GIS-based evaluation of maize cultivar lodging resistance performance in target growing environments

Mi Chunqiao[1,2*], Liu Zhe[3], Zhang Xiaodong[3], Peng Xiaoning[1,2], Huang Bin[1,2]

(1. *Department of Computer Engineering, Huaihua University, Huaihua 418000, China*; 2. *Key Laboratory of Intelligent Control Technology for Wuling-Mountain Ecological Agriculture in Hunan Province, Huaihua 418000, China*; 3. *Department of Geographic Information Engineering, China Agricultural University, Beijing 100083, China*)

Abstract: Lodging in maize is one of the major problems in maize production worldwide, which causes serious yield and economic losses annually. By evaluating cultivar lodging resistance performance in target growing environments before cultivar extension and application, the risks and losses can be significantly reduced. In this study, a GIS-based quantitative method for evaluating maize cultivar lodging resistance performance in target growing environments was established based on full cognition of environment stress, cultivar resistance, and the interaction between them. At first, comprehensive environment lodging stress is measured by three factors: 1) extreme wind event in maize vegetative stage which is the direct factor, 2) soil potassium content in target growing environment which is an indirect factor affecting corn stem sturdiness, and 3) planting density which is a human influence factor. Quantification methods of extreme probability analysis, spatial interpolation, normalization, and so on were used. Then, maize cultivar lodging resistance was determined using cumulative frequency distribution analysis of tested lodging data. At last, an evaluation matrix was established combining environment lodging stress and cultivar lodging resistance together, which was very simple and easy to understand method and the result is promising providing good direct support in practical cultivar application. The method used in this study, at county-level, cultivar-level and stress-level with GIS, can facilitate the identification of better-adapted growing environments for a specific maize cultivar, and provide direct support for maize cultivar recommendation and extension, so as to reduce the risk and loss of lodging in maize. It is more easy-operational and feasible than traditional surveying approach, especially for large-scale spatial trend analysis. So it is of both academic significance in accelerating precision agriculture development and practical significance in improving maize cultivar application.

Keywords: lodging in maize, environment lodging stress, cultivar lodging resistance, GIS, maize production, growing environment

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1 Introduction

The plants whose stalks are completely or partially broken or leaned at 30 degrees or more from the vertical are referred to lodged plants[1,2]. Lodging has a detrimental effect on a plant's translocation and photosynthetic activity so as to decrease yield[3]. Lodging in maize, including root lodging and stalk lodging, is one of the major problems in maize production worldwide, accounting for annual yield losses of 5%–25% in this crop[4,5]. Besides, it also results in reduced crop quality and more difficult harvest[6,7]. By evaluating maize cultivar's lodging resistance performance in target growing environments and avoiding choosing a cultivar that is susceptible to lodging for the growing environments with severe lodging stress, those risks and losses can be significantly reduced.

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Biographies: Liu Zhe, Ph.D, research interests: agriculture information technology. Email: liuzhe23@vip.qq.com. **Zhang Xiaodong,** Professor, research interests: geographic information system. Email: zhangxd@cau.edu.cn. **Peng Xiaoning,** Professor, research interests: computer science. Email: hhpxn@163.com. **Huang Bin,** Professor, research interests: computer science. Email: 1059564040@qq.com.

*__Corresponding author: Mi Chunqiao,__ Ph.D, research interests: agriculture information technology Address: No. 612 Yingfeng East Road, Huaihua, Hunan Province, 418008, China. Email: michunqiao@163.com.

There had been some related studies on lodging in maize. On the one hand, lodging resistance of maize cultivar had been related to cultivar's morphological characters[8,9], such as plant height, diameter and length of basal internode, thickness of rind and weight of 5 cm basal section, etc., or had been related to stalk chemical constituents[10,11], such as lignin, total nonstructural carbohydrates, potassium, etc. On the other hand, lodging stress of growing environments had been related to some extreme weather events[1-3,12,13], such as heavy winds, storms, wind direction, rainstorms, etc., of which the extreme wind event is the most important one[2,13]. However, lodging in maize is the result of genotype-by-environment interactions[14], which occurs only when maize cultivar's lodging resistance cannot overcome environment's lodging stress, otherwise not occur. However, all the above studies either only focused on cultivar lodging resistance or environment lodging stress, rather than combined these two aspects together. In addition to that, those previous studies usually paid more attention to evaluating cultivar performance in experimental plots rather than in target farm fields.

