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Determination of critical nitrogen concentration and dilution curve based on leaf area index for summer maize

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ABSTRACT

Injudicious nitrogen (N) fertilizer application has increased the risk of environmental pollution and decreased grain yields, farm profits, and N use efficiency. The plant based N diagnostic tools can be used to optimize N management of summer maize production. This study was designed to develop and validate a leaf area index (LAI) based critical N (N_c) dilution curve and to establish a theoretical framework to link the relationship of LAI and plant dry matter (DM) based curves, as well as to compare the differences between LAI, plant DM and growth stage-based N_c curves. Six field experiments were set with a range of N application rates (0–320 kg N ha^{-1}) and plant densities (6 to 8×10^4 plants ha^{-1}) using four summer maize cultivars (Zhengdan958, Denghai605, Xundan20, and Denghai661) in Henan province of China. LAI and plant N concentration (PNC) were determined from V6 to R1 stages in each experiment for the development of the N_c curve. LAI and PNC ranged from 1.28 to 6.12 and 1.34% to 3.31% under different N levels, respectively. Allometric relationships between LAI, plant DM, and critical N uptake (N_{uc}) were developed under non-N-limiting treatments. The relationship between N_c and LAI during vegetative growth period was described by a power function ($N_c = 3.84LAI^{-0.45}$). N nutrition index (NNI) increased with the increasing N application rate and ranged from 0.56 and 1.23 across different N treatments. Our results validated that plant N uptake was proportional with LAI, and the allometric parameter between LAI and plant DM of summer maize was close to the theoretical value 2/3. The newly developed LAI-based N_c curve could identify plant N status (N-limiting and non-N-limiting) during key N requirement period of summer maize and can be used for precision N management for summer maize grown in China.

1. Introduction

Nitrogen (N) is the major limiting nutrition element for crop growth and productivity. Judicious application of nitrogen (N) fertilizer has become imperative for precision N management for summer maize production in China (Miao et al., 2011). Summer maize production in China has gradually increased during the past five decades, mainly attributed to advances in plant breeding, high N fertilizer application along with advanced crop management practices (Zhao et al., 2017). N application rates of summer maize production in China have gone far beyond the agronomic and economic optimum levels, causing a reduction in grain yield and severe negative environmental impact (Ata-Ul-Karim et al., 2017a). Therefore, it is imperative to optimize the N fertilizer management during the summer maize growth period, which can not only reduce the N fertilizer application rates but also improve N use efficiency and environment sustainability.

It is essential to evaluate N status of summer maize precisely for optimizing N fertilizer management during crop growth period. The diagnostic tools for plant N status estimation were often derived from empirical relationships based on chlorophyll meters and remote sensing (Li et al., 2014; Zhao et al., 2018a). Previous studies indicated that these relationships were not very reliable across different regions and years (Ata-Ul-Karim et al., 2013), hence limiting their application for evaluating plant N luxury consumption. Lemaire and Salette (1984) summarized the regulation of plant growth and N uptake and proposed the concept of critical N (N_c) concentration that was defined as the

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Table 1
Characteristics of the six field experiments conducted in this study during 2015–2016.

Experiment No.	Soil characteristics	Sowing/ Harvesting date	N treatment (kg N ha^{-1})	Cultivar	Sampling stage
Experiment 1	Type: light loam soil	8-Jun	0 (N0)	Zhengdan958	V6
(2015 Xinxiang)	Organic matter: 12.26 g kg^{-1}	25-Sep	75 (N1)	(ZD958)	V9
	Total N: 0.74 g kg^{-1}		150 (N2)		V12
	Olsen-P: 35.67 mg kg^{-1}		225 (N3)		VT
	NH_4oAc-K^+: 84 mg kg^{-1}		300 (N4)		R1
Experiment 2	Type: sandy light loam soil	8-Jun	0 (N0)	Denghai605	V6
(2015 Xinxiang)	Organic matter: 10.43 g kg^{-1}	25-Sep	75 (N1)	(DH605)	V9
	Total N: 0.61 g kg^{-1}		150 (N2)		V12
	Olsen-P: 33.94 mg kg^{-1}		225 (N3)		VT
	NH_4oAc-K^+: 76 mg kg^{-1}		300 (N4)		R1
Experiment 3	Type: light loam soil	6-Jun	0 (N0)	Zhengdan958	V6
(2016 Xinxiang)	Organic matter: 14.2 g kg^{-1}	22-Sep	90 (N1)	(ZD958)	V9
	Total N: 0.83 g kg^{-1}		180 (N2)		V12
	Olsen-P: 44 mg kg^{-1}		270 (N3)		VT
	NH_4oAc-K^+: 90 mg kg^{-1}				R1
Experiment 4	Type: light loam soil	6-Jun	0 (N0)	Denghai605	V6
(2016 Xinxiang)	Organic matter: 9.5 g kg^{-1}	22-Sep	90 (N1)	(DH605)	V9
	Total N: 0.57 g kg^{-1}		180 (N2)		V12
	Olsen-P: 23.51 mg kg^{-1}		270 (N3)		VT
	NH_4oAc-K^+: 58.45 mg kg^{-1}				R1
Experiment 5	Type: sandy soil	15-Jun	0 (N0)	Xundan20	V6
(2015 Qinyang)	Organic matter: 8.8 g kg^{-1}	24-Sep	80 (N1)	(XD20)	V12
	Total N: 0.53 g kg^{-1}		160 (N2)		VT
	Olsen-P: 11.1 mg kg^{-1}		240 (N3)		
	NH_4oAc-K^+: 62.8 mg kg^{-1}		320 (N4)		
Experiment 6	Type: sandy soil	9-Jun	0 (N0)	Denghai661	V6
(2016 Qinyang)	Organic matter: 9.3 g kg^{-1}	26-Sep	75 (N1)	(DH661)	V12
	Total N: 0.56 g kg^{-1}		150 (N2)		VT
	Olsen-P: 12.5 mg kg^{-1}		225 (N3)		
	NH_4oAc-K^+: 67.4 mg kg^{-1}		300 (N4)		

