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Development of critical nitrogen dilution curve of Japonica rice in Yangtze River Reaches

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ABSTRACT

Plant-based analytical techniques of nitrogen (N) nutrition, established on the concept of critical nitrogen (N_c), can be used to diagnose the in-season N status of rice, which in turns can provide understanding of N nutrition and serve as a guide for the profitability and sustainability of agricultural production system. The objectives of present study were to develop an appropriate N_c curve for Japonica rice, to compare this curve with existing N_c dilution curve for Indica rice and to assess its plausibility to estimate the level of N nutrition for rice crop in east China. Three field experiments were conducted with varied N rates (0–360 kg N ha^{-1}) in three Japonica rice (*Oryza sativa* L.) hybrids, Lingxiangyou-18 (LXY-18), Wuxiangjing-14 (WXJ-14) and Wuyunjing (WYJ) in Jiangsu province of east China. Five hills from each plot were sampled from active tillering to heading for growth analysis. The N_c dilution curve for rice, based on whole-plant N concentration, was described by the equation ($N_c = 3.53W^{-0.28}$), when above-ground biomass ranged from 1.55 to 12.37 t ha^{-1}. However, for above-ground biomass <1.55 t ha^{-1}, the constant critical value $N_c = 3.05\%$ DM was applied, which was independent of aboveground biomass. Our N_c dilution curve was lower than the existing curve of Indica rice in tropics. The N nutrition index (NNI) and accumulated N deficit (N_{and}) ranged from 0.58 to 1.06 and 127 to −12 kg ha^{-1}, respectively, during main development stages under different N treatments in 2010 and 2011. Different N fertilizations were suggested for unit NNI increase or unit N_{and} decrease at different stages. LXY-18 have more N assimilation tendency than WXJ-14 for satisfying rice growth for same dry matter. The N_c dilution curve, resulting NNI and N_{and}, adequately identified situations of limiting and non-limiting N nutrition and could be used as a reliable indicator of N stress during the growing season of Japonica rice in east China.

1. Introduction

Land available for crop production is decreasing steadily due to urbanization and land degradation, while the demand for crop commodities continues to grow with the increment of world population and living standards. Hence, increasing crop yield per unit area is the main target for crop scientists. In order to achieve higher yield, excessive nitrogen (N) fertilizer has been used, especially in China (Zhu and Chen, 2002). Rice is one of the most important crops of China and China contributes 29% of global rice production. China's current per-hectare rice yield is 50% higher than the global average (FAOSTAT, 2010). As the largest user of N in the world, China accounts for 32% of the world's total N consumption, and around 18% of the N is applied to rice crop. China's national average rate of N use in rice cultivation (193 kg ha^{-1}) is about 90% higher than the world average (Heffer, 2009). In Jiangsu province of east China, the average rate of N fertilizer reached 387 kg ha^{-1} during the period of 2004–2008 (Chen et al., 2011). N use efficiency has been declining consistently in China from the past four decades, and this trend of excessive N fertilizer use will further lead to an abrupt decrease in N use efficiency, primarily in east China (Huang and Tang, 2010; Miao et al., 2011). Due to high application rate of N, only 20–30% of N is taken up by the rice plant and the rest of N is lost to the environment (Peng et al., 2006). Moreover, in China the recovery efficiency of N for rice plants is around 30–35% and could be as low as 20% in Yangtze River Reaches (YR) of east China (Li, 2000). A comprehensive study is thus crucially important to optimize N fertilizer requirements at different growth stages of rice for enhancing N use efficiency and agricultural sustainability in east China.

Abbreviations: DM, dry matter; DAT, days after transplanting; LSD, least significant difference; LXY-18, Lingxiangyou-18; N, nitrogen; Nacc, nitrogen accumulation; N_c, critical nitrogen concentration; N_t, total N concentration in above-ground dry matter; N_{na}, actual nitrogen accumulation; N_{and}, accumulated nitrogen deficit; N_{cna}, critical nitrogen accumulation; N_{min}, minimum nitrogen concentration; N_{max}, maximum nitrogen concentration; NNI, nitrogen nutrition index; WXJ-14, Wuxiangjing-14; WYJ, Wuyunjing; YR, Yangtze River Reaches.

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Plant-based analytical techniques, such as chlorophyll meter (Piekkielek and Fox, 1992), remote-sensing tools (Hansen and Schjoerring, 2003) are useful to assess N deficiency in crops and could be used for optimal N management to achieve the profitability and sustainability of crop production systems, however, these two techniques are of limited use for detecting excess N uptake (Dwyer et al., 1995). Another analytical technique to diagnose N status of crop plants is based on the concept of N_c concentration, i.e., the minimum N concentration required for maximum crop growth (Ulrich, 1952). It is well established that the N concentration in many crops decreased with increasing plant biomass (Greenwood et al., 1990; Lemaire and Gastal, 1997). The progressive decline of %N in the shoot biomass can be explained in terms of plant compartmentalization. Plant N content varies according to the proportion of two conceptual compartments in the plant; viz., metabolic and structural (Caloin and Yu, 1984). This decline in N is described by a negative power function called "dilution curve". The critical N (N_c) dilution curve can be used to analyze N deficiency and to administer the N use efficiency in crop simulation model. The N_c dilution curve for a crop could be used to determine N nutrition status of plant and therefore to calculate N nutrition index (NNI) and accumulated N deficit (N_{and}). The NNI is used to quantify the N status, developmental processes and radiation-use efficiency of the plant in response to N supply (Mills et al., 2009) and can be used as basis for making decisions on N application (Lemaire et al., 2008).