The objective of this study is to provide a GIS-based method to evaluate maize cultivar lodging resistance performance in target growing environments, which combines cultivar lodging resistance and environment lodging stress together. The result can provide direct support for maize cultivar recommendation and extension, and facilitate the identification of better-adapted target growing environments for a given cultivar, so as to reduce the risk and loss of lodging in maize.

2 Data and methods

The main maize production regions in the Northeast China, the North China, and the Huang-Huai-Hai Plain in China were selected as our study area shown in Figure 1. It covers ten provinces (Heilongjiang, Jilin, Liaoning, Inner Mongolia, Beijing, Tianjin, Hebei, Henan, Shanxi, and Shandong), 798 planting counties, and 225 national basic meteorology stations. The data used in this study include: a) station-level historical meteorology data (daily maximum wind speed) in recent 60 years, used to calculate wind-induced environmental lodging stress; b) county-level environment soil data (potassium content), used to calculate potassium-induced environmental lodging stress; c) county-level maize planting density data, used to calculate density-induced environmental lodging stress; d) national regional trials data of maize cultivar in recent nine years, including 1 045 tested maize cultivars with details of tested lodging percent in different trial plot, used to determine maize cultivar lodging resistance; and e) basic geographic data, used for spatial mapping and result display. The specific evaluation method is shown in Figure 2.

