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Using leaf dry matter to quantify the critical nitrogen dilution curve for winter wheat cultivated in eastern China

Xia Yao, Ben Zhao, Yong Chao Tian, Xiao Jun Liu, Jun Ni, Wei Xing Cao, Yan Zhu*

Nanjing Agricultural University, NO. 1 Weigang Nanjing, Jiangsu, 210095, China

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ABSTRACT

Accurate measurement of the nitrogen (N) required for plant growth helps optimize grain yield, farm profits, and N-use efficiency. Critical nitrogen (N_c) curves have been developed to describe N dilution in plant tissues during crop growth and to estimate the N status of whole plants; however, N_c curves for leaves have yet to be constructed. We constructed and validated a leaf N_c curve for winter wheat based on leaf dry matter (LDM) and compared it with published whole-plant N_c curves to explore the potential for estimating leaf N status of winter wheat in eastern China. Four field experiments were conducted using a range of N fertilization levels (0–375 kg ha^{-1}) applied to six wheat cultivars in eastern China. For our growth analyses, we determined LDM and leaf N concentration (LNC) in the developmental phases from spring regrowth to heading. The leaf N_c curve fit the following relationship: $N_c = 3.05\text{LDM}^{-0.15}$ when LDM ranged from 0.52 to 2.64 t ha^{-1}. However, when LDM was <0.52 t ha^{-1}, we applied a constant leaf critical value of 3.37%. The curve we constructed was lower than the reference whole-plant N_c curve. The N nutrition index (NNI) ranged from 0.34 to 1.31 during the vegetative stage across the 2009–2011 seasons. There was a significant positive relationship between the difference values of NNI (ΔNNI) and N (ΔN) applications over the four wheat developmental stages. We obtained a root-mean-squared-error (RMSE) of 24.53 kg ha^{-1} between the predicted and observed ΔN values when testing the models with independent data. The leaf N_c dilution curve correctly identified N-limiting and non-N-limiting statuses and may be used as a reliable indicator of N stress during the growing season of winter wheat in eastern China.

1. Introduction

The area of land available for crop production in China is decreasing steadily due to urbanization and land degradation, while at the same time, the demand for wheat commodities continues to grow relative to the increment in human population increase. Accordingly, maximizing crop yield per unit area has become a major aim of crop science; while poor land management is a limitation to maximizing crop yield and causing the problem of excessive N fertilization. N used in fertilizer for winter wheat production in China accounted for 24.8% of global N consumption during the period 2006–2007 (Heffer, 2009). Wheat and rice are rotated intensively in agricultural protocols practiced in eastern China (Timsina and Connor, 2001; Jing et al., 2009; Wang et al., 2009). Currently, about 180–250 kg ha^{-1} N is applied annually for wheat production, with 70% of this amount used as a basal fertilizer (Lu et al., 2006). Up to 50% of fertilizer applied may be lost because of the poor synchrony between N supply and wheat demand (Brye et al., 2003; Guarda et al., 2004), particularly during the early phase of plant development when the root mass is low (Raun and Johnson, 1999; Fageria and Baligar, 2005). Thus, N-use efficiency has decreased from 35% (Zhu and Wen, 1992) to 27.5% (Zhang et al., 2007) over the past 15 years, leading to increased N loss to the environment in the form of atmospheric emissions and to water or soil pollution via leaching (Zhu et al., 1997). Therefore, optimization of N requirements at different developmental stages of winter wheat growth has become an important area of research into N-use efficiency and environmental protection in eastern China.

Accurate diagnosis of N status in plants is required for precise N fertilizer management. Plant-based analytical technologies, such as the chlorophyll meter (Fox et al., 1994) and remote sensing tools (Hansen and Schjoerring, 2003), are used to assess N deficiency in crops and may be useful for optimal N management aiming to balance the profitability and sustainability of crop production systems. However, these technologies are easily affected by differences in environment and are limited in their use to the detection of excessive N uptake (Dwyer et al., 1995; Feng et al., 2008) because chlorophyll meters and remote sensing tools are subject to saturability when N treatments are adequate. An alternative technique is based on the concept of a dilution curve for critical N concentration

* Corresponding author. Tel.: +86 25 84396598; fax: +86 25 84396672.
E-mail address: yanzhu@njau.edu.cn (Y. Zhu).

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Table 1
Basic information about four experiments conducted in Nanjing and Yizheng.

