Field Crops Research 209 (2017) 88–95

Contents lists available at ScienceDirect

Field Crops Research

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

Tailoring NPK fertilizer application to precipitation for dryland winter wheat in the Loess Plateau

Hanbing Cao[a,b], Zhaohui Wang[a,b,*], Gang He[a,b], Jian Dai[a,b], Ming Huang[a,b], Sen Wang[a,b], Laichao Luo[a,b], Victor O. Sadras[c], Marianne Hoogmoed[c], Sukhdev S. Malhi[d]

[a] *State Key Laboratory of Crop Stress Biology in Arid Areas, Northwest A & F University, Yangling 712100, Shaanxi, China*
[b] *Key Laboratory of Plant Nutrition and Agri-environment in Northwest China, Ministry of Agriculture/College of Natural Resources and Environment, Northwest A & F University, Yangling 712100, Shaanxi, China*
[c] *South Australian Research and Development Institute, Waite Campus, 5063 SA, Australia*
[d] *Department of Renewable Resources, University of Alberta, Edmonton, Alberta T6G 2H1, Canada*

ARTICLE INFO

Keywords:
Fertilizer application
Wheat grain yield
Nutrient uptake
Seasonal rainfall
Dryland

ABSTRACT

Over-fertilization is economically and environmentally undesirable, and under-fertilization contributes to yield gaps. In dryland cropping systems, where precipitation is a major source of variation in yield, matching fertilizer to precipitation is critical. The aim of this study was to outline and test a method to match nitrogen (N), phosphorus (P), and potassium (K) fertilizer rate to precipitation for dryland winter wheat in the Loess Plateau of China. Based on field experiments at 52 sites from 2009 to 2013, the grain yield of winter wheat was found to increase quadratically with the precipitation in two periods: summer fallow, and summer fallow until jointing stage. The shoot N, P, and K nutrient uptake were linearly correlated with grain yield. Basal fertilizer requirement was calculated from target grain yield estimated as a function of fallow precipitation. The need for topdressing was determined by re-estimating target grain yield as a function of precipitation during summer fallow until jointing stage. Validation of this method using an additional dataset from long term studies in the same area suggested that adjusting fertilizer rates to summer fallow and summer fallow until jointing precipitation could correct the over application for N and P fertilizer, and deficient application for K fertilizer in the Loess Plateau.

1. Introduction

Wheat is a staple cereal worldwide and is cultivated in areas accounting for more than 20% of the world's arable land. Wheat producing regions are spreading over arid and semiarid environments, where water scarcity and low soil fertility limit primary production (Stewart, 1988; Li et al., 2009). In China, dryland farming is practiced on about one-third of the arable land. A large part of this area (about 40%) is on the mostly semiarid Loess Plateau, spanning 63×10^4 km^2 (Liu, 1999; Li, 2004). Winter wheat-summer fallow is the most common system under rain-fed production in this area. The annual precipitation ranges from 300 to 600 mm, with more than 60% occurring during the summer fallow (Jin et al., 2007). Therefore, precipitation stored in the soil during the summer fallow is one of the main water sources for winter wheat, as reported in other cropping systems (Nielsen et al., 2002; Unger et al., 2006).

Soil fertility also constrains crop yield in most of the world's drylands (Sadras and Angus, 2006; Li et al., 2009; van der Velde et al., 2014). In the Loess Plateau, around 67% of the soil organic matter content is less than 1.1% (Guo et al., 1992), hence the need to fertilise to reduce yield gaps; for the central dryland, N rates have increased from 45 to 185 kg N ha^{-1}, P from 45 to 112 kg P_2O_5 ha^{-1}, and K from 0 to 23 kg K_2O ha^{-1} in the three decades since the 1970s, whereas average grain yield increased from 1883 to 4269 kg ha^{-1} (Wang et al., 2014). In recent years, 42% of farm households applied N fertilizer at an average rate of over 200 kg N ha^{-1}, which is much higher than the N requirement of average grain yield around 4500 kg ha^{-1} (Zhao et al., 2013). High rates of fertilizers contributed marginally to yield, and decreased fertilizer use efficiency. In China, N use efficiency in summer fallow-winter wheat was less than 30 kg grain kg^{-1} of applied N (Liu et al., 2016) compared to 44 kg grain kg^{-1} of applied N for cereals worldwide (Dobermann and Cassman, 2005), with high nitrate-N residual in soil at harvest (Dai et al., 2015) and leaching during the wet summer fallow (Guo et al., 2010; Dai et al., 2016). Therefore, adjusting fertilizer rates are needed to match the crop requirement and decrease the negative environ-

