The International Society of Precision Agriculture presents the
15th International Conference on
Precision Agriculture
26–29 JUNE 2022
Minneapolis Marriott City Center | Minneapolis, Minnesota USA

In-Season Nitrogen Management of Maize based on Nitrogen Status Estimation and Lodging Risk Prediction

Rui Dong[1], Yuxin Miao[*2], Xinbing Wang[3]

1. College of Resources and Environmental Sciences, China Agricultural University, Beijing, 100193, China

2. Precision Agriculture Center, Department of Soil, Water and Climate, University of Minnesota, St. Paul., MN, 55108, USA

3. Institute of Crop Sciences, Chinese Academy of Agricultural Sciences, Beijing, 100081, China

A paper from the Proceedings of the
15th International Conference on Precision Agriculture
June 26-29, 2022
Minneapolis, Minnesota, United States

Abstract.

Development of effective precision nitrogen (N) management strategies is crucially important for food security and sustainable development. Lodging is one of the major constraints to increasing maize yield that can be induced by strong winds, and is also influenced by management practices, like N rate. When making in-season N application decisions, lodging risk should be considered to avoid yield loss. Little has been reported on in-season N management strategies that also incorporate lodging risks in the decision making. The objective of this research was to develop an in-season N management strategy for maize based on the estimation of N nutrition index (NNI) at V8 stage and the prediction of lodging risk at R3 stage using a lodging model. Field experiments were conducted in Northeast China from 2017 to 2019 involving different plant densities and N rates. The preliminary results indicated that the optimal N rate giving the maximum relative yield under low, medium, and high plant densities were 176, 193 and 203 kg ha^{-1}, respectively, while the corresponding critical N rates that would induce significant lodging risks in the study site-years would be above 195, 192 and 262 kg ha^{-1}, respectively. Some other factors like the economic benefit and meteorological conditions should be considered to select a suitable N rate. In general, a medium plant density (7.0 plants m^{-2}) matched with around 190~195 kg ha^{-1} N would produce both high marginal returns and low lodging risk for the study region. After that, 1/3 of the N could be applied before or at planting, and side-dress N could be further optimized based on estimated NNI. The NNI and the lodging risk could be estimated or predicted with the use of proximal sensing data according to our previous studies, and this would make the N management more efficient.

The authors are solely responsible for the content of this paper, which is not a refereed publication. Citation of this work should state that it is from the Proceedings of the 15th International Conference on Precision Agriculture. Dong, R., Miao, Y.& Wang, X. (2022). In-season nitrogen management of maize based on nitrogen status estimation and lodging risk prediction. In Proceedings of the 15th International Conference on Precision Agriculture (unpaginated, online). Monticello, IL: International Society of Precision Agriculture.

Keywords.
In-season nitrogen management, optimal N rate, nitrogen nutrition index, grain yield, lodging risk

Introduction

To ensure high grain yield, the excessive use of nitrogen (N) fertilizer is widely adopted by many farmers in maize production, which has led to many adverse environment and economic effects (Zhang et al., 2013; Gu et al., 2018; Zhang et al., 2020). Due to the integrative effect of soil, weather, topography, management practices and other factors, the N demand of crops often varies in space and time (Cassman et al., 2002; Shanahan et al. 2008). Therefore, it's necessary to develop precision N management strategies to improve N use efficiency. The rapid development and widespread use of remote sensing technology plays an important role in the accurate and efficient acquisition of the crop in-season N status information, which is important for the successful implementation of precision N management technology (Kyveryga et al., 2009; Samborski et al., 2009; Mulla et al., 2013; Wang et al., 2019). The N nutrition index (NNI) is a reliable indicator of crop N status (Justes et al., 1994; Lemaire et al., 2008). However, the research on NNI-based precision N management strategies is still limited.

In addition, current N management strategies mostly focus on achieving a target yield or economic benefit, but do not pay much attention to some possible emergencies during the production process, such as the lodging induced by uncertain weather conditions. Under the background of global climate change, extreme weather events occur frequently, and this aggravates the crop lodging risk. Some management practices including N application amount and plant density would have effects on the lodging-resistance capability of crops, and a reasonable or optimized management strategy can help to reduce the lodging risk and avoid the yield losses (Xue et al., 2017; Shah et al., 2017). However, few studies have proposed a N fertilizer recommendation algorithm or strategy with the consideration of the crop N status, yield as well as lodging risk.