minimum N concentration required for maximum crop growth. The N_c concentration has attracted considerable attention worldwide due to its accuracy and stability in plant N diagnosis. Plénet and Lemaire (2000) developed a statistical method for constructing maize N_c dilution curve based on plant dry matter (DM) in France. The N_c dilution curve could be described as follow:

$$N_c = 3.4DM^{-0.37} \quad (1)$$

Herrmann and Taube (2004) and Ziadi et al. (2008) have confirmed that the curve developed in France was valid to diagnose plant N status of maize in Germany and eastern Canada. The N_c curves of summer maize have also been developed on plant DM and leaf DM basis in China (Yue et al., 2014; Li et al., 2015; Zhao et al., 2017). The coefficients of the curves developed in China seemed lower than those developed in France. These difference might be due to the effect of the difference between climate and phenology (Yue et al., 2014; Zhao et al., 2017).

The plant DM-based N_c curve can provide effective information about plant N status for governing maize N management, yet its adaptation to the N management in modern agriculture had certain limitations. The calculation of N_c data points requires destructive and time-consuming steps for determining plant DM at each growth stage with field sampling, oven drying and balance weighing (Lemaire et al., 2008). Although remote sensing could be used to estimate plant DM, the estimation accuracy of this tool could not cope with the variation associated with high degree of the spatial distribution of plant DM in the field (Fitzgerald et al., 2010). Leaf area expansion can be used as an alternative functional approach to estimate plant N status of summer maize as plant N uptake and distribution process were regulated by leaf area expansion (Lemaire et al., 2007). Leaf area expansion not only provided a larger carbon supply in the shoot but also increased the storage capacity of plant N by Rubisco during maize growth (Plénet and Lemaire, 2000). This process could avoid the depletion of plant absorbed N by recirculating N to the roots through the phloem (Justes et al., 1994). Therefore, leaf area index (LAI) could be considered as a promising index for determining the N_c dilution value in maize.

Leaf area index is an important structural parameter that is closely related to the size of plant population and the final grain yield (Zhao et al., 2014). Its measurement is easier and quicker by using some non-destructive tools (LAI-2000, Sunscan, Li-3000) in the field or lab, as compared to plant DM (Zhao et al., 2014). This implies that LAI is a more suitable index to develop the N_c curve for managing N in modern agriculture, which can overcome the problems associated with plant DM-based method. The LAI-based N_c curves have been developed in rice ecotypes and winter wheat (Zhao et al., 2014; Ata-Ul-Karim et al., 2014, 2017a). Lemaire et al. (2007) suggested that plant N uptake in maize was proportional with LAI in Europe and Australia, and an isometric (similar relative rate in three dimensions of plant) growth pattern has been observed for maize in a dense stand. These perspectives have not yet been tested on maize grown in China. Moreover, no effort has been carried out to investigate the theoretical connection between LAI-based and plant DM-based N_c curves. Therefore, this study was endeavored to develop a new LAI-based N_c curve in summer maize, to compare it with the existing N_c curves of different crop species, to validate the reliability of this curve for assessing plant N status in summer maize, as well as to establish a theoretical framework to link the relationship between LAI-based and plant DM-based N_c curves. The projected results would provide a new methodology to estimate plant N status and guide field N management during the growth period of summer maize.

2. Materials and methods

During 2015 and 2016 growing seasons, six field experiments were carried out at Xinxiang (35.2 °N, 113.8 °E) and Qinyang (35.1 °N, 112.9 °E), using four summer maize cultivars. Tables 1 and 2 showed the detailed information about cultivars, sowing and harvesting dates, N application rates, soil characteristics, and weather conditions. The soil samples were collected at 0–20 cm layers before sowing. The soil