An agricultural decision support tool for wheat-maize cropping on the North China Plain based on a spatially-referenced biophysical process model of water, nitrogen and crop growth

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Abstract
The essential water and N fluxes for irrigated wheat-maize systems were quantified in a one hectare plot in Fengqiu County in the North China Plain (NCP). A spatially-referenced, process model (WNMM) was developed to simulate key water, carbon and nitrogen dynamics, crop growth and agricultural management practices. An agricultural decision support tool (ADST) based on WNMM dynamically coupled to a geographical information system (GIS) was developed to provide best management practices (BMPs) for irrigation and fertilizer use county-wide. Adoption of BMPs would reduce annual N fertilizer use by 20-23% and provide annual water savings of AUD10-45 per ha for no significant change in crop yield. The potential net benefits of the project were estimated at AUD216 million.

Key Words
Agricultural decision support tool, water and nitrogen dynamics.

Introduction

Irrigation and fertilizer use have contributed to the success of food production in China, particularly on the North China Plain (NCP), an important grain production base for China. However, there is growing concern about the environmental effects of intensive agriculture. Because of excessive use of water and nitrogen (N) fertilizer, groundwater resources have been over-exploited and nitrate (NO_3^-) concentrations in groundwater have risen to >50 mg NO_3-N L^{-1} (Norse and Zhu 2004). Emission of the greenhouse gas nitrous oxide (N_2O) have also increased, with agriculture now accounting for >60% of total N_2O emissions in China (Zheng *et al*. 2004). For sustainable high production, better management of water and N fertilizer is required, balancing both economic and environmental interests. Meeting this need requires a comprehensive understanding of the dynamics of water and N in the crop-soil system, the impact of soil and environmental variables and management practices on these dynamics, and socio-economic constraints. Such an understanding can be achieved through process-based simulation modelling, dynamically linked to a geographic information system (GIS), and leading to the identification of best management practices (BMPs) that can form the basis of an agricultural decision support tool (ADST).

We applied this approach to intensive wheat-maize rotations under irrigation on the NCP. This required comprehensive field measurements to quantify all essential water and N fluxes, the development of a spatially-referenced (GIS-based) biophysical model (WNMM), and development of a user-friendly ADST to help policy makers and advisers identify BMPs to improve farm productivity and regional environmental outcomes.

Methods

Field measurements

The project was carried out in Fengqiu County, Henan Province, which represented some of the major soil types in the NCP supporting irrigated wheat-maize rotations. The farmers sow winter wheat and summer maize in October and June and harvest in June and September, respectively. For wheat, N fertilizer is applied at sowing and in early spring at the rate of about 150 and 100 kg N/ha, respectively, and irrigations of 100 mm each are applied during the growing season. For maize, N fertilizer of 100 and 80 kg N/ha is applied in mid-July and August, respectively, usually followed by irrigations of 100 mm each. Groundwater was the main source of irrigation water.

A one ha (100 x 100 m) experimental plot (OHEP) was set up to carry out detailed field measurements of water and N fluxes and to parameterize the WNMM model. Some important properties of the dominant soil type are given in Table 1.

Table 1. Selected properties of the profile of the dominant soiltype at the experimental site.

Soil type[A]	Depth layer (cm)	pH (water)	Organic matter (g/kg)	Total N (g/kg)	Texture
Ochric Aquic Cambisol	0-20	8.5	10	1	Sandy loam
	20-60	8	7.3	-	Silty clay loam
	60-170	8	1.4	-	Loamy sand

[A]Research Group of China Soil Taxonomy System (1995)

Crop growth and changes in soil water content were measured and drainage losses below the root zone calculated from a daily water balance calculated for successive soil layers to 1.7 m depth. Nitrate concentrations in the soil solution, NH_3 volatilization, denitrification and N_2O emissions were measured directly. Soil temperatures at different depths were calculated from heat fluxes.

Development of the water and nitrogen management model (WNMM)

The WNMM model simulates key processes of water, C and N dynamics in the topsoil and subsoil during crop growth. Nitrogen fertilizer is an input and soil N transformations are simulated from the decomposition and mineralization of fresh crop residues and soil organic organic matter, microbial immobilization of N, nitrification, NH_3 volatilization, and denitrification leading to N_2O emissions. Three soil C pools are used: fresh residue C, microbial biomass C (living and dead), and humus C (active and passive in terms of mineralization).

A crop growth module was developed to simulate total crop dry matter, leaf area index, root depth and density distribution, harvest index, crop yield and N uptake. Agricultural management practices including crop rotation, method of tillage, stubble return, irrigation and any additional fertilizers were inputs to the simulation. The process model was fully integrated into a GIS by using a uniform data structure, ARC GRID ASCII format, which can be f operated both in the GIS environment and in the process model.