Therefore, the objectives of this study were to: (1) develop an in-season variable rate side-dress N fertilizer recommendation algorithm based on maize NNI; (2) develop a precision N management strategy to optimize maize yield, N use efficiency and lodging resistance at the same time.

Materials and methods

Experimental Design

Field experiments were conducted in Lishu County (43°02'–43°46'N, 123°45'–124°53'E), Jilin Province, Northeast China on black soil (classified as typic Haploboroll in USDA soil taxonomy) from 2017 to 2019. Three plant densities (5.5,000, 7.0,000, 8.5,000 plants ha^{-2}) were set up on the main plots with six N fertilizer rates (0, 60, 120, 180, 240 and 300 kg ha^{-1}) set up on the sub-plots. The experiments were carried out using a randomized block design, with three replications for each treatment combination. The N fertilizers were applied in two split applications with1/3 applied before sowing as basal N using ammonium sulfate and 2/3 applied at V8-V9 stage as side-dress N using urea, respectively. Sufficient phosphorus and potassium nutrients were applied before sowing with N fertilizers in each plot. The field was irrigated to ensure seedling emergence in 2018 and 2019 for the lack of rainfall after sowing.

Plant sampling and data acquisition

At V8 growth stage, three plants located in the four inner rows of each plot were selected as the representative samples and dissected at the ground level. All plant samples were oven-dried at 105 ℃ for 30 min, and then dried at 70 ℃ to a constant weight to determine the aboveground biomass (t ha^{-1}). After that, the samples were ground into fine powders to determine plant N concentration (PNC) using a modified Kjeldahl digestion method (Nelson & Sommers, 1973). The NNI was calculated using an equation according to Lemaire et al. (2008):

$$NNI = N_a / N_c \tag{1}$$

where N_a is the actual measured PNC and N_c is the critical PNC. And the N_c was calculated following the equation developed for spring maize according to Li et al. (2012):

$$N_c = 36.5W^{-0.48} \tag{2}$$

where W is the aboveground biomass (t ha^{-1}).

At R3 growth stage, seven plant parameters associated with lodging were measured in maize plants sampled in the inner rows of each plot to calculate lodgingrelated parameters. Natural frequency (Hz) was calculated according to Berry et al. (2000) as the number of oscillations observed during the timed period / timed period (s). It was measured on six typical plants isolated from any neighboring plants within each plot on a still day. The shoot of each plant was pulled by 20 cm from the vertical position and released. The time for three complete oscillations to occur in the line of displacement was recorded using a stopwatch timer. No natural frequency data was collected in 2017 due to the windy weather. After that, three plants of each plot were selected as the representative samples and dissected at the ground level. Plant height (cm) and height at center of gravity (distance between the balance point and the stem base) (cm) were measured with a tapeline. The bottom three internodes were considered as a whole in this study. The internode length (m) was measured using a ruler. The internode diameter (mm) was measured at the middle of the internode for two different orientations (along long axis and short axis) using digital calipers, and calculated by averaging the two values. A stalk strength tester (Zhejiang Top Instrument Co., Ltd., Hangzhou, China) was used to measure the stem breaking strength (Newton) by slowly pressing the “U”-shaped probe of the tester vertically aligned to the middle of the internode down. Then the internode was cut at the mid-point and two measurements of the wall width (mm) were taken at right angles and the average was taken.

At physiological maturity, the plants located in the inner eight rows and three meters in length in each plot were selected for manual harvest. The grain yield was determined by standardizing the moisture content of the grain to 14%.

Calculations

The stem failure moment (*Bs*, Nm) was calculated using the following formula as described in Berry et al. (2000):

$$Bs = Fs\mathrm{L} / 4 \tag{3}$$

where *Fs* is the breaking strength (N), and L is the internode length (m).

The plant parameters associated with lodging described above were inserted into the maize lodging model developed by Berry et al. (2021) to calculate the lodging risk (failure wind speed (m s^{-1})) in each plot.

The yield of each plot was normalized to relative yield as the ratio of the yield of each plot to that of the well-fertilized N reference plot. Similarly, the stem failure moment of each plot was also normalized to relative stem failure moment.

