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A simulation model assisted study on water and nitrogen dynamics and their effects on crop performance in the wheat-maize system: (II) model calibration, evaluation and simulated experimentation

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Abstract The test on the model with data collected from two years' field experiments revealed an ability to satisfactorily simulate crop parameters such as LAI, biomass accumulation and partitioning, yield, and variables influencing crop growth and development as nitrogen uptake by crops and partitioning in different organs, and dynamics of soil water and nitrogen including infiltration and leaching. With the model, crop yield, water use efficiency (WUE), nitrogen use efficiency (NYE) and water-nitrogen leaching at specific soil layers under various water and nitrogen management practices were simulated to provide data used as references for designing sustainable nitrogen and water management practices.

The outputs of the simulated experiment with various treatments of irrigation and nitrogen application indicated that crop yield was closely related to water and nitrogen application, crop water use was positively related to irrigation amount, and nitrogen fertilization could improve the crop water use and WUE within certain limits. This is a valuable evidence to be considered in water-saving farming. Nitrogen uptake had a positive relation to nitrogen application, while irrigation to some extent improved its uptake by crops and hence increased NYE. Additionally, irrigation and fertilization had great effects

on nitrogen leaching. Thus, in order to improve WUE and NYE, the model showed how nitrogen application and irrigation should be well coordinated.

Keywords wheat, maize, cropping system, water, nitrogen, simulation, model

1 Introduction

Water scarcity has become a limiting factor for sustainable development of agriculture in the North China Plain where irrigation contributes more than 70% to the total water consumption. In Hebei Province, with the available water resources per unit land area and per capita of 1/7 and 1/9 of the national total, and the average precipitation of 536 mm, however the depletion of groundwater exceeded the recharge capacity by $1.2 \times 10^{10} \text{ m}^3$ in 2005. The ground water tables are declining 1–2 m each year in plain areas of the province. Because 70% of the total rainfall occurs between July and September, while that during the wheat growing season from the beginning of October to the middle of June next year is only 100–180 mm, and therefore, the irrigation is crucial for wheat production to achieve a satisfactory output.

Wheat (*Triticum aestivum* L.)-maize (*Zea mays* L.) double cropping is the major cereal production system of the region, and with its average water use efficiency (WUE) being only $1.1\text{--}1.3 \text{ kg} \cdot \text{m}^{-3}$ (Hu, 2005; Liu, 2005) there is a great potential to increase yield and WUE in the cropping system (Liang et al., 2006). Untimely sowing or planting, unbalanced fertilization, improper sowing rate or planting density and poor irrigation practice are the major problems limiting crop yield and WUE in the system. Soil- and season-specific recommendations are urgently required for irrigation and fertilization. The current situation of water resources and over application of

Received June 19, 2008; accepted November 26, 2008

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nitrogen has made water and nitrogen management be the key factors for sustainable development of wheat-maize cropping system in Hebei Plain areas. However, due to the complexity of conducting experiments, there has been little in-depth research that maintains a system perspective and approach, in considering the two crops as components interacting with each other and soil-crop-management correlation under specific climate conditions.

Simulation modeling may offer powerful tools to assist research at a system level. Here, we calibrated the model introduced in the former part of this paper against two-years' field data and evaluated its reliability in simulating water and nitrogen dynamics in wheat-maize cropping systems under various management practices. The model was built to simulate the water and nitrogen dynamics in component soil layers to 2 m depth and was thus appropriate to assess the characteristics of sound water and nitrogen management practices.

2 Model calibration and evaluation

2.1 Model calibration

After the model was built, submodels were run individually and possible reasons were sought for any large differences between the measured data and simulated output (Liang et al., 2007). Then relevant parameters were adjusted sequentially within a range specific to crop or soil

conditions, commencing with the most sensitive parameter that caused the biggest difference in the submodel output. This procedure of adjustment continued until the output of the submodel was well compared with measured data. All submodels were calibrated following this procedure. Crop parameters were calibrated by running the model under conditions without nitrogen and water stresses; parameters related to soil water regime were adjusted by running the model without nitrogen stress. The whole model was run to calibrate the parameters related to nitrogen. Each procedure of model calibration was recorded in detail to avoid random adjustment of parameters. Parameters derived from data observed or measured in the experimental plots that fell in the reasonable range set to specific crop or soil conditions were not adjusted.

2.2 Experimental data for model calibration and evaluation

The experiments were conducted in Xinji county of Hebei Province in the northwest part of North China Plain for two years from the years 1997 to 1998 and 1999 to 2000 (Wang, 1999; Lü, 2001).

2.2.1 Field conditions at the experimental site

Soil characteristics of the experimental field and precipitation are listed in Table 1 and Table 2, respectively. The ground water table is 50 m below soil surface.

Table 1 Soil characteristics of the experimental field

depth/cm	texture	BD/(g·cm ⁻³)	OM/%	AN/ (mg·kg ⁻¹)	AP/ (mg·kg ⁻¹)	AK/ (mg·kg ⁻¹)	TN/%	FC/mm	soil retention curve ($S = A\theta^B$)	
									A	B
0–30	CL	1.4	1.12	43.226	40.85	96.47	0.082	117.6	1.71E3	-5.7
30–40	CL	1.47	0.91	30.816	20.23	90.32	0.089	55.89	1.28E3	-9.99
40–65	SL	1.32	1.04	20.468	10.93	86.76	0.054	100.70	2.10E3	-5.2
65–71	CL	1.33	0.95	21.123	9.59	86.31	0.051	33.53	1.53E3	-7.8
71–90	SL	1.38	0.90	22.535	6.35	87.52	0.050	76.10	3.05E4	-4.78
90–118	CL	1.42	0.79	20.000	3.44	78.00	0.033	112.11	1.28E3	-9.99
118–160	C	1.33	0.65	15.320	2.89	26.05	0.032	164.6	1.28E3	-9.99
160–200	S	1.39	0.5	10.000	2.22	15.32	0.028	160.00	3.68E3	-3.77

Note: CL, SL, C, S, BD, OM, AN, AP, AK, TN and FC represent clay loam, sandy loam, clay, sand, bulk density, organic matter, available nitrogen, available phosphorus (P₂O₅), available potassium (K₂O), total nitrogen and field capacity, respectively.

