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Evaluation of water and nitrogen use efficiencies in a double cropping system under different integrated management practices based on a model approach

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ABSTRACT

Irrigation, fertilization, and cultivation managements play important roles in crop production in the North China Plain (NCP). This study aims to compare crop yields, and water and N use efficiencies (WUE and NUE) in a wheat–maize cropping system under different integrated management practices and recommend the best management practices (BMPs). A two-year experiment involving four integrated management practices was conducted in Tai'an City, Shandong Province in the NCP. These management practices were designed as follows: (1) traditional farming practice (FP); (2) optimized combination of cropping and fertilization (OPT-1); (3) practice for high yield (HY), which does not consider the cost of resource inputs to maximize grain yield; and (4) further optimized combination of cropping and fertilization (OPT-2), which is based on the HY practice. Soil water movement, nitrate transport, and crop growth were all simulated using the soil water, heat, carbon, and N simulation (WHCNS) model. Results indicated that simulated soil water content and nitrate concentration at different depths in soil profiles, leaf area index, dry matter weight, and grain yield were all in good agreement with the field-measured data. Simulation results indicated that the amounts and dates of irrigation and fertilization, planting method, planting density, and sowing date had obvious effects on grain yield, water drainage, total N loss, WUE, and NUE. The annual average total N loss under the OPT-1 practice decreased by about 28.6% compared with the FP practice, whereas the annual average grain yield and NUE increased by 27.7% and 25.7%, respectively. The largest annual average grain yield and total N loss occurred in the HY practice (23,590 kg ha^{-1} and 240.6 kg N ha^{-1}, respectively). Although the annual average grain yield of the OPT-2 practice was 15.4% lower than that of HY practice, the NUE was 19.2% higher in OPT-2 than in HY. The annual average nitrate leaching under the OPT-2 practice was the lowest and reached 25.5%–60.0% compared with those under other practices. Among the four practices, the OPT-2 practice achieved the most preferable results; the lowest N loss and the highest NUE were obtained at the expense of a slight decrease in grain yield. Therefore, the OPT-2 practice was the BMPs among the four practices and should be recommended to maximize the economic and environmental benefits in the study region.

1. Introduction

The North China Plain (NCP) is one of the most important grain production regions in China. In this region, the prevailing cropping system is the winter wheat–summer maize rotation. At present, one of the important research aims for agronomists is to realize the dual goals of achieving both high crop yield and high use efficiency of resources (mainly water and fertilizer) and reducing the negative impact on the environment. However, some disadvantages are present in the traditional cropping system practiced by smallholders. The intensive field management practices adopted by smallholders, including excessive irrigation and fertilizer application, incorrect application rates and dates, and inadequate sowing rates and dates, do not match well with crop development requirements (Cao et al., 2012; Jin et al., 2012; Meng et al., 2012; Miao et al., 2011). The improper management practices of smallholders not only restrict the improvement of grain yield, and water and N use efficiencies (WUE and NUE), but also caused a series of

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environmental problems, such as groundwater nitrate contamination, surface water eutrophication, soil acidification, and air pollution (Guo et al., 2010; Ju et al., 2006; Liu et al., 2006; Zhu and Chen, 2002).

To improve grain yield, WUE, and NUE and reduce the environmental pollution caused by excessive N fertilizer application, a number of studies have been conducted to optimize the practices of irrigation and fertilization in the NCP (Chen et al., 2011; Fang et al., 2010a). Mack et al. (2005) found that optimized irrigation and fertilization practices could significantly reduce the losses of irrigation water and soil N (e.g., nitrate leaching and gaseous N emission). Hu et al. (2006) evaluated the management of water and N in a double cropping system using the root zone water quality model (RZWQM) in the NCP. Their study indicated that optimal economic, social, and environmental outcomes could be achieved by a reduction of approximately 50% in current water and N application rates. Wang and Huang (2008) used the RZWQM model to simulate irrigation (sewage water) and fertilizer management practices and obtained a preferable management practice. The RZWQM model was also used by Fang et al. (2010b) to explore irrigation strategies, and they found that the irrigation water ratio of 4:1 between wheat and maize seasons could improve the crop yield and WUE of the wheat–maize double cropping system in the NCP.