N recommendation method based on NNI

The optimal N application rates to produce an optimal relative yield under different plant densities were determined using linear wth plateau models based on the relationships between the relative yield and the total N application rates. The NNI response to basal N fertilizer application rates was modeled using quadratic relationship as follows:

$$NNI = a_0 + a_1 \times \text{basal N rate} + a_2 \times (\text{basal N rate})^2 \tag{4}$$

and the theoretical N supply amount correspond to the current NNI value could be determined:

$$\text{Basal N rate (NNI)} = \frac{-a_1 - \sqrt{a_1{}^2 - 4a_2(a_0 - NNI)}}{2a_2} \qquad (5)$$

where a_0, a_1 and a_2 were the coefficients representing the intercept, linear and quadratic terms, respectively.

The recommended side-dress N application rate was the difference between the total optimal N application rate and the theoretical N application rate corresponding to the current NNI.

The optimal N rate that can lead to a low lodging risk of maize

According to prior researches (Ji et al., 2020; Li et al., 2021), the current study proposes that the maize crops would have a relatively strong lodging resistance with the failure wind speed ≥ 18 m s^{-1} at a height of 10 m above the ground. In general, the anemograph installed on the meteorological station is at a height of 10 m. However, the calculated failure wind speeds using the lodging model in this study represent average wind velocities at crop height. To unify the wind speed height, the wind velocity logarithmic equation was used:

$$\frac{u(z)}{u(10)} = \frac{ln((z-d)/z_o)}{ln((10-d)/z_o)} \qquad (6)$$

where u(z) was the velocity at height of z above the ground, u(10) was the velocity at height of 10m above the ground, d was taken as three quarters of crop height, and z_o was assumed to be a constant (0.01m). Thus, the critical failure wind speed at crop height based on the lodging model was 11.4 m s^{-1}. Then the optimal N rates that can lead to a low lodging risk (at the critical failure wind speed and relative stem failure moment) of maize under different plant densities were determined according to the correlation between the failure wind speed and the relative stem failure moment and the response curve of the relative stem failure moment to the total N application rates.

Statistical analysis

The grain yield, stem failure moment and failure wind speed as affected by N rates under different plant densities were subjected to the analysis of variance (ANOVA), and the means of each treatment were compared using Duncan test at $P < 0.05$ level of significance. The marginal return under each optimal N rate was calculated as follows:

$$\text{Marginal return} = GY \times P_{GY} - \text{N rate} \times P_N - \text{Seed rate} \times P_S \qquad (7)$$

where GY was the grain yield (kg ha^{-1}), P_{GY} was the grain price (0.25 \$ kg^{-1}), N rate was the total N fertilizer amount (kg ha^{-1}), P_N was the N fertilizer price (0.92 \$ N kg^{-1}), Seed rate was the plant density (plants ha^{-1}), and P_S was the seed price (1.05 \$ 1000 $grain^{-1}$).

All the analyses were conducted using SPSS 21.0 (SPSS Inc., Chicago, Illinois, USA).

Results

Responses of grain yield, stem failure moment and failure wind speed to N rate

Both grain yield and stem failure moment were closely related to N rate and showed an increasing trend with the increase of applied N, while the failure wind speed was not very sensitive to the varied N rate (Fig. 1). However, the grain yield increased slightly when N rate reached 180 kg ha^{-1} and showed not significant difference from 180 to 300 kg ha^{-1} N rates. There was no significant difference of stem failure moment under high N treatment (240 and 300 kg N ha^{-1}) of low plant density (55000 plants/ha), while the stem failure moment did not vary much from 180 to 300 kg ha^{-1} N rates under medium (70000 plants/ha) and high (85000 plants/ha) plant densities. What's more, the stem failure moment showed some decreasing trends when N application rate exceeding a certain range.

Both the stem failure moment and the failure wind speed changed obviously under different plant densities, and showed a decreasing trend with the increase of density.