Development of the ADST

The spatially-referenced ADST was developed by simulating a large number of management scenarios and identifying the BMPs according to selected criteria. The selected criteria were expressed in terms of crop yield, irrigation water use efficiency (IWUE), nitrogen fertilizer use efficiency (NFUE), nitrate leaching, N_2O emission and total regional water use for agriculture. Because the concept of alleviating over-exploitation of water resources was difficult to quantify, the indicator ‘total regional water use for agriculture’ was adopted instead.

Results and applications

Developing and calibrating the WNMM model

WNMM ran at a daily time step at different scales, driven by lumped variables (climatic data and crop biological data) in text data format, and spatial variables (soil and agricultural practices) in ARC GRID ASCII data format. Figure 1 shows examples of simulated and measured variables for the OHEP at Fengqiu. There was good agreement for soil water storage, leaf area index, and NH_3 volatilization between 1 October 1998 and 30 September 2000, a period which covered two winter wheat and summer maize growing seasons. However, the correlation between simulated and measured evapotranspiration (ET) was weaker, partly because of the difficulty of obtaining reliable measurements of actual ET from lysimetry and the Bowen ratio method.

Development and applications of a GIS-based ADST

A user-friendly ADST was developed by simulating a large number of scenarios and selecting BMPs based on the evaluation criteria described above. Nominal weighing factors were allocated to each of these criteria. The ESRI MapObjects GIS component was used to manage the relevant spatial databases. The ADST is a GIS-based map display tool with a number of search/query functions for seeking site-specific BMPs. The performance of the cropping system under BMPs was compared with current practices, as determined from an extensive farmer survey.