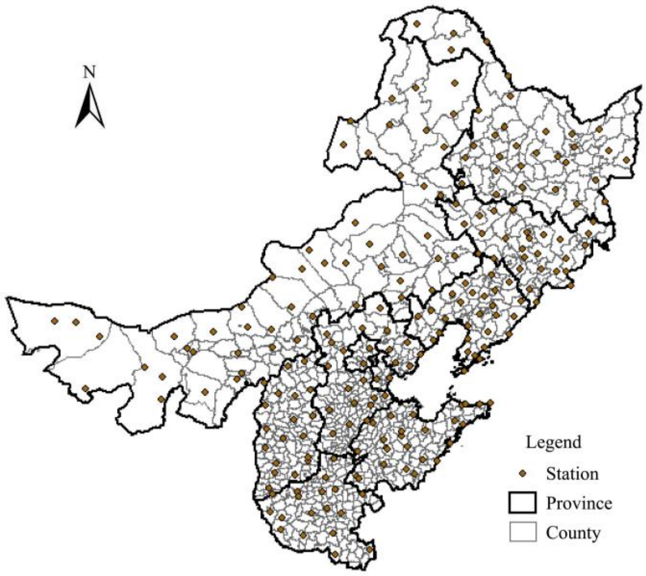

Figure 1 Locations of the study area

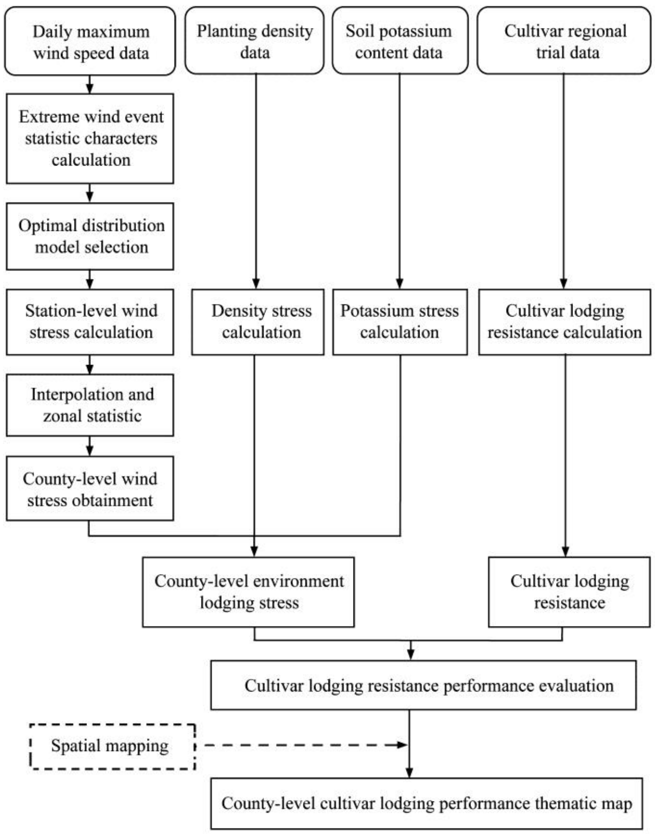

Figure 2 Method flow chart

2.1 Wind-induced environment lodging stress calculation

Many previous studies[1,2,12,13,15-17] had related maize lodging to extreme weather events, of which the extreme wind event is the most important one which is the direct factor leading to lodging in maize. Besides, by field investigation and observation, it is known that lodging in maize can easily happen when fresh gale (17.2-20.7 m/s) occurs. So in this study, we regard the extreme wind whose speed is equal to or larger than 19 m/s (= (17.2+20.7)/2) in maize vegetative stage as extreme wind event, and take its probability to measure wind-induced environmental lodging stress. The extreme wind event variable is denoted by *x*, which can be calculated by Equation (1), where *i* is the value of year (Y_B is the begin year, Y_E is the end year), *j* is the value of date (D_B is the beginning date of maize vegetative stage, D_E is the end date of maize vegetative stage), d_{ij} is the daily maximum wind speed in year *i* date *j*, and x_i is the extreme wind event value in year *i* during maize vegetative stage.

$$x_i = \max\{d_{ij}\}, \quad i = Y_B, \cdots, Y_E; j = D_B, \cdots, D_E \tag{1}$$

According to our previous study[36], the optimal probability distribution of extreme wind event variable *x* is Gumbel distribution (also known as extreme-I distribution). So the probability value of extreme wind event in maize vegetative stage (denoted by *p*) can be calculated by Equation (2), where μ and σ are the location and scale parameters of Gumbel distribution, respectively, which can be estimated by Equation (3), $\bar{x}$ and *s* are the mean and standard deviation of *x*, respectively, which are calculated by Equation (4).

$$p = \int_{19}^{+\infty} \frac{1}{\sigma} \exp\{-\frac{(x-\mu)}{\sigma} - \exp\{-\frac{(x-\mu)}{\sigma}\}\} dx \tag{2}$$

$$\begin{cases} \hat{\mu} = \bar{x} - 0.5772\hat{\sigma} \\ \hat{\sigma} = \dfrac{\sqrt{6}}{\pi} s \end{cases} \tag{3}$$

$$\begin{cases} \bar{x} = \dfrac{1}{Y_B - Y_E} \displaystyle\sum_{i=Y_B}^{Y_E} x_i \\ s = \sqrt{\dfrac{\sum_{i=Y_B}^{Y_E} (x_i - \bar{x})^2}{Y_B - Y_E + 1}} \end{cases} \tag{4}$$

Then, in order to get county-level extreme wind probability, the calculated probabilities at all meteorology stations were extended into all planting counties using spatial interpolation and zonal statistical methods. By cross validation, we concluded that the optimal interpolation model was ordinary Kriging (semivariogram model: spherical, search radius: variable, search number of points: 12, output cell size: 2 000 m). These processes were finished in ArcGIS 10.0 and the specific method was shown in Figure 3. After interpolation, the final extreme wind probability of each planting county was determined by Equation (5), where $S_{\text{w,county}}$ was the wind-induced environmental lodging stress of a county.

$$S_{\text{W, county}} = \begin{cases} \bar{P}_{\text{W, station}}, & \text{if station number in the county} \geq 1 \\ P_{\text{W, interpolatedvalue}}, & \text{other} \end{cases} \tag{5}$$