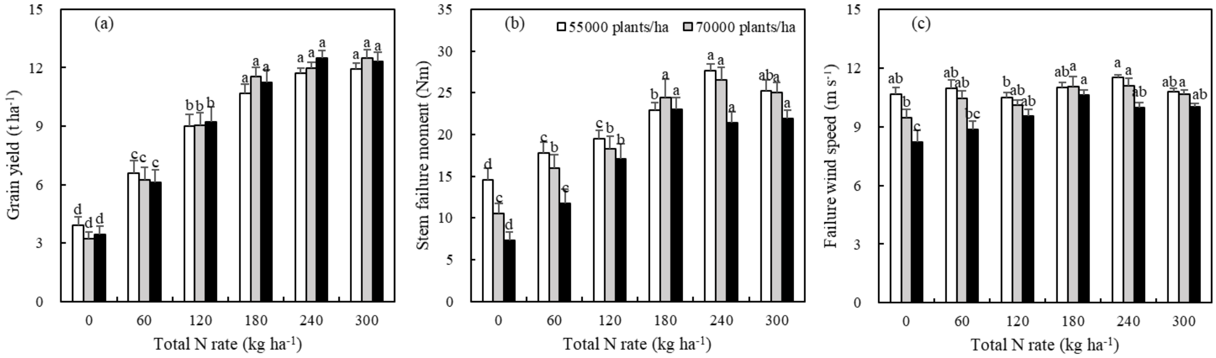

Fig. 1. The response of maize grain yield (a), stem failure moment (b) and failure wind speed (c) to N rate under different plant densities. Note: Different letters indicate that the grain yield, stem failure moment or failure wind speed differed significantly at $P < 0.001$ significance level under a same plant density.

The optimal N rate to achieve optimal yield and critical lodging resistance

The optimal relative yield of maize and the corresponding optimal N rate were different under different densities, and higher values were shown at a higher plant density. In this current study, the optimal relative yield of maize under low, medium, and high plant density was 0.95, 0.97, and 0.99, respectively, and the corresponding optimal total N rate was 176, 193, and 203 kg ha^{-1}, respectively (Table 1).

Table 1. The response of maize relative yield to N rate under different plant densities.

Plant density (plants ha^{-1})	Linear-plateau model	Optimal N rate (kg ha^{-1})	Optimal relative yield	R^2
55000	$y = 0.00353x + 0.324, x < 176$ $y = 0.946, x \geq 176$	176	0.95	0.81
70000	$y = 0.00367x + 0.259, x < 193$ $y = 0.966, x \geq 193$	193	0.97	0.90
85000	$y = 0.00353x + 0.276, x < 203$ $y = 0.992, x \geq 203$	203	0.99	0.91

Since the failure wind speed was not sensitive to N rate, in this study, the amount of N required for a relatively low lodging risk of maize was determined according to the response of stem failure moment to N rate due to its obvious variation affected by N rate. The stem failure moment was normalized as grain yield in order to eliminate the influence of other factors in addition to N, such as year.

There was a good linear correlation between the relative stem failure moment and failure wind speed calculated from the lodging model (Fig. 2). As mentioned above, the maize crops would have a low lodging risk when the failure wind speed at crop height was lower than 11.4 m s^{-1}. Then the critical relative stem failure moment could be calculated as 0.86 based on the linear relationship showed in Fig. 2.

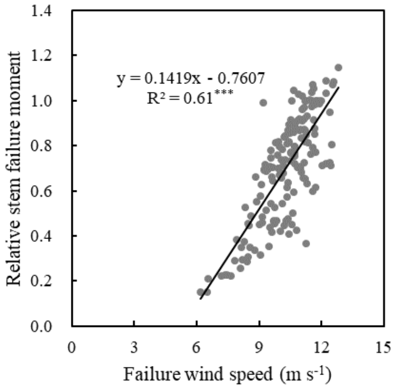

Fig. 2. The linear relationship between the relative stem failure moment and the failure wind speed of maize.

Note：* indicate significant at *P* < 0.001 significance level**

There was a quadratic relationship between the relative stem failure moment and the total N rate under each plant density (Fig. 3). In general, the relative stem failure moment decreased with the increase of plant density. Under low (55000 plants ha^{-1}) and medium (70000 plants ha^{-1}) plant densities, the relative stem failure moment maintained an increasing trend when N rate was less than 300 kg ha^{-1}. However, the relative stem failure moment began to decrease when N rate reached a certain level (262 kg ha^{-1} in this study) under high plant density.