---

[*] Corresponding author at: State Key Laboratory of Crop Stress Biology in Arid Areas, Northwest A & F University, Yangling 712100, Shaanxi, China.
E-mail address: w-zhaohui@263.net (Z. Wang).

http://dx.doi.org/10.1016/j.fcr.2017.04.014
Received 22 February 2017; Accepted 21 April 2017

mental effects of over-fertilization.

Matching fertilizer to precipitation is a major challenge for dryland agriculture (Lopez-Bellido et al., 1996; Pala et al., 1996; Sadras et al., 2016). Successful calculation of fertilizer rate depends largely on estimating the target crop yield and the corresponding nutrient uptake. Wheat yields have been reported to correlate with water stored in soil at sowing (Musick et al., 1994; Shangguan et al., 2002; Schillinger et al., 2008), and also to soil water and N topdressing at the early jointing growth stage (López-Bellido et al., 2005; Zhao et al., 2016). However, it is unfeasible for small household farmers (0.1–0.3 ha per field in most areas in China) to measure plant available water in a 2 m-deep soil profile. Since soil moisture is directly charged via precipitation in drylands (Stewart, 2005), the already occurred precipitation at sowing or at critical growing stages may be a more practical measure to calculate target yield and fertilizer rate.

Therefore, the question here is: can we use precipitation during summer fallow, and precipitation during summer fallow until jointing stage to predict grain yield, nutrient uptake and associated fertilizer rates? The objectives of this study were to: (1) quantify the relationship between grain yield and precipitation during summer fallow, and during summer fallow until jointing stage; (2) quantify the relationship between nutrient uptake and wheat yield; (3) develop a fertilizer recommendation based on the target yield estimated from precipitation, and nutrient uptake; and (4) compare this approach with current fertilizer recommendations and farmers' practices.

2. Materials and methods

2.1. Description of experimental sites

From 2009 to 2013, field experiments were conducted at six counties in the central Loess Plateau of China, covering the area of almost 48 000 km^2 from 106°40′E to 110°36′E and 34°29′N to 35°36′N (Table 1). This region has a warm temperate continental monsoon climate with an average annual temperature of $\sim 12\ ^{\circ}C$, and a mean precipitation of ~550 mm (more than 60% during July–September in summer) (http://data.cma.cn/). The soil is loess-derived and classified as a silt loam texture according to the US Department of Agriculture (USDA) soil classification system, and its chemical properties are presented in Table 2. Winter wheat-summer fallow is the major cropping system, where wheat is usually sown in early October and harvested in late May or early June of the following year, with an intervening summer fallow.

2.2. Survey of local farmers' fertilizer rates and winter wheat grain yield

Predesigned questionnaires were used between 2009 and 2013, and 10–15 farmers living near each experimental site were randomly selected (making a total of 723 farms) for information of usage of N, P, and K fertilizer and the corresponding grain yield of winter wheat.