Table 2 Precipitation during the experimental years (mm)

year	Jan.–Mar.	April	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.	annual
1997	66	1.88	27.6	22.3	21.6	26.4	46.4	19.7	9.3	7.8	249.0
1998	21.6	22.6	66.4	22.9	71.4	84.3	1.3	10.6	0.2	0.0	301.3
1999	0.5	7.8	43.2	23.3	54.0	96.3	25.4	22.4	16.2	0.0	289.1
2000	3.1	9.65	29.7	33.5	248.0	34.5	84.6	15.0	13.4	7.9	479.8
30-yr ave.	20.0	22.1	28.1	53.4	147.5	137.3	46.8	27.3	12.0	3.4	498.0

2.2.2 Design of experiments

In experimental year of 1997–1998, three irrigation levels were applied to wheat including the control group with no irrigation during the growing season, only one irrigation at stem elongation, and two irrigations, one each at stem elongation and flowering, respectively. Maize was irrigated once at the 12-leaf stage. Fertilization comprised $225 \text{ kg} \cdot \text{hm}^{-2} \text{ P}_2\text{O}_5$ and $180 \text{ kg} \cdot \text{hm}^{-2} \text{ K}_2\text{O}$ applied to wheat as basal application together with half of the nitrogen rate of $375 \text{ kg} \cdot \text{hm}^{-2}$. The second half of the nitrogen was top-dressed at stem elongation. Nitrogen, phosphorus and potassium application rates on maize were the same to those on wheat but timing of N application was different. All phosphorus and potassium were applied at seedling stage while nitrogen was applied 20% at seedling and 80% at 12-leaf stage. Irrigation and nitrogen application rates are listed in Table 3. The cultivars were Henong 859 for wheat and Hudan 4 for maize. There were three replications in randomized block design with plot size of 35 m^2 . There was a 3 m wide buffer between plots to prevent horizontal water movement.

In the experimental year of 1999–2000, there were three irrigation and four nitrogen levels as presented in Table 4. Wheat was sown on October 27, 1999 and harvested on June 15, 2000, while maize was sown on June 22 and harvested on October 2, 2000. Wheat was irrigated twice during growing period: once at stem elongation and the other between heading and flowering, with no irrigation applied to maize. $400 \text{ kg} \cdot \text{hm}^{-2} \text{ P}_2\text{O}_5$ and $400 \text{ kg} \cdot \text{hm}^{-2} \text{ K}_2\text{O}$ were applied before wheat sowing, with no P and K applied to maize. Half of nitrogen for wheat was applied as basal application and the other was top-dressed

at stem-elongation. For maize half was applied at seedling stage and the other at 12-leaf stage. Wheat cultivar was Lankao 906 and maize Ludan 14. Three replications were designed for each treatment level with randomized block designed and plot size of $5 \text{ m} \times 7 \text{ m}$.

2.2.3 Data collection

The soil moisture content at various soil layers to 200 cm depth in the plots was measured every 10 days by using a neutron probe in the years 1997–1998 and TDR (time domain reflectometry) in 1999–2000. Both instruments were calibrated by the correlation to data measured with the classical drying-and-weighing method.

The soil $\text{NO}_3^- \text{-N}$ content was measured with phenoldisulfonic acid colorimetry (Institute of Soil Science and Chinese Academy of Sciences, 1978) by taking soil samples from various layers to 200 cm depth before wheat and maize sowing, after stem elongation and after irrigation, respectively.

The crop biomass was measured by taking five to twenty plants (smaller number for larger plants) from each plot which were separated into green leaves, dead (yellow) leaves, stems and sheaths, and ears, dried in an oven at 105°C for 30 min and then at 80°C for 48 h, or until there was no weight change. The individual parts were weighed separately and retained for total nitrogen measurement.

The total nitrogen content in crop organs was measured with the diffusion and titration method (Institute of Soil Science and Chinese Academy of Sciences, 1978) by grinding the dried crop samples and digesting them in $\text{H}_2\text{SO}_4\text{-H}_2\text{O}_2$ to extract nitrogen.

Table 3 Irrigation and nitrogen treatments (1997–1998)

item	winter wheat		summer maize		annual	
	irrigation /mm	nitrogen rate /($\text{kg} \cdot \text{hm}^{-2}$)	irrigation /mm	nitrogen rate /($\text{kg} \cdot \text{hm}^{-2}$)	irrigation /mm	nitrogen rate /($\text{kg} \cdot \text{hm}^{-2}$)
I	88	375	90	375	178	750
II	88 + 60	375	90	375	238	750
III	0	375	90	375	90	750

Table 4 Irrigation and nitrogen treatments (1999–2000)

treatment	winter wheat		summer maize		annual
	irrigation /mm	nitrogen rate /($\text{kg} \cdot \text{hm}^{-2}$)	nitrogen rate /($\text{kg} \cdot \text{hm}^{-2}$)	irrigation /mm	nitrogen rate /($\text{kg} \cdot \text{hm}^{-2}$)
I1F0	60 + 135	0	0	195	0
I1F1	60 + 135	100	100	195	200
I1F2	60 + 135	200	200	195	400
I1F3	60 + 135	300	300	195	600
I2F2	60 + 90	200	200	150	400
I2F3	60 + 90	300	300	150	600

2.3 Test and evaluation of the model

Model outputs and soil variables were compared with the experimental data from several treatment levels to evaluate the performance of simulated crop.

2.3.1 Test of the phenostage sub-model

Results of observed and simulated phenostages are listed in Table 5. The comparison shows that the sub model performs well. The difference between simulated and experimental data is not significant ($\chi^2_{0.05,4} = 9.493$, $\chi^2_{0.05,3} = 7.81$, $\chi^2_{0.05,5} = 11.07$).

2.3.2 Test of the sub-model of biomass production and partitioning

2.3.2.1 Yield of the crops

Simulated and observed yields of the various treatments are listed in Table 6. Simulated and observed data accord well with each other except for wheat in treatments I (one irrigation at stem-elongation and adequate nitrogen supply) in 1997–1998 and in I1F0 (no nitrogen but adequate irrigation) in 1999–2000. Apart from possible sampling errors in the experiment, the explanation might be that the timing of irrigation on yield formation is underestimated in this model.

Table 5 Comparison of simulated and observed phenostage dates

crop	phenostage	observed	simulated	difference	χ^2_c	$\chi^2_{c,4}$
wheat Henong 859	S	25/10/1997	25/10/1997	–	–	
	E	9/11/1997	7/11/1997	–2	0.0181	
	SE	10/04/1998	09/04/1998	–1	0.1111	
	H	28/04/1998	28/04/1998	0	0	
	F	02/05/1998	01/05/1998	–1	0.0323	
	M	07/06/1998	06/06/1998	–1	0.0149	0.1764
maize Ludan 14	S	15/06/1998	15/06/1998	–	–	$\chi^2_{c,3}$
	E	21/06/1998	20/06/1998	–1	0.0500	
	SE	14/07/1998	12/07/1998	–2	0.0952	
	T	06/08/1998	06/08/1998	0	0	
	M	10/10/1998	12/10/1998	2	0.0299	0.1751
wheat Lankao 906	S	28/10/1999	28/10/1999	–	–	$\chi^2_{c,5}$
	E	12/11/1999	13/11/1999	1	0.00632	
	SE	09/04/2000	08/04/2000	–1	0.00432	
	H	30/04/2000	01/05/2000	1	0.00410	
	F	03/05/2000	04/05/2000	1	0.00408	
	M	12/06/2000	15/06/2000	3	0.09398	0.1775
maize Ludan 14	S	22/06/2000	22/06/2000	–	–	$\chi^2_{c,4}$
	E	27/06/2000	26/06/2000	–1	0.00368	
	SE	19/07/2000	18/07/2000	–1	0.00354	
	T	18/08/2000	16/08/2000	–2	0.03030	0.1760
	M	30/09/2000	01/10/2000	1	0.00312	

Note: S, E, SE, H, F, M and T represent sowing, emergence, stem-elongation, heading, florescence, mature and tasseling, respectively.