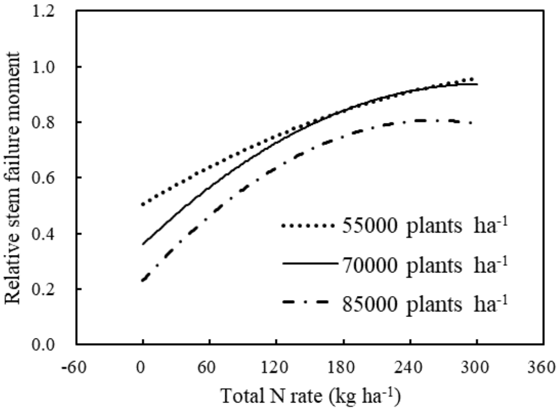

Fig. 3. The response of relative stem failure moment to total N rate under different plant densities.

According to the quadratic relationships between the relative stem failure moment and the total N rate (Table 2), the optimal N rate for the maize crops to reach the critical values of the lodging indicators (stem failure moment or failure wind speed) under low and medium plant density was 195 and 192 kg ha^{-1}, respectively. And these were relatively similar to the N rates that were required for maximum yield, especially for the N rate under medium plant density. The highest value of the relative stem failure moment under the high plant density was 0.81 when the N rate was 262 kg ha^{-1}, and this was still lower than the critical value (0.86) set in this study.

Table 2. The quadratic equations of the relationships between maize relative stem failure moment and total N rate under different plant densities.

Plant density (plants ha^{-1})	Equation	R²
55000	$y = -0.00000296 x^2 + 0.00239 x + 0.506$	0.72
70000	$y = -0.00000623 x^2 + 0.00379 x + 0.361$	0.69
85000	$y = -0.00000837 x^2 + 0.00439 x + 0.231$	0.73

The algorithm for N recommendations based on NNI

There was a quadratic relationship between NNI and basal N rate ($R^2 = 0.81$) at V8 growth stage

(Fig. 4). In the range of 0 to 100 kg N ha^{-1}, the NNI increased with the increase of N rate.

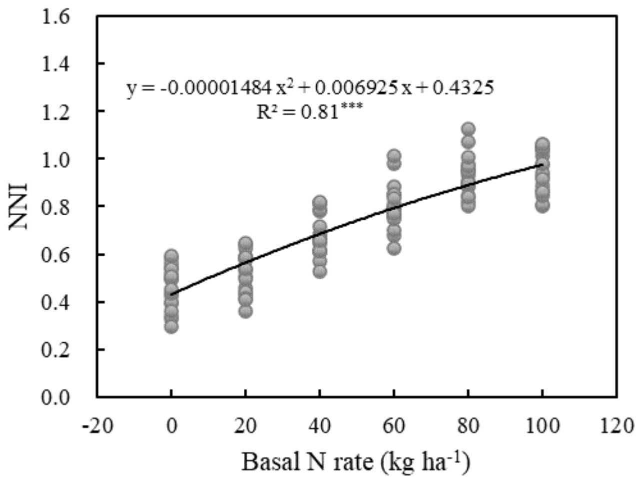

Fig. 4. Relationship between maize NNI at V8 growth stage and basal N rate.

Note：* indicate significant at *P* < 0.001 significance level.**

Based on the optimal N rates to achieve the maximum yield and low lodging risk, the recommended side-dress N rate was calculated using the quadratic model in Fig. 4. In general, a bigger amount of N fertilizer was recommended under a lower basal N rate while less N fertilizer was needed under high basal N treatments (Fig. 5). The recommended N rates calculated based on the optimal N rate to achieve a relatively low lodging risk under high plant density were significantly higher than the recommended N rates under the other two plant densities.

