Field Crops Research 164 (2014) 65–73

Contents lists available at ScienceDirect

Field Crops Research

journal homepage: www.elsevier.com/locate/fcr

A reappraisal of the critical nitrogen concentration of wheat and its implications on crop modeling

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ARTICLE INFO

Article history:
Received 15 January 2014
Received in revised form 7 May 2014
Accepted 9 May 2014
Available online 12 June 2014

Keywords:
Maximum N concentration
Shoot biomass
Developmental stage
N dilution curve
APSIM

ABSTRACT

The concept of critical nitrogen (N) concentration (Ncc) has been used for both diagnostic purposes and modelling of wheat-N relations. Ncc has been derived with two contrasting approaches: one against above ground biomass (Ncc-biomass), and one against developmental stages (Ncc-stage). While the former has been claimed in diagnostic use, both approaches are adopted in wheat simulation models. This paper provides data from North China Plain (NCP) to re-exam the Ncc-stage relationships used in two widely used wheat models (APSIM and CERES) and to compare the Ncc-biomass vs. Ncc-stage relationships. The results revealed significant higher maximum and critical N concentrations in leaves of wheat in NCP than the values used in the APSIM-wheat model. Recalibration of the APSIM model with the new N concentrations led to improved simulations for wheat biomass and N uptake, particularly under low N input. Our results also show that the Ncc-stage relationship appeared to be more robust than the Ncc-biomass relationship, and it helped explain the variations in wheat Ncc-biomass curves from different regions. This likely reflects the fact that Ncc-stage curve captures the stage-driven formation of structural biomass and carbohydrate reserves of wheat, which is the main cause for N dilution. The implications of the findings on modelling of wheat–nitrogen relationships and on nitrogen management practices are also discussed.

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1. Introduction

Nitrogen (N) concentration in shoots and leaves of field crops has been widely used as an indicator for crop nutritional status to maintain optimal growth (Cui et al., 2009; Greenwood and Barnes, 1978; Justes et al., 1994; Lemaire and Salette, 1984; Sheehy et al., 1998; Yue et al., 2012a). The concept of critical N concentration (Ncc) in aerial biomass (shoots) was defined as the minimum concentration of N necessary to achieve maximum above ground biomass at any moment of vegetative growth (Lemaire and Salette, 1984). This concept has been used in both physiologically-based crop simulation models (Brisson et al., 2003; Porter, 1993; Ritchie et al., 1985; Wang et al., 2002) and in the development of diagnostic tools to assist nitrogen management for crops (Cui et al., 2009; Justes et al., 1994; Ziadi et al., 2010). However, two different approaches have been used to derive the critical N concentration and its change with crop growth and development. One approach relates the critical N concentration of a crop to its developmental stage, while the other approach derives critical N concentration as a function of above ground biomass (as a biomass dilution curve). Little efforts have been made to reconcile these two approaches so far.

Some crop models also define maximum and minimum N concentrations, in addition to the critical N concentration, for the simulation of crop N demand and N stresses for various processes. We refer these N concentrations (maximum, critical and minimum) to as threshold N concentrations. The Agricultural Production Systems model (APSIM) (Keating et al., 2003; Wang et al., 2002) and the CERES model (Jones et al., 2003; Ritchie et al., 1985) are two of the most commonly used models that define threshold N concentrations as functions of developmental stages of crops. For wheat crop, CERES-wheat model (Ritchie and Otter, 1985) uses the critical and minimum N concentrations for shoots derived separately for spring and winter wheat from literature data.

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http://dx.doi.org/10.1016/j.fcr.2014.05.004
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APSIM-wheat model uses threshold N concentrations derived separately for leaves and stems from literature data which were subsequently modified with experimental data obtained in Australia (Wang et al., 2002). The current version of APSIM-v7.5 does not distinguish spring and winter wheat for threshold N concentrations. Other crop models using a similar approach include Daisy (Hansen et al., 1991), AFRCWHEAT2 (Porter, 1993) and SPASS-wheat (Wang and Engel, 2002). Such an approach normally assumes that the critical N concentration of wheat changes only with developmental stages, and it does not change between different wheat genotypes. While both the APSIM-wheat and CERES-wheat models have been frequently applied to simulate wheat response to N applications, to the best of our knowledge, no studies have further checked the critical N concentrations used in the models with recent experimental data.

Due to the decline of N concentration (Nc) with increasing crop biomass, the critical N concentration has also been derived as a negative power function of biomass, called a dilution curve. For wheat, critical N concentration dilution curves were developed for winter wheat in France (Justes et al., 1994), for spring wheat in Canada (Ziadi et al., 2010) and for winter wheat in China (Yue et al., 2012a; Zhao et al., 2012). Based on the biomass-derived critical N concentration, various diagnostic tools were established for the assessment of N status of wheat crop for the purpose of improving N management practices (Cui et al., 2009; Justes et al., 1994; Ziadi et al., 2010). This approach has also been used in crop models like STICS (Brisson et al., 2003) and CropSyst (Stockle et al., 2003). A common feature of these N dilution curves is that they describe the declining critical N concentration in wheat shoots with increasing above-ground biomass from a biomass around 1 Mg/ha up to the flowering stage of wheat. However, the derived critical N dilution curves are not consistent, they differ between geographical regions and even between different wheat cultivars (Angus, 2007; Zhao et al., 2012). These differences have been attributed to the variation in both climatic conditions and wheat genetics. In addition, previous N dilution curves based on dry weight always refer to the shoot N concentration and pay no attention to the differences between wheat organs such as leaves and stems.