Table 6 Comparison of simulated and observed yields in various treatments ($\text{kg}\cdot\text{hm}^{-2}$)

crop		treatment (1997–1998)			treatment (1999–2000)			
		I	II	III	I1F0	I1F1	I1F2	I1F3
winter wheat	simulated	6222	6248	3039	5402	6037	6004	5304
	actual	5840	6365	3678	5800	6030	5957	5298
	error/%	–6.56	1.50	–4.38	6.86	–0.12	–0.78	–0.28
summer maize	simulated	7213.2	7840	6634.5	4952	8184	8631	8301
	actual	7285.8	7639	6525.9	5213	8150	8445	7957
	error/%	0.996	–2.63	–1.66	5.00	–0.42	–1.71	–4.32

2.3.2.2 LAI and biomass accumulation

The simulated and the measured LAI and biomass were well compared in the two years, indicating good performance of the model in simulating these two variables (Figs. 1–3). The small difference between the simulated and measured data might be caused by sampling error and/or pest and disease damage on the sampled crops.

2.3.3 Testing soil water and nitrogen sub-models

Soil water and nitrogen contents at sowing were set at the initial condition for simulation. Comparisons of simulated and measured data are presented in Figs. 4–9. The bigger difference between the measured and simulated data than that of the observed data was not unusual for crop. The variation in soil water and nutrient content measurements

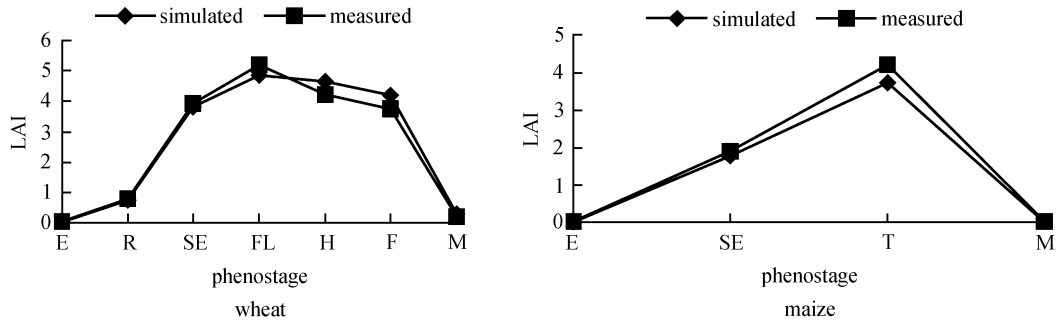


Fig. 1 Comparison of simulated and measured LAI (II 1997–1998)

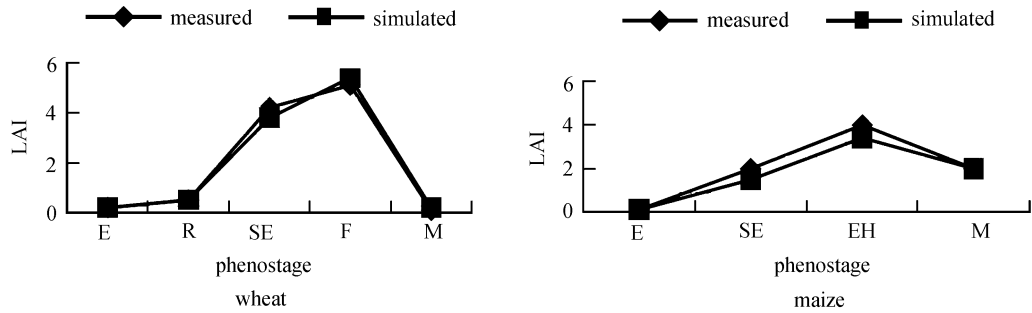


Fig. 2 Comparison of simulated and measured LAI (II F2 1999–2000)

Note: R, FL and EH represent green-recovering, flagging and ear-heading, respectively.

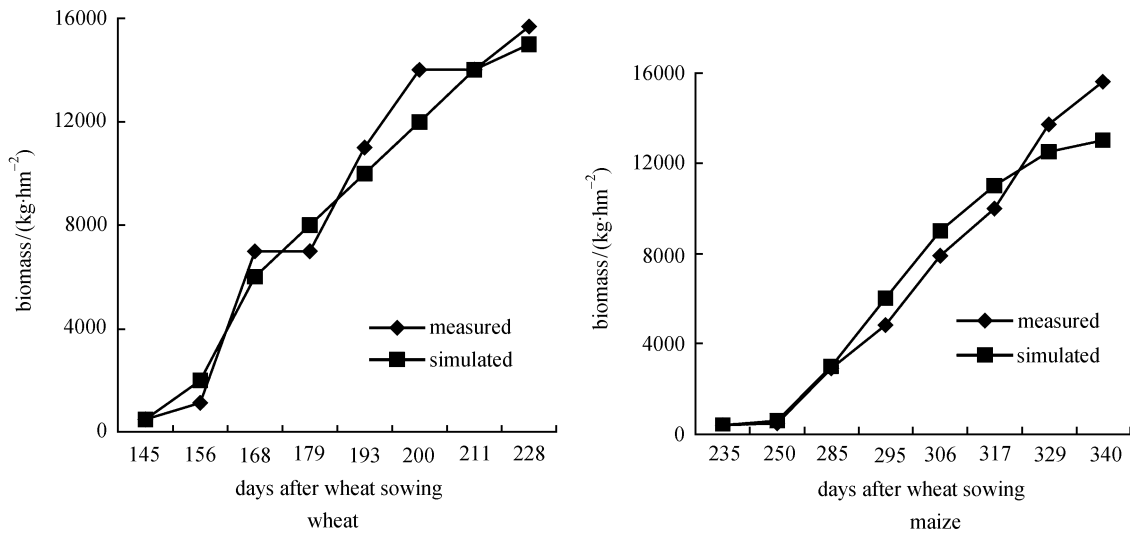


Fig. 3 Comparison of simulated and measured biomass (II F2 1999–2000)