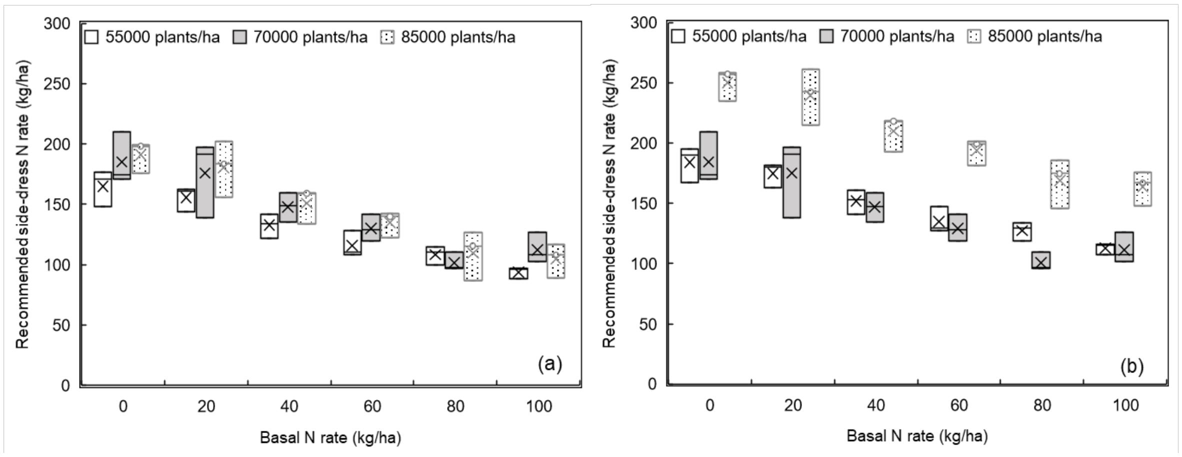

Fig. 5. The recommended side-dress N rate calculated using NNI based on the optimal N rate to achieve the maximum yield (a) and low lodging risk (b), respectively.

The margin returns using the optimal N rates that can realize the optimal relative yields and the critical relative stem failure moments under different plant densities were then calculated and compared (Fig. 6). Under low and medium plant density, the optimal N rate that can achieve the optimal relative yield and the optimal lodging resistance was similar, which led to similar economic benefits, especially for the medium plant density. However, there was an obvious difference between the marginal returns that can be obtained by applying the optimal N rate to achieve the optimal relative yield and the low lodging risk, and a significant higher economic benefit could be achieved by applying N rate without the consideration of lodging.

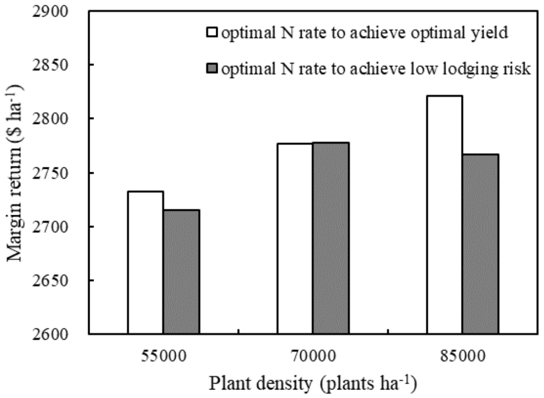

Fig. 6. The marginal returns using the N rates that can realize the optimal relative yields and the critical relative stem failure moments under different plant densities.

Conclusions

The optimal N rate was 176, 193, and 203 kg ha^{-1} at low, medium, and high plant densities, respectively, according to the relationship between maize relative yield and total N application rate. With the consideration of maize lodging risk, this study also determined the optimal N rate based on the critical lodging resistance (critical failure wind speed and stem failure moment), and the optimal total N rate was 195 and 192 kg ha^{-1} under low and medium plant density, respectively. The maize stem could not reach the critical lodging resistance (relative stem failure moment = 0.86) set in the study by simply adjusting the N application amount, although a maximum relative stem failure moment could be reached at the N rate of 262 kg ha^{-1}. The amount of N fertilizer could be determined based on the NNI values using the algorithm proposed in this study, which would be beneficial for the precision N management. This N recommendation method relied on the determination of the optimal total N rate. In general, medium plant density with the N rate of 190~195 kg ha^{-1} was recommended for this study region for both low lodging risk and high economic benefits at the same time. However, the high plant density may be preferred to produce higher grain yield when the weather conditions are fair with less winds and the predicted lodging risk is low. More research is needed for the prediction of meteorological conditions.

Acknowledgements

The research was financially supported by the UK Biotechnology and Biological Sciences Research Council (BB/P004555/1), and the Norwegian Ministry of Foreign Affairs (SINOGRAIN II, CHN-17/0019).

References

Berry, P. M., Griffin, J. M., Sylvester-Bradley, R., Scott, R. K., Spink, J. H., Baker, C. J., & Clare, R. W. (2000). Controlling plant form through husbandry to minimise lodging in wheat. *Field Crops Research*, 67(1), 59-81.