2.3. Field experiments

The field experiments included 10 non-replicated treatments randomized in each farmer's field, and were carried out in 52 fields. The plot size of each treatment ranged from 60 to 100 m^2. The 10 treatments included: (1) Farmer practice (FP) using the average N, P, and K rates of the nearby 10–15 farmers obtained from the farm surveys; (2) FP – N (N omission for FP); (3) FP – P (P omission for FP); (4) FP – K (K omission for FP); (5) Soil test (ST), where N, P, and K rates were decided based on a soil test method (Li et al., 2011; Cao et al., 2014); (6) ST – N (N omission for ST); (7) ST – P (P omission for ST); (8) ST – K (K omission for ST); (9) Stanford Equation (SE), which was proposed by Stanford (1973). For example, the N rate was calculated as the difference in N uptake requirement for the target yield and N supply by soil divided by the recovery efficiency of fertilizer N; and (10) Control, where no fertilizer was applied.

The fertilizer sources were urea, superphosphate (12% P_2O_5) or triple superphosphate (46% P_2O_5), potassium sulphate (50% K_2O) or potassium chloride (60% K_2O). All the fertilizers were broadcast and incorporated into top 20 cm soil at sowing. Winter wheat was sown at 150 kg seed ha^{-1} with 15 cm or 20 cm row spacing from late September to early October, and harvested around mid-June in the following year. The high-yielding, local winter wheat cultivars "Jinmai 47/54" and "Xinong 189/928/986/979" were used, and other agronomic practices were in accordance with the native cultivation custom. Daily precipitation was measured at each experimental site with a pluviograph 3554 Watch Dog 1 (3554WD1, Spectrum Technologies Company, US) (Table 1).

2.4. Sampling and laboratory procedures

At maturity, wheat shoots with one hundred ears were randomly sampled and separated in ears and straw. After air-drying, the ears were threshed, and the grain, glume, and straw were weighed. Subsamples of 10–30 g were oven-dried at 75 °C to a constant weight for chemical analysis. For the determination of grain yield, four or five 1-m^2 samples were also randomly harvested and threshed, grain samples about 200 g were oven-dried to calculate dry weight. The grain yield and shoot biomass were all expressed as dry weight.

Subsamples for chemical analysis were ground and digested using H_2SO_4-H_2O_2 at constant 375 °C. Total N and total P in the digest were measured with a high-resolution digital colorimeter Auto Analyzer 3 (AA3, SEAL Company, Germany), and the total K was analyzed by a flame photometer (Model 410, Sherwood Company, England). Shoot nutrient uptake was calculated by aggregating the nutrient content of grains, glumes and straw.

2.5. Calculations for tailoring NPK fertilizer application to precipitation

2.5.1. Estimation of target yields from precipitation and its validation

Cumulative precipitation was computed for summer fallow and each growing stage (Zadoks et al., 1974). Using the data from the field experiments, regression analysis was performed to determine relationships between yield and precipitation during summer fallow and the various growth stages. The yield data used were just from FP, ST, and SE treatments, which resulted in the highest yields with no significant difference (Table 3). Precipitation during two stages: *summer fallow* and *summer fallow until jointing stage,* were found to give the nonlinear correlations with the winter wheat grain yields (only results for these correlations are reported). The *Summer fallow* is the period from the harvest of winter wheat in the first growing season (early/mid-June every year) to the sowing of the next growing season of winter wheat (late-September/early-October). The *summer fallow until jointing stage* is the period from the start of summer fallow to the initiation of winter wheat jointing (late-March/early-April).

The regressions were suggested for estimating target yield and were validated using an additional dataset (Table S1) from long term field experiments conducted in the central Loess Plateau. The normalized Root Mean Square Error (nRMSE) was used to measure the relative difference (percentage of the mean value, $\overline{M}$) of estimated (E_i) vs reported (M_i) data (Dettori et al., 2011). The deviation statistics was defined as follows:

$$nRMSE = \sqrt{\frac{\sum_{i=1}^{n} (E_i - M_i)^2}{n}} \times \frac{100}{\overline{M}} \quad (1)$$

2.5.2. NPK fertilizer rates as a function of precipitation derived target yield and nutrient uptake

2.5.2.1. Determination of target yield based on precipitation. For basal fertilizer recommendation at sowing, the target yield ($Y1_{target}$) was