Recently, some new agricultural management practices have been suggested by agronomists for improving grain yield and resource (e.g., water and fertilizer) use efficiency (Jin et al., 2012; Lü et al., 2011a, 2011b). These management practices include cropping system, planting date, planting density, and tillage practice. Meng et al. (2012) compared the WUE and NUE of four cropping systems and found that both 2 year-three harvest system (winter wheat, summer maize, and spring maize rotation) and continuous monoculture (spring maize) system could reduce the application rates of water and N fertilizer. Jin et al. (2012) reported that the grain yield, N partial factor productivity, and NUE for direct-seeding summer maize were 67.0%, 104.0% and 53.5% higher than those for relay-intercropped summer maize, respectively. Sun et al. (2007) suggested that the net income and WUE obtained when maize is harvested at early October and when wheat is sown in the middle of October were greater than in those other treatments. Dai et al. (2013) found that increasing the seeding rate of winter wheat could enhance root length density, crop N uptake, grain yield, and NUE in Shandong Province. Ma et al. (2007) simulated crop production and N loss in drainage flow for different tillage practices and crop rotations in Nashua, IA. Their results showed that the amount of N lost in drainage flow decreased with the reduction of tillage intensity from moldboard plow to no-tillage.

Single management practice, such as irrigation, fertilization, tillage, cropping system, and cultivation, may play an important role in crop development, grain yield, resource use efficiency, and environmental effect. Apparently, integrating multiple management practices can be significant to current crop production systems. However, few studies have been devoted to the evaluation of crop growth, WUE, and NUE of the integrated management practices (irrigation, fertilization, and cultivation) in the winter wheat–summer maize double cropping system using a model approach. Moreover, a soil–crop system model, which is adopted to simulate crop growth under comprehensive management practices, such as combining planting density with irrigation and fertilization, is unavailable. Recently, a soil water, heat, carbon, and N simulation (WHCNS) model was developed based on a previous model (Hu et al., 2007, 2008). In the present study, irrigation, fertilization, and cultivation were integrated into different comprehensive management practices, and the WHCNS model was used to evaluate the crop yields, WUEs, and NUEs under four different integrated management practices.

The objectives of this study are: (i) to validate and apply the WHCNS model to assess water consumption and N fate under the four integrated management practices, and (ii) to evaluate the crop yields, WUEs and NUEs under the four practices and so as to recommend the best management practices (BMPs) among the four practices.

2. Materials and methods

2.1. Experimental site

Field experiments were conducted from October 2009 to June 2011 in Dawenkou research field (35°58′ N, 117°03′ E, 90 m above sea level), which is located in Tai'an City, Shandong Province of China. The region was characterized as a temperate continental monsoon climate. The annual mean temperature is 13 °C and the mean annual precipitation is 697 mm; 70%–80% of the annual precipitation occurs from July to September. The soil, developed from fluvial deposits, is classified as Aquic Cambisol (FAO/Unesco, 1988).

The rotation of winter wheat–summer maize is the most commonly practiced cropping system in this region. Groundwater is used for irrigation, and the common practice is flood irrigation, which was also used in this study.

Some fertility properties of the surface soil are as follows: soil organic matter (SOM), 16.7 g kg^{-1}; total N (TN), 1.01 g kg^{-1}; available phosphorous (AP), 52.65 mg kg^{-1}; and available potassium (AK), 96.15 mg kg^{-1}. Soil physical and hydraulic properties for a typical soil profile in the study area are listed in Table 1.

2.2. Experimental design

Four integrated management practices were designed to evaluate the utilization efficiencies of water and N: (1) traditional farming practices (FP); (2) optimized combination of cropping systems and fertilization (OPT-1); (3) practice for high yield (HY); and (4) further optimized combination of cropping systems and fertilization (OPT-2). The FP treatment followed local farmers' traditional planting mode. The two OPT treatments aimed to test the optimal combinations of planting methods, planting density, sowing and harvest dates, and fertilizer application period and rate. The HY treatment aimed to maximize grain yield by optimizing soil and management practices, regardless of the cost of resource inputs. The total experimental area was 24 m × 163 m, and the size of each plot was 6 m × 40 m. A randomized block design with four replications was used. A 1 m distance between neighboring blocks was ensured. The main crop varieties used in this region were cultivars 'Tainong 18' and 'Zhengdan 958' for winter wheat and summer maize, respectively. Table 2 presents the details on sowing dates, planting methods, planting densities, and field management.

The FP treatment was generally irrigated at the five development stages of winter wheat (i.e., emerging stage, wintering stage, turning-green stage, flowering stage, and jointing stage) with a water amount of 75 mm each time. The three other treatments were only irrigated four times (i.e., no irrigation was applied at the wintering stage). To ensure maize germination, plants in all four treatments were irrigated at the emerging stage.

The total fertilizer (urea) application rate data in the four treatments are given in Table 2. For winter wheat, the ratio of basal application and topdressing (jointing stage) of N fertilizer for the FP treatment was 5:5, whereas the ratio was 4:6 for the three other treatments. For the summer maize, no basal N fertilizer was applied for the FP and HY treatments, and the ratios of basal application and topdressing of N fertilizer were 2:5 and 1:5 for the OPT-1 and OPT-2 treatments, respectively. Each treatment received 90–180 kg P_2O_5 ha^{-1} (as calcium superphosphate)