Experiment	Season	Soil characteristics (20 cm)	Cultivar	N rate (kg N ha^{-1})	Sampling period
1 (Nanjing)	2007/2008	Type: sandy soil Organic matter: 16.46 g kg^{-1} Total N: 1.3 g kg^{-1} Available P: 54 mg kg^{-1} Available K: 90.5 mg kg^{-1}	Ningmai9 (NM9)	0 (N0) 90 (N1) 180 (N2) 270 (N3)	Spring re-growth Jointing Booting Heading
2 (Nanjing)	2007/2008	Type: sandy soil Organic matter: 10.43 g kg^{-1} Total N: 0.9 g kg^{-1} Available P: 13.94 mg kg^{-1} Available K: 151 mg kg^{-1}	Aikang58 (AK58) Yangmai12 (YM12) Huaimai17 (HM17)	75 (N1) 150 (N2) 225 (N3)	Spring re-growth Jointing Booting Heading
3 (Yizheng)	2009/2010	Type: clay soil Organic matter: 18.9 g kg^{-1} Total N: 1.5 g kg^{-1} Available P: 34 mg kg^{-1} Available K: 90 mg kg^{-1}	Ningmai13 (NM13) Yangmai16 (YM16)	0 (N0) 75 (N1) 150 (N2) 225 (N3) 300 (N4)	Spring re-growth Jointing Booting Heading
4 (Yizheng)	2010/2011	Type: clay soil Organic matter: 13.5 g kg^{-1} Total N: 1.1 g kg^{-1} Available P: 43 mg kg^{-1} Available K: 82 mg kg^{-1}	Ningmai13 (NM13) Yangmai16 (YM16)	0 (N0) 75 (N1) 150 (N2) 225 (N3) 300 (N4) 375 (N5)	Spring re-growth Jointing Booting Heading

(N_c), which is the minimum N concentration required for maximum crop growth (Lemaire and Gastal, 1997). Curves of N_c have been generated for many crops, such as potato (Tei et al., 2002), winter rape (Colnenne et al., 1998), maize (Plénet and Lemaire, 1999), rice (Sheehy et al., 1998), and wheat (Justes et al., 1994). Such curves have been used in crop production worldwide. However, N_c curves vary among different regions, species, and even genotypes within species (Justes et al., 1994; Sheehy et al., 1998; Xue et al., 2007; Yue et al., 2012). Moreover, constructing such curves using data from whole-plant specimens may not always be appropriate. Stress responses can change the allocation of dry matter (DM) to different plant parts, therefore the shapes of the dilution curves may change depending on which parts in plant organs are included in an analysis (Kage et al., 2002). During vegetative growth, leaf is the center of plant growth, which is the important organ of photosynthesis function; the partitioning of dry matter and N-containing nutrients among different plant parts (leaf and stem) is optimized to satisfy the growth demand of leaves. Under these circumstances, the shape of the leaf N_c dilution curve is stable. The N_c curves for cotton leaves provide a reliable tool for diagnosing N status in leaves (Xue et al., 2007). Leaf dry matter (LDM) can be easily, quickly, and reliably estimated by remote sensing (Holben et al., 1980; Gitelson et al., 2003). In addition to estimating LDM, remote sensing could be used to directly monitor the aboveground DM, but certain limitations restrict its application to commercial crop production. Recorded spectral responses in remote sensing procedures are mainly related to the interaction between the sun's radiance and plant canopies (Guyot et al., 1989), and the correlations between aboveground dry matter and spectral responses or vegetation indices are usually poor, especially in the case of closed canopies, whose spectral responses become saturated and lose sensitivity to aboveground dry matter (Nafiseh et al., 2011). Thus, information on the N concentration in the leaf organ rather than in the whole plant may have more accuracy and stability in the future application of nitrogen management at the regional scale.

LDM is an important indicator of crop growth potential and a measure of light-energy utilization, DM production, and yield formation in winter wheat (Castal and Felanger, 1993; Hammer and Wright, 1994; Zhao et al., 2005). LDM increases as more N fertilizer is applied, although differences in LDM are small under high fertilization levels (Feng et al., 2008). Therefore, construction of a N_c curve based on LDM during the vegetative growth of winter wheat would be a worthwhile objective.

Our aims in the present study were (i) to construct and validate a leaf N_c curve, (ii) to compare this curve with published data, and (iii) to explore its potential for estimating winter wheat leaf N status in eastern China.

2. Materials and methods

2.1. Experimental design

Data were obtained from four field experiments in which we varied N applications, wheat cultivars, sites, and years, as summarized in Table 1. In all the experiments, the cultivars were arranged in a completely randomized block design with three replicates. N fertilizer was applied before the sowing stage (50%) and at the jointing stage (50%). The amounts of P and K applied to satisfy plant growth demand were based on soil test recommendations. Further crop management procedures followed common agricultural practices to ensure maximum potential productivity, i.e., no factor other than N was limiting.

The results of Experiments (Exp) 3 and 4 were used to construct a leaf N_c curve. The results from Exp 1 and 2 were used to test the accuracy of this curve.

2.2. Sampling and measurement

We collected 20 plants per plot (24 m^2) at different developmental stages for determination of LDM and leaf nitrogen concentration (LNC). LDM was obtained by a forced-draft oven drying at 80 °C to constant weight, followed by analytical balance weighing. Dried leaves were ground in a sample mill, passed through a 1 mm sieve, and stored in plastic bags for chemical analysis. LNC was determined by the micro-Kjeldahl method (Bremner and Mulvancy, 1982).

2.3. Model calibration

2.3.1. Construction of the critical N dilution curve

Construction of a leaf N_c curve requires identification of critical data points at which N neither limits growth nor enhances it. The experimental data we used for this determination were collected during the 2009–2011 seasons. An N-limiting treatment was defined as one in which additional N application led to a significant increase in LDM. A non-N-limiting treatment was defined one in