.jschina.com.cn/system/2013/05/28/017425198.shtml.

54. Yang ZH (2013) First summer thunderstorm weather alleviated drought, but brought disaster in Saline Lake District. http://www.sxsqxj.gov.cn/show.aspx?id=90216&cid=52

55. Hu B (2013) Wind and rain led to wheat lodging of Huangheya town, Dezhou city. http://www.idzwb.com/n-10-11480-1-1.html

56. Tie J (2013) Dezhou city: wheat lodging severe, grain yield decline. http://club.dzwww.com/thread-3540321-1-1.html.

57. Wang Q (2013) Heavy rains led to some wheat lodging in Ningyang county. http://www.1545ts.com/taiannews/news/697/216868.html.

58. Huang ZH, Wang YC (2013) Agricultural experts went to Pavilion Lake to guide wheat remedial work after disaster. http://www.farmers.org.cn/Article/ShowArticle.asp?ArticleID=282633

59. Yi Y (2013) Storm raid resulted in villages’ wheat severe lodging. http://news.dfzs.js.cn/local/economy/2013/0529/366858.shtml.

60. Mei Y (2013) Rainstorm in winter wheat region both pros and cons, wheat lodging in Shandong, Henan, Jiangsu and Anhui. http://www.xn121.com/zxwx/1655894.shtml.

61. Xuzhou bureau of meteorology (2013) Influence of heavy rain on May 25 to 27, 2013, on Xuzhou wheat production. http://www.xzqjx.com/showNews.asp?ID=1547

62. Gui SY (2013) Storm caused wheat lodging of some counties in Hebei. http://daming.hebnews.cn/2013-06/03/content_3283315.htm.

63. News Hebei (2013) Gale and hail hit Daming county. http://daming.hebnews.cn/2013-06/05/content_3288388.htm.

64. Wen M (2013) Wheat lodging. http://tieba.baidu.com/p/2380865314.
65. Che JJ (2013) Heavy rain led to wheat lodging, experts proposed remedial measures. http://news.china.com.cn/live/2013-05/30/content_20279103.htm
66. Gao Z (2013) Technicians of Wuqiao county survey wheat lodging situation. http://www.farmers.org.cn/Article/ShowArticle.asp?ArticleID=282404.
67. China weather channel (2013) Heavy rain hit Hebei, large-scale wheat lodging. http://www.mywtv.cn/jiemu/2013-06/08/content_933699.htm.
68. Wei Q (2013) Shijiazhuang city branch of China PICC survey wheat lodging. http://shijiazhuang.auto.ifeng.com/xinwen/2013/0614/5256.html.
69. Qi K (2013) Continuous rainfall caused wheat lodging in Longyao country of Hebei. http://v.ku6.com/show/R_YrZdYbFOQoPCPyT8pDXA.html?nr=1
70. Qin QX (2013) Heavy rain caused serious water in wheat field and wheat lodging in Xingtai city. http://www.hebradio.com/xwgb/201306/t20130609_1121773.html.
71. Zhai T (2013) Experts suggested to prevent wheat lodging after heavy rain in Luohe city. http://www.Luohe.com.cn/html/xwzx/lhxw/2013-05/48788.html.
72. Wang SD (2013) Rain stops tomorrow in Henan, rain again the day after tomorrow, agricultural production affected. http://roll.sohu.com/20130526/n377098930.shtml
73. Mobile Xinxiang (2013) After heavy rain, wheat lodging. http://www.tv373.com/lanmu/caixin/pic.view.php?id=130527090302963&page=6.
74. Geng YF, Su RR (2013) Strong wind, frost and other weather led to crop damage in Hubei, Ningxia and other places. http://env.people.com.cn/n/2013/0408/c74877-21054610.html.
75. Tao XQ (2013) Convective weather caused wheat serious lodging in Yongji country of Shanxi. http://pic.gmw.cn/cameramanplay/128176/634913/0.html.
76. Li FM (2013) Severe convective weather hit Yuncheng city, disaster and danger appeared. http://www.sxsqxj.gov.cn/show.aspx?id=90212&cid=52.
77. Xiong JW (2013) Storm caused Heze nearly 17,000 hectares wheat lodging, but has little effect on summer harvest. http://heze.dzwww.com/news/201305/t20130528_8431650.htm
78. Pang LL (2013) Wind and rain hit Shandong, Weifang's wheat lodging. http://www.sd.xinhuanet.com/wf/2013-05/28/c_115937767.htm