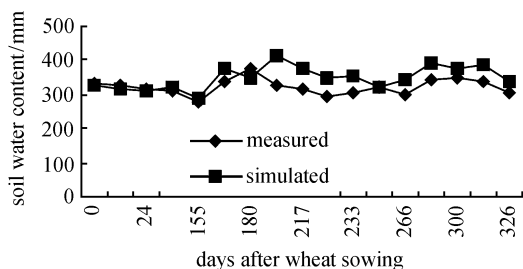


Fig. 4 Comparison of simulated and measured soil moisture content in treatment level II at 120 cm soil depth (1997–1998)

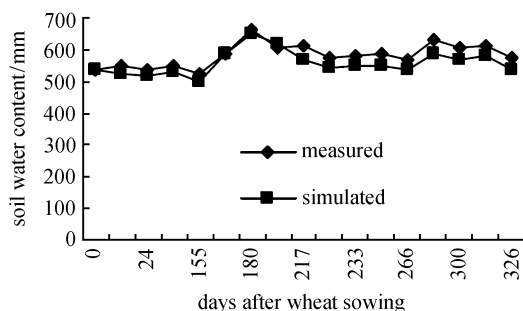


Fig. 5 Comparison of simulated and measured soil moisture content in treatment level II at 200 cm soil depth (1997–1998)

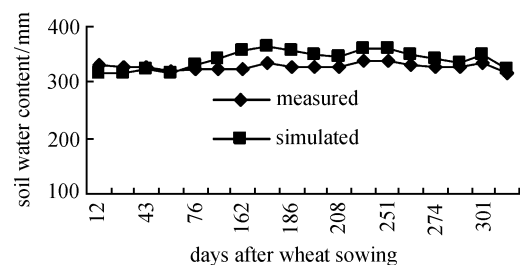


Fig. 6 Comparison of simulated and measured soil moisture content in treatment level IIF2 at 120 cm soil depth (1999–2000)

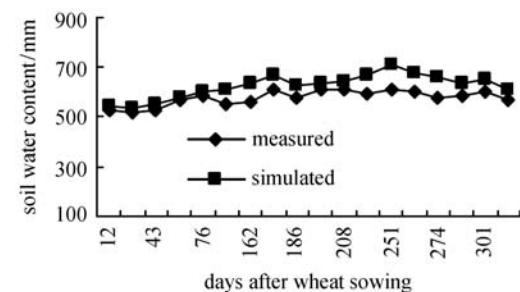


Fig. 7 Comparison of simulated and measured soil moisture content in treatment level IIF2 at 200 cm soil depth (1999–2000)

was usually much greatly resulted from the spatial variation in field and the additional steps of laboratory chemical analysis. Given that, the result was satisfactory except for topsoil, for which the variation cannot be explained.

Effects of rainfall and irrigation on soil water, and effects of irrigation and fertilization on soil NO_3^- -N can be seen in Figs. 4–9. The dates of the two irrigations are marked on days 158 and 188 and the three fertilizations on days 158, 273 and 284, respectively. It can be seen from the soil water dynamics illustrated in Fig. 8 that the 2nd irrigation of 135 mm increased the soil moisture content in the subsoil significantly. In the dynamics of soil NO_3^- -N illustrated in Fig. 9, the 1st irrigation of 60 mm and the 1st fertilization of $150 \text{ kg N}\cdot\text{hm}^{-2}$ increased NO_3^- -N content at all soil layers, and the top layer changed the most. After the 2nd irrigation, apparent leaching was observed in the 0–70 cm profile together with NO_3^- -N accumulation in 90–200 cm soil layers. There was no irrigation during the grow-ing period of maize. NO_3^- -N content in the top 0–40 cm increased after top-dressing with nitrogen fertilizer while autumn rainfall moved it to the layers below 40 cm.

2.3.4 Testing nitrogen uptake and allocation of sub-model

Simulated and measured nitrogen contents in leaf and grain are compared in Fig. 10 and Fig. 11, respectively. The results are satisfactory for the reasons mentioned above—the model performs well in simulating crop nitrogen uptake and partitioning.

3 A virtual experiment with the model

A virtual experiment with treatments of widespread water and nitrogen application rates was designed to examine effects of irrigation and fertilization at various crop phenostages and application rates on yield, WUE and NYE, for which the model was run with the designed irrigation and fertilization data to provide outputs.

3.1 Treatment levels of the virtual experiment

Timing of irrigation and fertilization during wheat–maize growing is a current popular practice in the North China plain.

A pre-sowing irrigation of 90 mm was given to wheat in each of the following four treatments: I_1 —one irrigation at stem elongation; I_2 —irrigations at stem elongation and heading; I_3 —irrigations at stem elongation, heading and grain filling; I_4 —irrigations before winter, at stem elongation, heading and grain filling, while a 40 mm irrigation was given to maize before sowing, without any subsequent irrigation.