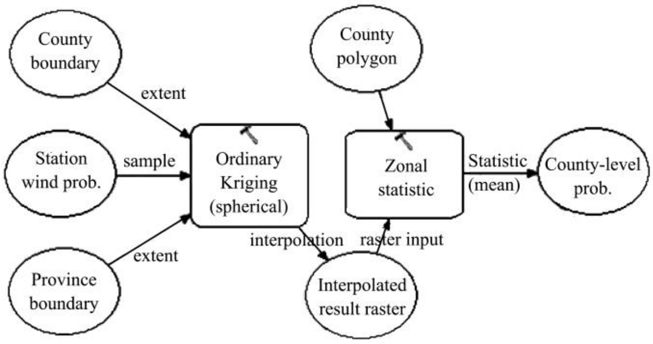

Figure 3 Method flow of spatial interpolation and zonal statistic on extending extreme wind probability

2.2 Potassium-induced environment lodging stress calculation

Lodging in maize is the result of corn stalk lodging resistance and environment lodging stress interactions. Corn stalk lodging resistance has a close relationship with soil potassium content[18], which can promote the development of vascular stem cellulose and enhance stem lodging resistance[19,20]. Corn stalk would become very thin and weak, and be prone to lodging when lack of potassium[21-23]. Therefore, in this study, soil potassium content was used as one factor to measure environment lodging stress, and the lower the potassium content the severer the lodging stress.

So for each planting county, its potassium-induced environment lodging stress (denoted by S_K) is calculated by Equation (6), where X_K is county soil potassium content value, and $X_{K,\max}$ and $X_{K,\min}$ are the maximum and minimum ones, respectively.

$$S_K = \frac{x_{K,\min} - x_K}{x_{K,\max} - x_{K,\min}} \tag{6}$$

2.3 Density-induced environment lodging stress calculation

Planting density is an important factor affecting the lodging of corn; high density can easily lead to inadequate sunlight and fertilizer resulting in weak stalks and underdeveloped roots, so as to increase the incidence of corn lodging[24,25]. Feng et al.[24] examined the relationship between planting density and corn lodging by specific cultivar trials and testing, and the results showed that corn lodging and plant density is significantly positively correlated and lowering planting density can improve corn resistance to lodging. Huang[25] further pointed out that the density of 7.5×10^4/hm^2 (or 4 995/mu) was a sensitive density turning point. When planting density was higher than this point, corn stem strength would be greatly reduced and lodging incidence would become very severe. Therefore, in this study, planting density is also used as one factor to measure environment lodging stress, and the higher the planting density, the severer the lodging stress.

So for each growing county, its density-induced environment lodging stress (denoted by S_D) is calculated by Equation (7), where X_D is county planting density value, and $X_{K,\max}$ and $X_{K,\min}$ are the maximum and minimum ones respectively. If planting density is up to 7.5×10^4/hm^2 then the stress becomes 1, which means the severest stress.

$$S_D = \begin{cases} 1, & if\ x_D \geq 75000 \\ \dfrac{x_D - x_{D,\min}}{75000 - x_{D,\min}}, & \text{other} \end{cases} \tag{7}$$

2.4 Comprehensive environment lodging stress calculation

After getting three single-factor-induced environment lodging stresses, a weighted integration approach was used to obtain comprehensive environment lodging stress (denoted by S) according to different influences of the three factors. The specific integration method is shown in Equation (8), where W_W, W_K, W_D are the weights of wind-induced stress, potassium-induced stress, and density-induced stress, respectively. Based on our above analysis and according to some expertise, it is known that extreme wind event is the most important director factor causing corn lodging, soil potassium content is an indirect factor affecting corn stem lodging resistance, and planting density is an important agronomic measure affecting corn lodging. So, in this study, the weights of W_W=0.7, W_K=0.1, W_D=0.2 were used. In other applications, researchers can make changes according to practical conditions.

$$S = W_W \times S_W + W_K \times S_K + W_D \times S_D \tag{8}$$

In order to compare with maize cultivar lodging resistance and facilitate understanding, comprehensive environment lodging stress is further classified into five grades according to Equation (9), where Ls is county lodging stress grade (1: very light stress, 2: light stress, 3: medium stress, 4: heavy stress, and 5: very heavy stress). The obtained county-level comprehensive environment lodging stresses in our study area are shown in Figure 4.

$$Ls = \begin{cases} 1, & S \leq 0.2 \\ 2, & 0.2 < S \leq 0.4 \\ 3, & 0.4 < S \leq 0.6 \\ 4, & 0.6 < S \leq 0.8 \\ 5, & 0.8 < S \end{cases} \tag{9}$$