The concept of a N_c dilution curve based on whole-plant N concentration was developed for tall fescue (*Festuca arundinacea* Schreb.) by Lemaire and Salette (1984) and is represented by a power equation:

$$N_c = aW^{-b} \tag{1}$$

where W is the aerial biomass expressed in t ha^{-1}, N_c is the N concentration in shoots expressed as a percentage of shoot dry matter, while a and b are estimated parameters. The parameter a represents the N concentration in the shoot biomass (t ha^{-1}); the parameter b represents the coefficient of dilution describing the relationship between N concentration and shoot biomass. The curve defined by Eq. (1) differentiates N status into three categories, i.e., N limiting (below the curve), non-N-limiting (above the curve) and optimum N concentration (on the curve) for the plant growth. During the early stages of growth (shoot biomass <1 t ha^{-1}), N_c takes a constant value due to the small decline of N_c with increasing shoot biomass and the absence of competition for light in well-spaced plants resulting in a constant N concentration value (Lemaire and Gastal, 1997).

Previous research established general relationships between the N_c concentration and the aerial biomass (t ha^{-1}) for C_3 ($5.7W^{-0.5}$) and C_4 ($4.1W^{-0.5}$) species (Greenwood et al., 1990). Another report proposed relatively lower N_c as $4.8W^{-0.34}$ (C_3) and $3.6W^{-0.34}$ (C_4) species as an average relationship (Lemaire and Gastal, 1997). These relationships showed that C_4 species accumulated 25% more dry matter than C_3 species with same amount of N taken up; however, the slope of %N decline is identical in all plants irrespective of their carbon metabolism, and depends mainly on light interception (Le Bot et al., 1998). Lemaire and Gastal (1997) suggested that every species should have its own N_c dilution curve according to its histological, morphological and eco-physiological characteristics. Species-specific N_c dilution curves have been determined for winter wheat (*Triticum aestivum* L.) (Justes et al., 1994; Yue et al., 2012), potato (*Solanum tuberosum* L.) (Greenwood et al., 1990; Bélanger et al., 2001), winter rapeseed (*Brassica napus* L.) (Colnenne et al., 1998), corn (*Zea mays* L.) (Plénet and Lemaire, 1999; Ziadi et al., 2008), grain sorghum (*Sorghum bicolor* L.) (Van Oosterom et al., 2001), tomato (*Lycopersicon esculentum* Mill.) (Tei et al., 2002), and spring wheat (*T. aestivum* L.) (Ziadi et al., 2010). For high yielding Indica rice (*Oryza sativa* L.) in tropics, this allometric function was estimated by Sheehy et al. (1998). Previous reports pointed out interspecies and intraspecies dissimilarities in the N_c curve (Justes et al., 1994; Bélanger et al., 2001), as well as between experimental sites (Greenwood et al., 1990).

Japonica cultivars differ from Indica cultivars in their morpho-anatomical properties of leaves. At the same level of total leaf N, Japonica cultivars showed lower net assimilation of photosynthates due to higher dark respiration rate (Weng and Chen, 1987). Anatomical differences, including greater stoma density, leaf conductance, well developed xylem vessel system and sparsely arranged chlorenchyma cells, were observed in Indica, as compared with Japonica cultivars (Weng and Chen, 1987). However, comparison of the critical N dilution curves between Indica and Japonica rice cultivars under different environmental conditions is still lacking.

The Yangtze River Reaches (YR), having subtropical-temperate climate with cold winter and hot summer without the humidity of tropics, is one of the major agriculture regions of China. YR provides more than 65% of the national rice production in China and is suitable for planting several ecotype rice cultivars and has been dominated by Japonica types in recent years. The average rate of N fertilizer for rice in east China is much higher than that of national average of China; therefore, a comprehensive study is crucially important to optimize N fertilizer rates and to develop a N_c dilution curve for the Japonica rice in pedoclimatic conditions of east China, a heavily N fertilized area.

Therefore, the objectives of this study were to (1) develop an appropriate N_c dilution curve for Japonica rice; (2) compare this curve with existing N_c dilution curve for Indica rice; (3) assess the plausibility of N_c curve to estimate the N nutrition status in Japonica rice.

2. Materials and methods

2.1. Experimental design

Three field experiments were conducted with varied N rates (0–360 kg N ha^{-1}) in three Japonica rice (*O. sativa* L.) hybrids, Lingxiangyou-18 (LXY-18), Wuxiangjing-14 (WXJ-14) and Wuyunjing (WYJ), in Jiangsu province of east China, as detailed in Table 1. Data used to develop the N_c dilution curve came from two experiments conducted in 2010 and 2011 that consist of five N fertilizer rates ranging from zero to non-limiting amounts of N. The data for validation of N_c dilution curve came from an independent experiment conducted in 2007 with three levels of N fertilizer, ranging from N limiting to non-limiting amounts of N.

2.2. Plant sampling and tissue N determination

2.2.1. Plant sampling

Five hills from each plot were sampled for growth analysis. The number of sampling dates was six during each year of experiment. Plant sampling occurred from active tillering to heading (before the onset of flowering) at the intervals of 10–12 days, starting from 16 and 18 days after transplanting (DAT) in 2010 and in 2011, respectively. The sampling dates are presented in Table 1. Whole plants were manually uprooted and samples were divided into green leaf blade (leaf) and culm plus sheath (stem).

2.2.2. Biomass and shoot N determination

Shoot biomass (t ha^{-1}) was determined by severing five plants from each plot at ground level on each sampling date. Fresh plants were separated in to green leaf blade (leaf) and culm plus sheath (stem). Dry matter (DM) was determined after oven-drying each sampled component at 80 °C for 48 h. Samples were subsequently ground to a powder to pass through a 1-mm sieve in a Wiley mill and stored at room temperature until further chemical analysis.