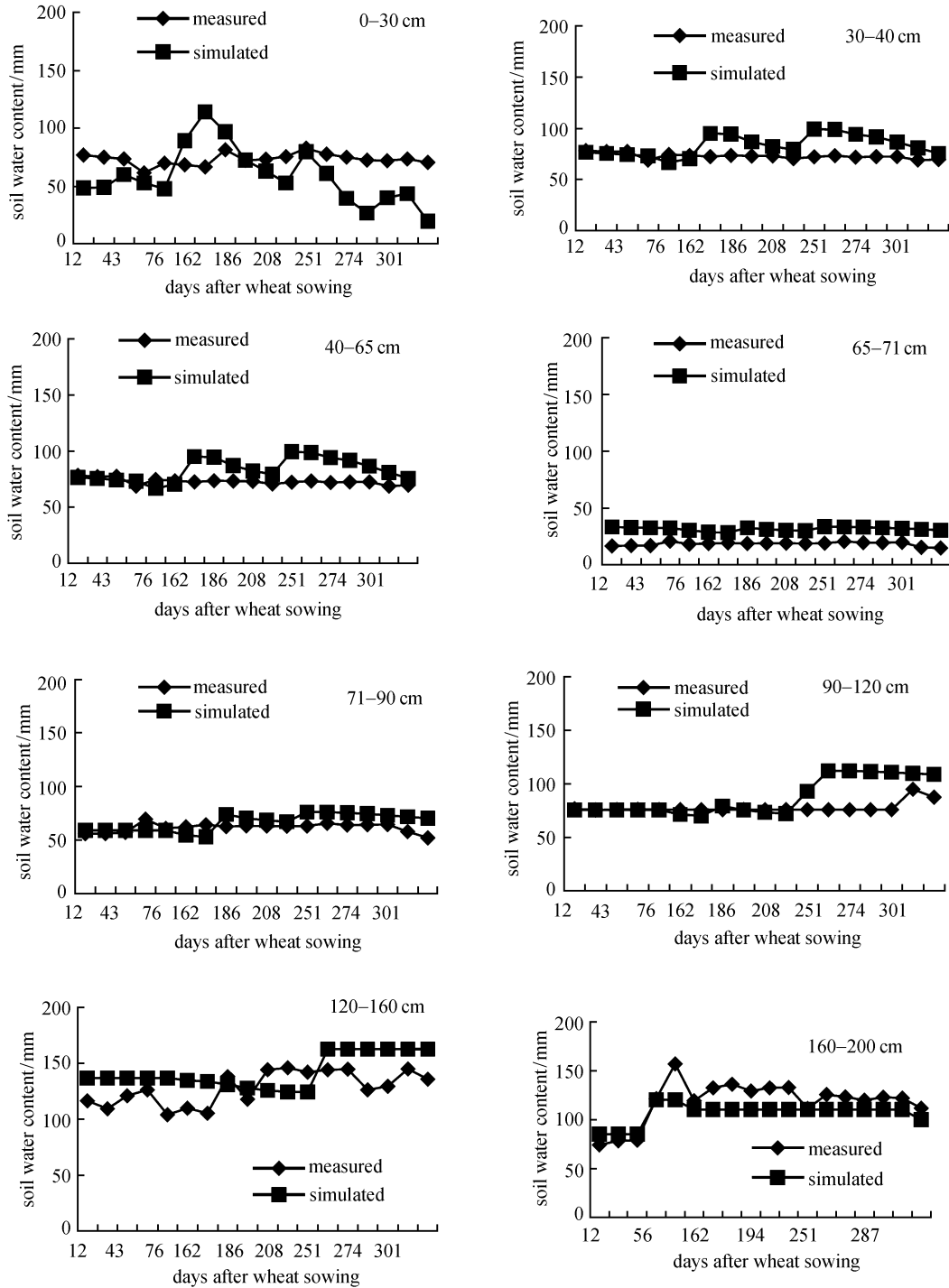


Fig. 8 Comparison of simulated and measured moisture content at different soil layers in treatment I1F2 (1999–2000)

The rates of fertilization for wheat and maize were the same in the experiment in 1997–1998, with the same potassium and phosphorus in the experiment in 1999–2000. Half of nitrogen for wheat was applied before sowing and the rest was topdressed at stem elongation together with irrigation. For maize, half of nitrogen was topdressed at seedling stage and the remainder at 12-leaves stage. Details of the treatment levels are listed in Table 7.

3.2 Results and analysis of the virtual experiment

3.2.1 Yield, WUE and NYE corresponding to different treatment levels

Simulated yield, WUE and NYE of the various water and nitrogen management strategies for the climate pattern in the year of 1999–2000 are presented in Tables 8, 9 and 10,

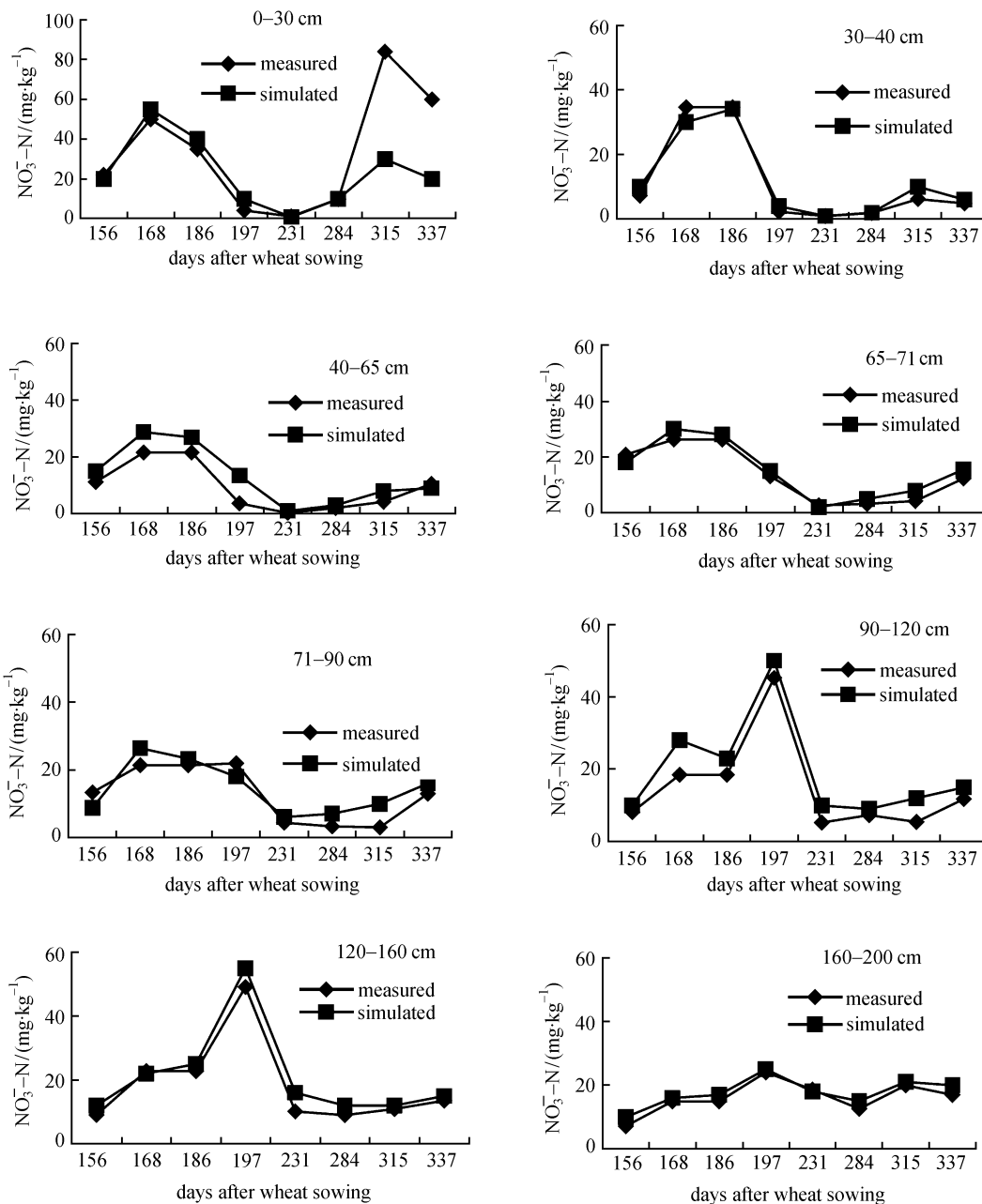


Fig. 9 Comparison of simulated and measured NO_3^- -N content at different soil layers in treatment I1F2 (1999–2000)

Table 7 Treatment details of the virtual experiment

treatment		winter wheat		summer maize		annual
		total	composition	total	composition	
irrigation/mm	I1	180	90 + 90	40	40	230
	I2	270	90 + 90 + 90	40	40	310
	I3	360	90 + 90 + 90 + 90	40	40	400
	I4	450	90 + 90 + 90 + 90 + 90	40	40	490
N fertilization/(kg·hm ⁻²)	F1	100	50 + 50	100	50 + 50	200
	F2	200	100 + 100	200	100 + 100	400
	F3	300	150 + 150	300	150 + 150	600
	F4	400	200 + 200	400	200 + 200	800