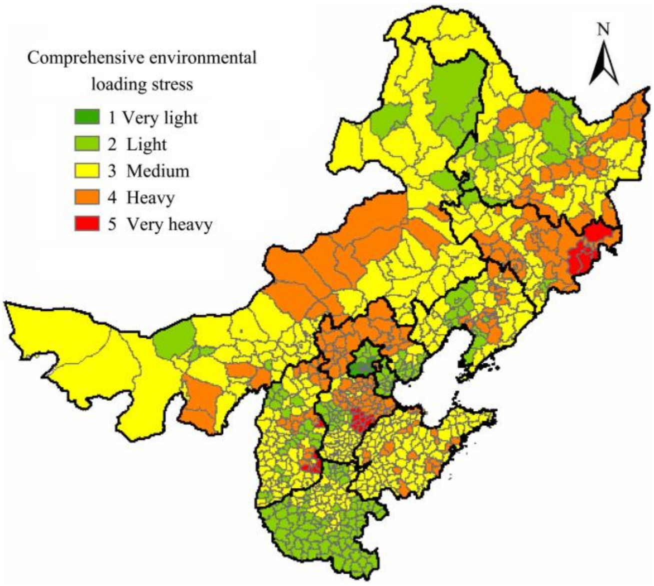

Figure 4 Obtained county-level comprehensive environment lodging stresses in maize growing environments

2.5 Maize cultivar lodging resistance calculation

It is known that, for a given cultivar in multiple location-by-year cultivar trials, the higher the tested lodging percent, the weaker its lodging resistance. So in this study, we used average tested lodging percent to determine a cultivar's lodging resistance and the higher the average tested lodging percent, the weaker the cultivar's lodging resistance. Besides, in practical application, if a maize cultivar's average tested lodging percent is higher than a certain threshold value, it can hardly be released and recommended into the market no matter how good its other traits are. In order to investigate the threshold value, in this study a method of cumulative frequency distribution analysis is employed using the lodging testing data of all 1 045 cultivars in recent nine years. According to the fact that 95% of tested cultivars usually could get released if only considered from lodging resistance perspective, all tested cultivars are first sorted in ascending by average tested lodging percent, and then the value that placed at 96% position is used as the threshold value, which is 18% in this study. Based on these, a simple linear relationship between cultivar lodging resistance (denoted by *r*) and average tested lodging percent (denoted by *t*) is constructed to calculate maize cultivar lodging resistance, which is shown in Equation (10), where h is a constant and equates to the threshold value 18% in this study. Similar to comprehensive environment lodging stress, the calculated cultivar lodging resistance is also classified into five grades according to Equation (11), where *Ls* is cultivar lodging resistance grade (1: very weak resistance, 2: weak resistance, 3: medium resistance, 4: strong resistance, and 5: very strong resistance).

$$r = \begin{cases} 1 - \dfrac{t}{\mathrm{h}}, & 0 \le t \le \mathrm{h} \\ 0, & t > \mathrm{h} \end{cases} \quad (10)$$

$$Lr = \begin{cases} 1, & r \le 0.2 \\ 2, & 0.2 < r \le 0.4 \\ 3, & 0.4 < r \le 0.6 \\ 4, & 0.6 < r \le 0.8 \\ 5, & 0.8 < r \end{cases} \quad (11)$$

2.6 Maize cultivar lodging resistance performance evaluation

Lodging in maize is the result of genotype-by-environment interactions, which only occurs when lodging resistance of a cultivar cannot overcome the lodging stress of local growing environments. In a lodging stressful growing environment, the lodging probability of a bad-resistant cultivar is very high, and the risk and loss will be very great. Based on these facts, we combine cultivar lodging resistance (denoted by *Lr*) and environment lodging stress (denoted by *Ls*) together to evaluate maize cultivar lodging resistance performance in target growing environment, which is specifically determined by the evaluation matrix shown in Figure 5. There are five evaluated results in the matrix, where 1: extreme bad performance, 2: very bad performance, 3: bad performance, 4: medium performance, and 5: good performance.