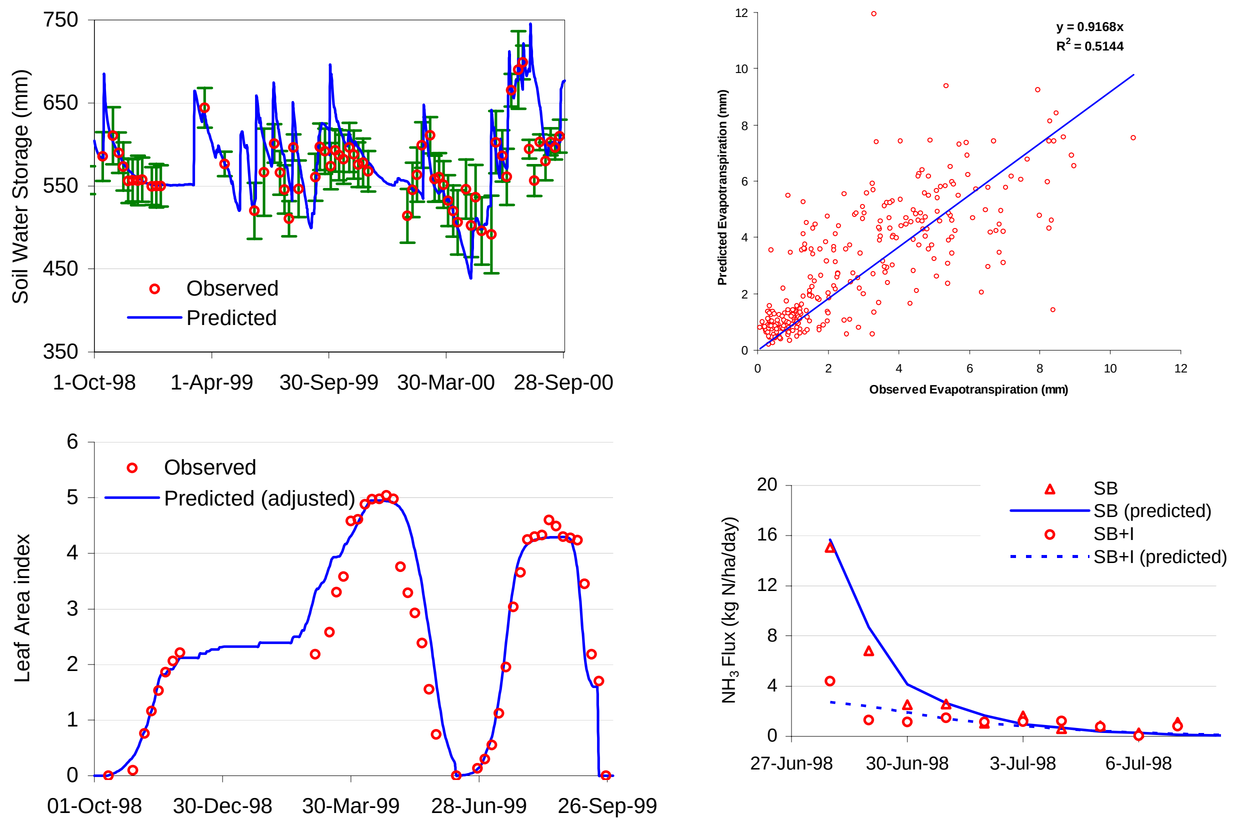

Figure 1. WNMM simulations and measured data of soil water storage (0-170 cm) (top left), actual ET (top right), leaf area index (bottom left), and NH_3 volatilization (bottom right) in the OHEP at Fengqiu County (SB denotes surface-broadcasting and SB+I surface-broadcasting immediately followed by irrigation) (Yong *et al*. 2007).

Applying BMPs identified by the ADST in Fengqiu County would result in a reduction of 115 kg /ha/year in fertilizer N (26% less than the average) and 150 mm/year of irrigation water (33% less than the average), while the average crop yield would be comparable to the current surveyed yield (Table 2). IWUE and FNUE would increase by 32% and 20%, respectively. Nitrate leaching and N_2O emission would be decreased by 60% and 25%, respectively. The potential reduction in irrigation water use would be 56 million m^3 for the whole county, which amounts to 13% of the total water used for agriculture. For an average sized farm, if recommendations on fertilizer use and irrigation were fully adopted, input costs would fall by 12-18% and income per household increase by 5%, equivalent to an increase in household income of AUD50-109 per year.

Table 2. Comparison of outcomes from current agricultural practices and BMPs provided by the ADST in Fengqiu County.

Indicators	Current practices	BMPs	
		Amount	Change (%)
Irrigation amount (mm)	450	300	-33%
Fertilizer amount (kg/ha)	450	335	-26%
Crop yield (kg/ha)	10300	10000	-3%
IWUE (kg/ha/mm)	25	33	32%
FNUE (kg/kg N)	25	30	20%
NO_3^- leaching (kg N/ha)	56	22	-60%
N_2O emission (kg N/ha)	24	18	-25%
Total in field water use for wheat-maize rotations (m^3 x 10^6)[A]	168	112	-33%

[A]The wheat-maize cropping area is 37,150 ha

Use of the ADST has facilitated the adoption of better management practices. The actual project benefit in the year of completion is summarized in Table 3, as reported by Harris (2004). The adoption rate for fertilizer advice was high at 55%, but adoption of irrigation advice was much lower at only 10%. About 95% of total project benefit comes from fertilizer savings and only 3% from water savings. The low adoption rate of irrigation advice is most likely due to the low water price in Fengqiu County, such that the cost of irrigation accounts for only 14%, while fertilizer accounts for up to 40%, of total input costs. The overall net benefits attributed to the project were estimated at AUD216 million (Harris 2004), which showed the significant poverty-reduction potential of the project.

Table 3. Project benefits in Fengqiu County by the year of completion, 2003-2004.

Cost saving per household after adoption	12-18%	Increase in income per household	5%
Adoption rate for fertilizer use	55%	Cost saving from fertilizer use (AUD million)	1.008
Adoption rate for irrigation	10%	Cost saving from irrigation (AUD million)	0.03
Total project benefit (AUD million)	1.04	Proportion of water saving in total county water use	13%

The change in benefit for crop yield was assumed to be zero

Conclusions and future directions

Both field measurements and WNMM simulations of water and N cycling showed excessive use of irrigation water and N fertilizer for wheat-maize rotations in Fengqiu County, NCP. Of the total N cycling in the soil-plant system, there was a surplus of about 20% in the soil after allowing for all the losses. Ammonia volatilization was the main pathway of N loss if fertilizer was surface broadcast. Nitrate leaching was as high as 82 kg N/ha/year, or 16% of the applied fertilizer. Denitrification loss was less significant in these light-textured soils, averaging 5% of applied N, of which 50% was lost as N_2O. BMPs derived from the ADST could reduce these losses with considerable cost savings. Catchment-based management is more appropriate than management based on local administrative units (villages and counties) and WNMM is being extended to a catchment scale by integration with a 3-D hydrological model. Climatic variability, particularly of rainfall, can also be incorporated into the ADST. A more comprehensive socio-economic component is being developed to take account of farmers' perceptions of the relative importance of farm productivity, profitability and environmental effects.

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