Berry, P. M., Baker, C. J., Hatley, D., Dong, R., Wang, X., & Blackburn, G. A., et al. (2021). Development and application of a model for calculating the risk of stem and root lodging in maize. *Field Crops Research*, 262, 108037.

Cassman, K. G., Dobermann, A., & Walters, D. T. (2002). Agroecosystems, nitrogen-use efficiency, and nitrogen management. *AMBIO*, 31 (2), 132-140.

Gu, B., Ju, X., Wu, Y., Erisman, J. W., Bleeker, A., & Reis, S., et al. (2018). Cleaning up nitrogen pollution may reduce future carbon sinks. *Global Environmental Change*, 48, 56-66.

Justes, E., Mary, B., Jean-Marc, M., Machet, J. M., & Huché-Thélier, L. (1994). Determination of a critical nitrogen dilution curve for winter wheat crops. *Annals of Botany*, 74(4), 397-407.

Ji, L., Xi, Z., Liu, Y., Du, G., & Liu, Z. (2020). Spatio-temporal variation characteristics of extreme wind speed in Jilin province and its relationship with climate warming. *Journal of Arid Meteorology*, 38(3), 388-395. (In Chinese)

Li, M., Yi, Y., Huang, W., Huang, A., Liu, S. (2021). The lodging index of wind disaster in the middle and late grouting stages of maize and the effects on grain yield. *Journal of Hunan Agricultural University (Natural Sciences)*, 47(1),9-16. (In Chinese)

Kyveryga, P. M., Blackmer, A. M., & Zhang, J. (2009). Characterizing and classifying variability in corn yield response to nitrogen fertilization on subfield and field scales. *Agronomy Journal*, 101(2), 269-277.

Lemaire, G., Jeuffroy, M. H., & Gastal, F. (2008). Diagnosis tool for plant and crop N status in vegetative stage: Theory and practices for crop N management. *European Journal of Agronomy*, 28(4), 614-624.

Li, W., He, P., & Jin, J. (2012). Critical nitrogen curve and nitrogen nutrition index for spring maize in North-East China. *Journal of Plant Nutrition*, 35(11), 1747–1761.

Mulla, D. J. (2013). Twenty-five years of remote sensing in precision agriculture: Key advances and remaining knowledge gaps. *Biosystems Engineering*, 114(4), 358-371.

Nelson, D. W., & Sommers, L. E. (1973). Determination of total nitrogen in plant material. *Agronomy Journal*, 65(1), 109–112.

Samborski, S. M., Tremblay, N., & Fallon, E. (2009). Strategies to make use of plant sensors-based diagnostic information for nitrogen recommendations. *Agronomy Journal*, 101(4), 800-816.

Shah, A. N., Tanveer, M., Rehman, A. U., Anjum, S. A., Iqbal, J., & Ahmad, R. (2017). Lodging stress in cereal—effects and management: an overview. *Environmental Science and Pollution Research*, 24(6), 5222-5237.

Shanahan, J. F., Kitchen, N. R., Raun, W. R., & Schepers, J. S. (2008). Responsive in-season nitrogen management for cereals. *Computers & Electronics in Agriculture*, 61(1), 51-62.

Wang, X., Miao, Y., Dong, R., Chen, Z., Guan, Y., Yue, X., Fang, Z., & Mulla, D. J. (2019). Developing active canopy sensor-based precision nitrogen management strategies for corn in Northeast China. *Sustainability*, 11(3), 706.

Xue, J., Xie, R., Zhang, W., Wang, K., Hou, P., Ming, B., Gou, L., & Li, S. (2017). Research progress on reduced lodging of high-yield and -density maize. *Journal of Integrative Agriculture*, 16(12), 2717-2725.

Zhang, F., Chen, X., & Vitousek, P. (2013). An experiment for the world. *Nature*, 497, 33-35.

Zhang, L., Liang, Z., He, X., Meng, Q., Hu, Y., Schmidhalter, U., Zhang, W., Zou, C., & Chen, X. (2020). Improving grain yield and protein concentration of maize (*Zea mays* L.) simultaneously by appropriate hybrid selection and nitrogen management. *Field Crops Research*, 249, 107754.