Ls \ Lr	1	2	3	4	5
1	4	5	5	5	5
2	3	4	5	5	5
3	2	3	4	5	5
4	1	2	3	4	5
5	1	1	2	3	4

Figure 5 Maize cultivar lodging resistance performance evaluation matrix (*Lr*: cultivar lodging resistance, *Ls*: environment lodging stress)

3 Results and discussions

In our study, a new commercial maize cultivar named NH101 was selected as an example to illustrate our modeling and calculating procedures. The average tested lodging percent of NH101 is 4.71%. By Equations (10) and (11), its lodging resistance value and grade are 0.74 and 4, respectively. The calculated environment lodging stress grades in target growing environments are shown in Figure 4. Combining cultivar lodging resistance and environment lodging stress by the evaluation matrix shown in Figure 5, final evaluated lodging resistance performance results of NH101 are obtained which is shown in Figure 6. From this figure we can see that NH101's lodging resistance performance is good in most growing counties of our study area, except for some few counties in the northeast and Huang-Huai-Hai Plain with bad performance. Therefore, in practical extension application, we should avoid recommending NH101 into these bad-performance areas where the lodging risk for NH101 is very high. These results obtained are consistent with the actual situations.

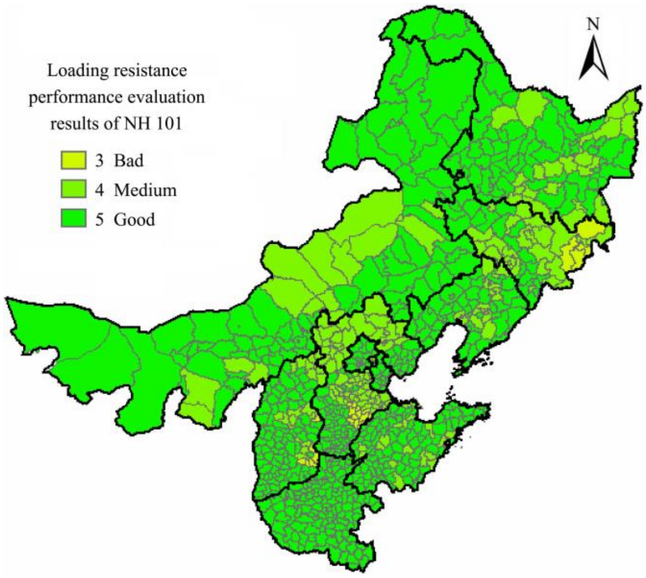

Figure 6 Lodging resistance performance evaluation results of NH101 in target growing environments

There are some differences between this study and related previous studies. Firstly, some previous studies[26-28] usually focused on evaluating cultivar's yield potential performance rather than resistance performance to environment stress. However, it was demonstrated that yield increase of maize cultivar in recent years was mainly due to increased stress tolerance, and the yield improvement potential in the future through increased stress tolerance is still very large[29]. Therefore, like this study, evaluating the cultivar stress resistance performance becomes increasingly important. Secondly, some previous studies[26,30-32] usually paid more attentions to cultivar performance under experimental conditions than in target growing environments, but due to the huge difference between experimental plots and farm fields, the results obtained from experimental conditions can hardly be applied to field situations. So, like this study, evaluating cultivar performance in target growing environments is of practical significance. Thirdly, in a previous study[33], field survey data on lodging were traditionally used to study lodging in maize, but it is known that the cost of large-scale survey is very high and it is not feasible to do it every year. So, like this study, it is more versatile and easy-operational to measure environment lodging stress using mathematical models based on local meteorology and statistic data than using traditional field survey approach. Lastly, some previous studies[15,34,35] considered only one factor, the extreme wind event which is the direct factor causing lodging, to measure environment lodging stress. While it is well known that a cultivar's final performance on lodging is also affected by other indirect factors and human agricultural practices, such as soil fertilizer content and planting density. In this study, we used three factors, extreme wind event, soil potassium content, and planting density, to calculate comprehensive environment lodging stress, owing to which the results obtained are more reliable.