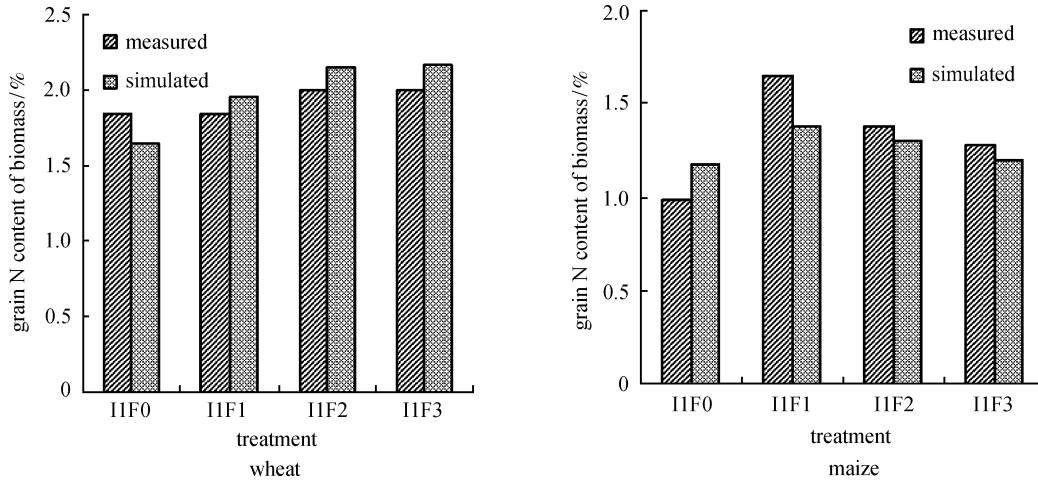


Fig. 10 Simulated and measured grain nitrogen content in different treatment (1999–2000)

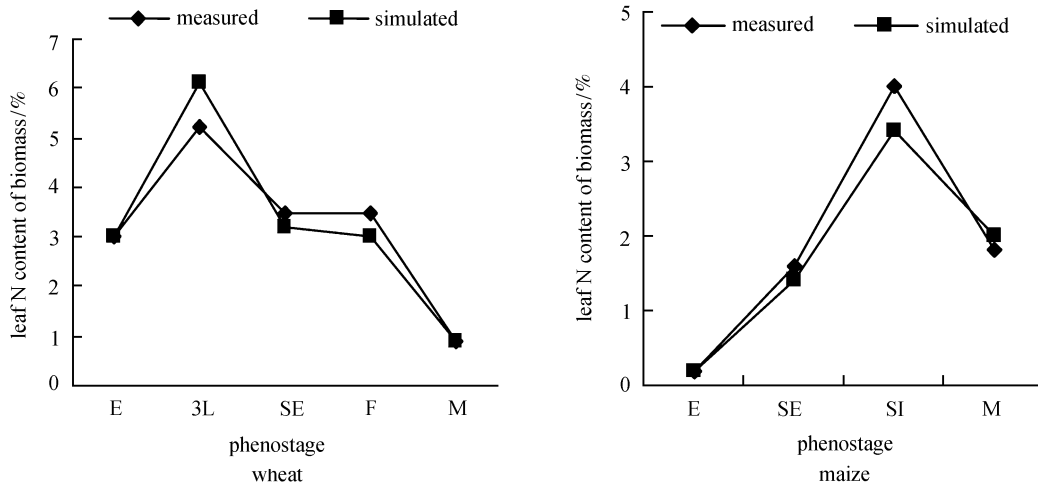


Fig. 11 Simulated and measured leaf nitrogen content in treatment IIF2 (1999–2000)

Note: 3L is 3 leaves and SI is silking.

respectively. It can be seen in Table 8 that crop yields increase with the increase of irrigation amount and fertilization rate. The highest wheat yield and annual yield of wheat-maize double cropping were achieved in treatment level I₃F₃, while the highest yield of maize was achieved with the treatment of I₄F₃. Variance analysis on wheat and maize yields reveals that wheat yield is sensitive to irrigation and nitrogen fertilization while maize yield is only sensitive to nitrogen application since there is no irrigation during maize growth and rainfall was adequate. This result demonstrates the reliability of the simulation method in another way with evidence on wheat seen in Table 8. At lower N application levels, the maximum yield appears at a low irrigation level and with less irrigation, and the maximum yield by N application appears at a low nitrogen rate. In irrigation treatment I₁, the wheat yield declines at nitrogen level F₃, whilst in irrigation treatments I₂, I₃ and I₄ the crop yield continues to increase up to

nitrogen level F₄. Under nitrogen levels of F₁ and F₂, the wheat yield declines at irrigation level I₃, while under nitrogen levels F₃ and F₄, the yield keeps increasing until irrigation treatment I₄. The maize yield increases with the increase of nitrogen rate and irrigation until irrigation treatment level I₄ and nitrogen level F₄. Since there is a big interval between these nitrogen treatment levels, the actual levels at which the crop yield declines may be lower or higher than those observed in this experiment (Zhang et al., 2005).

The simulated WUE and crop water use (ET) of the various treatments are listed in Table 9. It can be seen that the ET during wheat growth and the annual ET are positively relative to amount of irrigation, while WUE initially increases with the increase of irrigation amount but the relationship becomes negative when irrigation amount exceeds 360 mm. There is an interaction between water and nitrogen that affects crop water use and WUE.

Table 8 Simulated crop yields under various water and nitrogen treatment levels ($\text{kg} \cdot \text{hm}^{-2}$)

crop	treatment	F1	F2	F3	F4	F-test
wheat	I1	4822	5283	5077	4203	$F_{\text{row}} > F_{0.05}$
	I2	5412	6056	6032	5341	$F_{\text{column}} > F_{0.05}$
	I3	5170	5996	6155	5646	
	I4	4095	5104	5445	5119	
maize	I1	6359	7680	8293	8198	$F_{\text{column}} > F_{0.05}$
	I2	6523	7773	8315	8150	
	I3	6680	7860	8331	8094	
	I4	6830	7939	8339	8032	
annual	I1	11181	12963	13370	12401	
	I2	11935	13829	14347	13491	
	I3	11850	13856	14486	13740	
	I4	10925	13043	13784	13151	

