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Exploring options to grow rice using less water in northern China using a modelling approach
II. Quantifying yield, water balance components, and water productivity

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ABSTRACT

Because of increasing competition for water, water-saving technologies such as alternate wetting and drying and aerobic rice are being developed to reduce water use while maintaining a high yield of rice. The components of the water balance of these systems need to be disentangled to extrapolate water savings at the field scale to the irrigation system scale. In this study, simulation modelling was used to quantify yield, water productivity, and water balance components of alternate wetting and drying and aerobic rice in the conjunctive surface-groundwater Liuyuankou Irrigation System, Henan, China. The study on aerobic rice was supported by on-farm testing.

In the lowland rice area, where groundwater tables are within the root zone of the crop, irrigation water savings of 200–900 mm can be realized by adopting alternate wetting and drying or rainfed cultivation, while maintaining yields at 6400–9200 kg ha^{-1}. Most of the water savings are caused by reduced percolation rates, which will reduce groundwater recharge and may lead to decreased opportunities for groundwater irrigation. Evaporation losses can be reduced by a maximum of 60–100 mm by adopting rainfed cultivation. In the transition zone between lowland rice and upland crops, groundwater tables vary from 10 cm to more than 200 cm depth, and aerobic rice yields of 3800–5600 kg ha^{-1} are feasible with as little as two to three supplementary irrigations (totaling 150–225 mm of water). Depending on groundwater depth and amount of rainfall, either groundwater recharge or net extraction of water from the soil or the groundwater takes place.

1. Introduction

The lower Yellow River Basin is one of China's important food-producing areas. Since rainfall is limited, crop growth depends heavily on irrigation from the Yellow River and, more recently, from groundwater. The Liuyuankou irrigation system (LIS) is a typical conjunctive surface-groundwater irrigation system in the lower Yellow River Basin (Loeve et al., 2003, 2004; Khan

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Shabaz et al., 2006). It is located in Kaifeng City Prefecture, about 70 km east of Zhengzhou, the capital of Henan province. It currently covers an area of about 56,000 ha of which about 31,000 ha is cropped. The 30-year average annual rainfall is about 670 mm, 70–80% of which falls between May and September. The groundwater in the area is recharged by rainfall, by percolating surface irrigation water, and by seepage from the canals and from the Yellow River itself. Upstream in LIS, there is ample surface irrigation water available and flooded lowland rice is grown on some 5000 ha in summer. In this area, seepage from the canals and the Yellow River, and percolation from the rice fields have resulted in relatively shallow groundwater tables. Downstream of the lowland rice area, the availability of surface water gradually diminishes and groundwater is pumped from shallow (usually down to 10 m) tubewells to irrigate upland crops such as corn, cotton, and soybean.

Concerns over water availability in LIS arise from decreasing water allocations from the Yellow River and from increasing water use by nonagricultural users (Loeve et al., 2004). Diversions from the Yellow River to Kaifeng City Prefecture decreased from 943 million m^3 in 1968–1978 to 392 million m^3 in 1989–2000. Industrial, municipal, and the livestock sectors increased their share of water use from 13% in 1968 to 37% in 2000. Kaifeng City prefecture responded by a large increase in groundwater extraction. In 1968, total groundwater use by all sectors was 151 million m^3, but by 2000, this had risen to 1153 million m^3. The large amounts of groundwater extraction now raise concerns of groundwater depletion (Loeve et al., 2004). In the rural areas, groundwater levels have been steadily going down by about 0.8 m between 1996 and 2002 in the upstream part and by about 2.8 m in the downstream part.

Because rice receives more irrigation water than other grain crops, water-saving irrigation technologies for rice are seen as a key component in any strategy to deal with water scarcity (Li and Barker, 2004). In 2001, a study was initiated in LIS to investigate the potentials of alternate wetting and drying (AWD) and aerobic rice to reduce the amount of irrigation water for rice while realizing high yields and increasing water productivity (Barker et al., 2004). In the context of LIS, it is important to quantify not only the reductions in irrigation water use, but also whether these arise from reductions in evaporation, transpiration, or percolation. Because of the shallow groundwater tables and heavy groundwater pumping, we can assume that a considerable fraction of water currently percolating from rice fields recharges the groundwater and is reused downstream. Therefore, on the one hand, reductions in percolation flows may be real water savings at the individual field level but may not translate into real water savings at the LIS level. On the other hand, evaporation is a real depletion flow and any savings in this component at the field level are also real savings at the system level. Therefore, the study aimed to quantify yield–water use relations, water productivity, and the components of the water balance of rice under different water table depths and under the different water-saving technologies. Since evaporation, transpiration, and percolation are not easily measured in the field, the study used a modelling approach supported by field experiments and farmers' trials. The rice growth model ORYZA2000 was parameterized using the experimental data (Feng et al., this issue) and then used to extrapolate the experimental results and to disentangle the components of the water balance at different groundwater depths. For aerobic rice, the scenario simulations were further evaluated against results from farmers' testing of the technology. In this paper, we present the results of the scenario analyses and of the farmers' trials.

2. Materials and methods

2.1. Scenario analyses

First, we used ORYZA2000 to estimate the yield potential of the lowland and aerobic rice systems without any limitations to water using 24 years of weather data from 1981 and 2004 obtained from Huibei station in the target area. For lowland rice, we used variety XD90247 transplanted on June 22 using 37-day-old seedlings, and for aerobic rice, we used variety HD297 dry seeded on July 1.

Second, we studied the effect of decreasing groundwater table depth on yield, water use, and water balance components of continuously flooded lowland rice and of aerobic rice with soil water content kept around field capacity (supposedly non-limiting conditions). Groundwater depths were 30, 60, 90, 120, 150 and 190 cm, and infinitely deep. For lowland rice, we used the soil parameters of the lowland rice area in LIS, and for aerobic rice, we used the soil parameters of the transition zone between lowland rice and upland crops where farmers pioneer the cultivation of aerobic rice (see Feng et al., this issue, for parameter values). All groundwater scenarios were run using the 24 years of weather data.

Third, we explored the effects of water-saving irrigation regimes on yield and water balance components under current groundwater table depths. For lowland rice, we simulated continuously flooded conditions, AWD with periods without ponded water on the surface ranging from 0 to 30 days with increments of 3 days, and purely rainfed conditions. The simulations were done with the groundwater table at 30 cm depth, representing current conditions in the area. For aerobic rice, water-saving regimes consisted of the application of 75 mm irrigation water when the soil water tension at 15–20 cm depth reached 10, 11, 12, . . ., 30 kPa. Groundwater tables were set at 60, 120, and 190 cm depth, as derived from the observations during our field experiments (Feng et al., this issue). We selected a relatively dry year, 1986, and a relatively wet year, 1984, for the simulations.

2.2. Calculations

The seasonal water balance of the root zone of a field is:

$$I + R + C = E + T + P + dS\,(\mathrm{mm}) \qquad (1)$$

where I is irrigation, R rainfall, C capillary rise into the root zone, E evaporation, T transpiration, P deep percolation beyond the root zone, and dS is the change in soil water storage. The rainfall was input from the weather data and all other components were simulated by ORYZA2000. For the seasonal water balance, the daily components were summed from transplanting till physiological maturity for lowland rice and from emergence till physiological maturity for aerobic