4 Conclusions

In this study, a GIS-based quantitative method for evaluating maize cultivar lodging resistance performance in target growing environments is established based on full cognition of environment stress, cultivar resistance, and the interaction between them. In calculating environment lodging stress, three factors are used in this study, which are the direct factor extreme wind event, indirect factor soil potassium content and human influence factor planting density. Quantification methods, such as extreme probability analysis, spatial interpolation, normalization, and so on are also used for each factor calculation. This method of measuring environment stress is more easy-operational and feasible than traditional surveying approach, especially in large-scale spatial trend analysis. In determining maize cultivar lodging resistance, a method of cumulative frequency distribution analysis is used, which is very practical. After that, an evaluation matrix is established combining environment lodging stress and cultivar lodging resistance together, which is very simple and easy to understand, and the result has a good direct support in practical cultivar application.

The method used in this study is at county-level, cultivar-level, and stress-level with GIS, which needs not be restricted to evaluating maize cultivar lodging resistance performance, but may be extended to evaluate other crop cultivars about other stresses resistance performance. It can facilitate the identification of better-adapted growing environments for a specific cultivar, and provide direct support for cultivar recommendation and extension, so as to reduce the risk and loss of cultivar application. So it is of both academic significance in accelerating precision agriculture development and practical significance in improving crop yield and quality. However, further studies are also needed to make the method better and better.

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[References]

[1] Esechie H A, Rodriguez V, Al-Asmi H. Comparison of local and exotic maize varieties for stalk lodging components in a desert climate. European Journal of Agronomy, 2004; 21(1): 21－30.

[2] Remison S U, Akinyele D. Relationship between lodging, morphological characters and yield of varieties of maize (*Zea mays* L.). Journal of Agricultural Science, 1978; 91(03): 633－638.

[3] Maranville J W. What's new in sorghum physiology, in: Proceedings of the 29th Annual Corn and Sorghum Research Conference, Chicago, Illinois, 1974; 22－28.

[4] Zuber M S, Kang M S. Corn lodging slowed by sturdier stalks. Crop Soils, 1978; 30: 13－15.

[5] Kang M S, Din A K, Zhang Y, Magari R. Combining ability for rind puncture resistance in maize. Crop Science, 1999; 39(2): 368－371.

[6] Esechie H A. Relationship of stalk morphology and chemical composition to lodging resistance in maize (*Zea mays* L.) in a rainforest zone. Journal of Agricultural Science, 1985; 104(02): 429－433.

[7] Pellerin S, Trendal R, Duparque A. Relationship between morphological characteristics and root lodging susceptibility of maize (Zea mays). Agronomie, 1990; 10(6): 439－446.

[8] Thompson D L. Stalk strength of corn as measured by crushing strength and rind thickness. Crop Science, 1963; 3: 323－329.

[9] Hondroyianni E, Papakosta D K, Gagianas A A, Tsatsarelis K A. Corn stalk traits related to lodging resistance in two soils of differing quality. Maydica, 2000; 45: 125－133.

[10] Zuber M S, Grogan C O, Michaelson M E, Gehrke C W, Monge J F. Studies of the interrelation of field stalk lodging, two stalk rotting fungi, and chemical composition of corn. Agronomy Journal, 1957; 49(6): 328－331.

[11] Esechie H A. Relationship between potassium, total nonstructural carbohydrates and lodging in maize in the rainforest zone. Samaru Journal of Agricultural Research, 1985; 3: 61－66.

[12] Pinthus M J. Lodging in wheat, barley, and oats: the phenomenon, its causes, and preventive measures. Advances in Agronomy, 1973; 25(1974): 209－263.

[13] Flesch T A, Grant R H. Corn motion in the wind during senescence: I. Motion characteristics. Agronomy Journal, 1992; 84(4): 742－747.

[14] Bänziger M, Setimela P S, Hodson D, Vivek B. Breeding for improved abiotic stress tolerance in maize adapted to southern Africa. Agricultural Water Management, 2006; 80(1): 212－224.

[15] Mi C Q, Zhang X D, Li S M, Yang J Y, Zhu D H, Yang Y, et al. Assessment of wind-induced environmental lodging stress for maize based on GIS. ICSDM 2011 - Proceedings 2011 IEEE International Conference on Spatial Data Mining and Geographical Knowledge Services, 2011; 467－470.