In this paper, we aim to present data on N concentration of winter wheat collected in the field experiments at Wuqiao, Hebei Province in the North China Plain (NCP), and compare them with the threshold N concentrations used in both APSIM-wheat and CERES-wheat models as well as the N concentration dilution curves in several other studies. The objectives are to: (1) analyse whether significant differences exist between measured threshold N concentrations for a modern winter wheat at NCP and those reported previously as well as those used in the two wheat models, (2) study how possible changes in threshold N concentrations could impact on wheat growth simulations in APSIM, (3) compare the Ncc-biomass dilution curves vs. Ncc-stage relationships where possible, and (4) discuss the need for reconciling these two Ncc approaches and the implications on crop modelling and N management practices.

2. Material and methods

2.1. Study site

The study site was Wuqiao (WQ) (37°29′–37°47′ N, 116°19′–116°42′ E, altitude 14–23 m above sea level, groundwater table 6–9 m) in the middle of Heilonggang catchment in Hebei province. The average annual rainfall at the site was 550 mm (1961–2010), most of which falls in the summer months from July to September. The mean annual temperature is 12.9 °C. The main cropping system is a winter wheat and summer maize rotation. The growing season for wheat is from mid-October to early June, and for maize from mid-June to early October. Average maximum and minimum temperature during the wheat cropping season from 1981 to 2010 were 13.6 and 1.6 °C, respectively. The soil at the site is classified as a Calcaric Fluvisol (FAO, 1990) with a sandy clay loam texture and a potential plant available water holding capacity of 452 mm down to the depth of 2 m. On average, the topsoil (0–20 cm) had a pH of 8.12 and contained about 11.2 g kg^{-1} organic matter, 1.1 g kg^{-1} total N, 49 mg kg^{-1} Olsen-P, and 132 mg kg^{-1} exchangeable K.

2.2. Experimental data collection

All the data used in this study are from field experiments (Table 1) conducted at Wuqiao site in 2009–2010 and 2010–2011 wheat seasons aimed to study the response of wheat growth to irrigation water and nitrogen inputs. All the experiments were conducted with randomized complete block design with irrigation water supply ranging from 75 mm to 375 mm per season and fertilizer-N (urea-N) application rates ranging from 0 to 330 kg/ha, each with three or four replicates. The wheat cultivar 'SJZ15' was sown early to mid October with plant densities ranging from 350 to 600 plants m^{-2}. Weeds, insect pests and diseases were properly controlled and the crops were not limited by other nutrients.

Crop samples were collected 5–7 times from 0.2 m^2 quadrates at main growth stages of over-wintering (just before frost), turning-green, jointing, booting, flowering, grain filling, and maturity. Measurements included LAI, above-ground biomass, grain yield and yield components. From the jointing stage, the above-ground biomass was measured separately for leaves, stems (including leaf sheath), glumes and grain. All plant samples were oven dried at 70 °C to constant weight to measure biomass. The N concentrations of leaves, stems, glumes and grain were determined using the standard Kjeldahl method (Horowitz, 1970). Nitrogen content of leaves, stems, glumes and grain were calculated from the N concentrations and biomass.

2.3. Developmental stages of wheat

The observed developmental stages of wheat in the experiments can be expressed as the Feekes stages (Large, 1954) and the decimal code or DC stages (Zadoks et al., 1974). Both the DC stages and Feekes stages are used here to investigate the measured N

Table 1
Water, nitrogen and sowing date treatments in experiments at Wuqiao.

Experiment	Year	Irrigation[a]	N Application[b] (KgN/ha)	Sowing Dates (day/month)
Exp1	2009	W2, W3, W4	192, 270	10/10, 16/10, 22/10
Exp2	2009	W3	0, 123, 192, 261, 330	12/10
Exp3	2010	W1, W2, W3, W4, W5	123, 192, 279	10/10, 17/10, 24/10
Exp4	2010	W2, W3	0, 60, 123, 157.5, 185, 226.5, 261	12/10, 15/10

[a] W1-W4 represents one to four times of irrigation, each of 75 mm applied at sowing, jointing, flowering and mid grain filling, respectively. W5 – 75 mm applied at sowing, upstanding, jointing, booting and mid grain filling.

[b] All the N was applied at sowing if N rate was less than 160 kgN/ha. Otherwise, 123 kgN/ha was applied at sowing, and the rest at jointing.

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