Table 9 Crop water use and WUE under various water and nitrogen treatments

crop	treatment	F1		F2		F3		F4	
		WUE	ET	WUE	ET	WUE	ET	WUE	ET
wheat	I1	11.88	405.8	13.04	405.0	12.54	404.9	10.36	405.6
	I2	12.43	435.4	14.00	432.5	13.90	433.9	12.13	440.1
	I3	11.17	462.9	13.15	456.0	13.46	457.3	12.10	466.7
	I4	8.10	505.7	10.49	486.7	11.21	485.9	10.25	499.2
maize	I1	15.68	405.5	18.96	405.1	20.52	404.1	20.36	402.6
	I2	16.08	405.5	19.19	405.0	20.57	404.1	20.25	402.4
	I3	16.48	405.4	19.41	404.9	20.62	403.9	20.12	402.2
	I4	16.85	405.4	19.61	404.8	20.65	403.8	19.97	402.1
annual	I1	13.78	811.3	16.00	810.1	16.53	809.1	15.34	808.2
	I2	14.19	840.9	16.51	837.5	17.12	838.1	16.01	842.5
	I3	13.65	868.3	17.11	809.9	16.82	861.3	15.81	868.9
	I4	11.99	911.1	14.63	891.5	15.49	889.7	14.59	901.3

Note: WUE is in $\text{kg} \cdot \text{hm}^{-2} \cdot \text{mm}^{-1}$, and water use is in mm.

Table 10 Simulated NYE and nitrogen uptake of different water and nitrogen treatments

crop	treatment	F1		F2		F3		F4	
		NYE	NU	NYE	NU	NYE	NU	NYE	NU
wheat	I1	35.18	137	34.04	155	31.19	163	26.65	164
	I2	35.7	152	35.16	172	35.45	183	29.97	184
	I3	29.62	174	29.70	201	28.07	219	24.75	228
	I4	16.95	241	17.63	289	16.62	328	13.91	368
maize	I1	19.81	321	21.62	355	21.81	380	20.38	402
	I2	20.07	325	21.71	358	21.74	382	20.15	404
	I3	20.30	328	21.78	361	21.65	384	19.90	407
	I4	20.53	333	21.84	363	21.55	387	19.64	409
annual	I1	24.41	458.0	25.42	510.0	24.62	543.0	21.91	566.0
	I2	25.02	477.0	26.09	530.0	25.39	565.0	22.94	588.0
	I3	23.61	502.0	24.65	562.0	24.02	603.0	21.64	635.0
	I4	19.03	574.0	20.00	652.0	19.28	715.0	16.93	777.0

Note: NYE is in $\text{kg} \cdot \text{kg}^{-1}$ and NU is in $\text{kg} \cdot \text{hm}^{-2}$.

The highest WUE on wheat is achieved by treatment F_3I_3 while the highest annual WUE of the cropping system is obtained with both F_3I_2 and F_2I_3 . Under all irrigation levels, WUE of maize increases with the increase of nitrogen application, up to the rate of F_4 when both yield and WUE of maize declines.

Nitrogen uptake (NU) and NYE of water and fertilizer treatment levels are listed in Table 10 revealing that nitrogen uptake is positively relative to nitrogen fertilization and irrigation amount for whole wheat-maize double cropping system.

NYE of maize is mainly determined by the rate of nitrogen fertilization since there is relatively adequate rainfall and little or no irrigation during maize growth. NYE increases with the increase of nitrogen application to $300 \text{ kg} \cdot \text{hm}^{-2}$, but then declines.

According to a survey covering 389 wheat-maize farming households, the average nitrogen application rate of the cropping system in the area is $498.5 \text{ kg} \cdot \text{hm}^{-2}$, of which 61% is given to wheat and 39% to maize (Liang et al., 2006). Usually there is very little variation in irrigation and fertilization of wheat between years, but there is a great variation in irrigation of maize caused by variability in rainfall during the maize season. The average irrigation frequency in the area is 3.5 and 2.3 for wheat and maize respectively. The year 2005 was droughty, so the irrigation frequency on maize is much higher than usual.

3.2.2 Water drainage and nitrogen leaching

Water flow through the soil profile is directly affected by irrigation amount, while leaching of nitrogen is affected by fertilization rate also. With the designed treatment levels in

this simulation experiment and under the average rainfall pattern, simulated water and nitrogen flow at 90 cm soil depth are shown in Fig. 12. The result from the same fertilization rate but different irrigation amounts is shown in Fig. 12(a). It can be seen that the down flow of water and nitrogen increases with the increase of irrigation amount, and the increase of down flow of water and nitrogen during wheat growth is more significant than that during maize growing period, because there is little irrigation during maize growing, single rainfalls are light and hence the difference in down flows is caused mainly by the difference in wheat. Nitrate down flow in wheat growing in a dry and cool weather ranges from 120 to $190 \text{ kg} \cdot \text{hm}^{-2}$ while it ranges from 220 to $237 \text{ kg} \cdot \text{hm}^{-2}$ in maize growing under a hot and rainy climate. Simulated water and nitrate down flows at different fertilization rates with same irrigation amount are shown in Fig. 12(b). It can be seen that nitrate down flow increases with the increase of fertilization rate, while there is no significant variance of water down flow with the change of fertilization rate—the minor differences are caused by the differences in evapotranspiration.

The simulated down flow of water and nitrate at 200 cm soil depth showed that there was no drainage of water and leaching of nitrate below the soil layer in all treatment levels, but the water down flow occurred below 160 cm soil depth during maize growing period with 3 or 4 times of irrigation in wheat. In these cases, there was a small water down flow of 78.6 mm or less, and a nitrate down flow of $50 \text{ kg} \cdot \text{hm}^{-2}$ or less at the soil depth, which indicates that there is a nitrate accumulation at the lower layer of the root zone with the increase of irrigation and fertilization, forming a risk of nitrate leaching below the root zone.