[16] Liu Z, Li S M, Yang J Y, Yang Y, Mi C Q, Wang H, et al. Method of test environments selection for corn lodging resistance. Transactions of the CSAE, 2010; 26(10): 167－171. (in Chinese with English abstract)

[17] Wind scale and wind speed, wind force list. Available at http://www. 98cns.com/qxyq/feng.htm. [01-03- 2013].

[18] Mi C Q, Zhang X D, Li S M, Yang J Y, Zhu D H, Yang Y. Assessment of environment lodging stress for maize using fuzzy synthetic evaluation. Mathematical and Computer Modelling, 2011; 54(3): 1053－1060.

[19] Potassium loss and more potassium is needed for crops. Available at http://www.cv-nz.com/b2b_html/6/54570.html. [01-03- 2013].

[20] Potassium Boron polymerization. Available at http://www.nwkj.com/ display.asp?id=141. [01-03- 2013].

[21] Corn nutritional deficiency performance and remedial measures. Available at http://www.nmagri.gov.cn/fwq/syjs/zzy/42118. shtml. [01-03- 2013].

[22] The symptoms for corn potassium deficiency. Available at http://www. xinnong.com/yumi/jishu/604880.html. [01-03-2013].

[23] Crop performance to main nutrient elements and rational

fertilization. Available at http://www.hljagri.gov.cn/21data/hcnjtg/tgjsu. Htm. [2013-01-03].

[24] Feng G, Li Y Y, Jing X Q, Cao Z B, Lu B S, Huang C L. Relationship of root and stem characters with lodging resistance of summer maize. Henan Agricultural Sciences, 2010; 11: 20－22.

[25] Huang J. Study on density tolerance character of super High-yielding population. MS Dissertation, Shihezi University, 2008.

[26] Abeysiriwardena S D Z. Statistical analysis of on-farm yield trials for testing adaptability of rice. Euphytica, 2001; 121(3): 215－222.

[27] Fan X, Kang M, Chen H, Zhang Y, Tan J, Xu C. Yield stability of maize hybrids evaluated in multi-environment trials in Yunnan, China. Agronomy Journal, 2007; 99(1): 220－228.

[28] Gauch H G, Piepho H P, Paolo A. Statistical analysis of yield trials by AMMI and GGE: Further considerations. Crop Science, 2008; 48(3): 866－889.

[29] Tollenaar M, Lee E A. Yield potential, yield stability and stress tolerance in maize. Field Crops Research, 2002; 75(2): 161－169.

[30] Samonte S O, Wilson L T, McClung A M, Medley J C. Targeting cultivars onto rice growing environments using AMMI and SREG GGE Biplot Analyses. Crop Science, 2005; 45(6): 2414－2424.

[31] Asrat A, Fistum A, Fekadu G, Mulugeta A. AMMI and SREG GGE biplot analysis for matching varieties onto soybean production environments in Ethiopia. Scientific Research and Essay, 2009; 4(11): 1322－1330.

[32] Gonçalves P D S, Moraes M L T D, Silva M D A, Gouvêa L R L, Aguiar A T D E, Costa R B D. Prediction of Hevea progeny performance in the presence of genotype-environment interaction. Brazilian Archives of Biology and Technology, 2009; 52(1): 25－33.

[33] Mi C Q, Zhang X D, Li S M, Yang J Y, Zhu D H. Evaluation of maize variety suitability on lodging in target environments based on GIS. Annals of GIS, 2011; 17(4): 265－270.

[34] Mi C Q, Zhang X D, Li S M, Yang J Y, Zhu D H. Evaluation of wind-induced lodging risk for maize cultivar based on GIS. Proceedings - 2011 19th International Conference on Geoinformatics, Geoinformatics. 2011; No.: 5980713: 1－5.

[35] Mi C Q, Zhang X D, Li S M, Zhu D H, Yang J Y. Analysis of lodging resistance competitiveness of maize cultivars in target growing environments. Sensor Letters, 2013; 11(6-7): 1282－1287.

[36] Mi C Q, Zhu D H, Bernard A E, Li S M, Zhang X D, Yang J Y. Research on probability distribution of extreme wind speed in maize growth period. Sensor Letters. 2012; 10(1-2): 535－540.