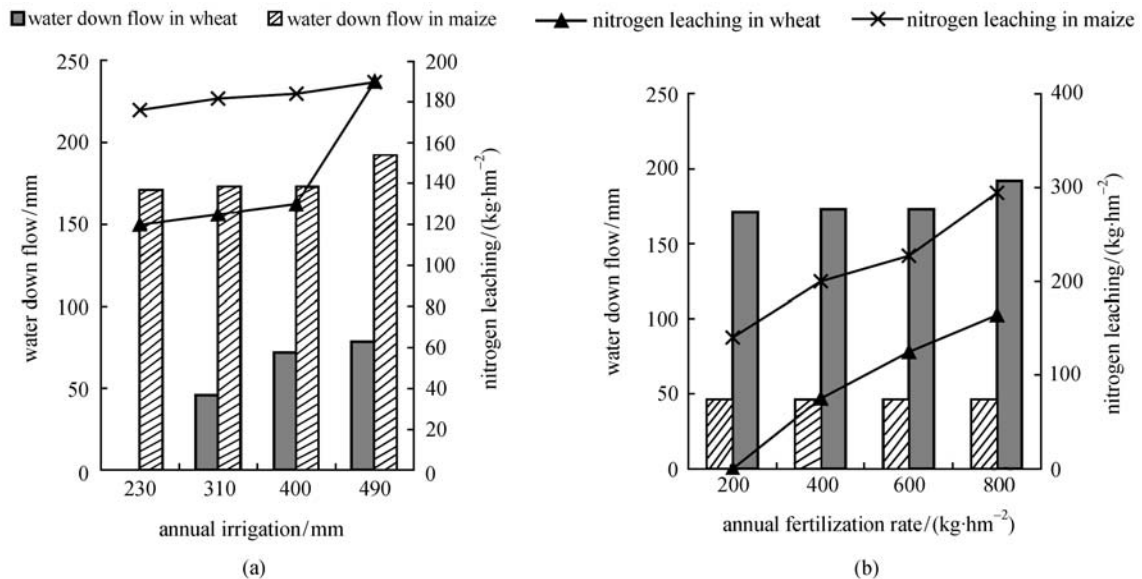


Fig. 12 Nitrate and water down flow at 90 cm soil depth in various water (a) and fertilizer (b) treatment levels

4 Conclusions and discussion

In order to make the simulation model scientifically sound and reliable, soil water, nitrogen and crop growth and development have been integrated. In simulating dynamics of soil water and nitrogen, their movements in the profile, nitrogen transformation and root uptake have all been taken into consideration. Soil water potential has been used in simulating soil moisture balancing and crop-water relation so the mechanism and result can be widely applicable. In soil nitrogen balance sub-model, soil nitrate is taken as a solute so its dynamics is simulated based on the principles of solute movement; simulation of transformation of nitrogen takes mineralization, fixation and denitrification, and the transformation coefficient has been adjusted according to temperature and humidity; Uptake of nitrogen by crops should take in to consideration the effects of water and nitrogen supply, crop nitrogen demand and nitrogen content in different crop organs. Therefore, without much innovation in the model, it is a good enough integration of principles in crop and soil sciences to meet the need of the research. The model is basically reliable. However, since there are still some unknown factors in crop growth and development, there exist some unsatisfactory issues in this model, those include: some of the parameters or coefficients were determined empirically, for example, the fixed partitioning coefficients were used in simulating biomass partitioning; in simulating the effects of soil water and nitrogen on crop growth and development, only the total photosynthesis was considered while simulating the partitioning of photosynthate to different organs under different water and nitrogen conditions was still not possible; and the maximum nitrogen demand and partitioning coefficients of nitrogen to various crop organs had to be determined empirically too. Also, since there is no multi-site long term data available, a great potential to improve the model with that kind of data exists. In the wheat-maize double cropping system, management practices for obtaining high yield, high WUE or NYE and for reducing water-nitrate leaching are usually different, and sometimes conflict with each other. This simulation model can be used as an efficient tool to screen the optimum management practices in different conditions in a time-saving and cheap way. This model only simulates effects of water and nitrogen in the cropping system. However, this does not affect its use in assisting decision-making and research on irrigation and fertilization and even for other purposes.

There are several other weak points that need to be mentioned about this model. One of them is that it is assumed in this study that the maximum LAI a wheat canopy can achieve is 5. This value is set according to an existing theory saying that a population with a LAI higher than 5 would be subject to lodging and shading of top leaves over lower leaves, but this value might be too small

since in very highly-yielding plots ($9 \text{ t} \cdot \text{hm}^{-2}$), LAI over 9 has been observed (Zhao et al., 2002; Sun et al., 2007). The assumed maximum LAI for maize is 3 (Tong and Cheng, 1997) for the same reason, but the maize population density has been greatly increased. So the model needs to be improved with the most recent achievements in population dynamics research. Another issue that needs to be mentioned is that, since there is much greater influence of management as tillage and fertilization in the topsoil, and hence there exist much bigger sampling errors in this layer. It is essential to improve techniques of such to improve the accuracy of data collection for a better performance of the model simulating soil and water dynamics in topsoil so as to give advice on water management in seedling stage before and during winter. Since there are various irrigation practices being used by the farmers in the area, it is necessary to have a thorough understanding of different irrigation practices on seedling growth under various soil and climate conditions. To achieve a satisfactory simulation output of that, more accurate measurement of moisture and nitrogen contents in the top soils and better estimation of surface evaporation from the soil surface—this might be a good topic for further efforts in the future.

Acknowledgements The authors wish to give their sincere thanks to Dr. Ren Tusheng of China Agricultural University for his important assistance by providing his up-to-date knowledge and experiences in soil physics and laboratory work. He has been also very helpful in giving constructive suggestions in model building. Thanks also give to Professor Hu Chunsheng of Chinese Academy of Sciences in Shijiazhuang for providing kind help with the field experiment and data analysis.

Professors Li Yanming, Cui Yanhong and Zhang Jianping at Agricultural University of Hebei have given much advice on biology and management of wheat and maize. Mr. Zhao Yingmu, Miss Xie Zhixiao and Miss Shi Xiupeng in Xinji County of Hebei Province dedicated their time and efforts in managing the experimental fields and providing facilities and other assistance for accomplishing the experiment. Mr. Chen Jianwei, Miss Zhao Xiaoyan and some students from Zhangjiakou Agricultural College also assisted in field management, taking samples and processing data. The authors thank them all for the great assistance.

This study is a part of the key program of the China National Scientific Technical Support for the 11th Five-Year Plan 'The study and demonstration of technology integration on the double cropping system of wheat and maize in the central and northern three-H Plain (Hebei)' (No. 2006BAD02A08).

This research has also been financed by the International Collaboration Funds of the Ministry of Science and Technology of China.

References

- Hu C S (2005). Farmland ecosystem at the piedmont of Taihang. In: Sun H L, ed. Chinese Ecosystem. Beijing: Science Press, 1052–1085 (in Chinese)
- Institute of Soil Science, Chinese Academy of Sciences (1978). Physical and Chemical Analysis of Soil. Shanghai: Shanghai Science and Technology Press (in Chinese)
- Liang W L, Lü H Z, Xia A P (2006). A preliminary analysis on the yield

- gap of winter wheat between demonstration plots and farmers' fields. *Journal of Food, Agriculture & Environment*, 4(3 & 4): 143–146
- Liang W L, Lü H Z, Wang G Y, Connor D J, Rimmington G M (2007). A simulation model assisted study on water and nitrogen dynamics and their effects on crop performance in the wheat–maize system I: The Model. *Front Agric China*, 1(2): 155–165
- Liu X H (2005). *Science of Farming System*. Beijing: China Agricultural University Press, 247–255 (in Chinese)
- Lü H Z (2001). Simulation of water and nitrogen behavior and their effects on yield and sustainability of wheat–maize double cropping system. Dissertation for the Master Degree. Baoding: Agricultural University of Hebei (in Chinese)
- Sun Y H, Li R Q, Dang H K, Zhang X W, Li H L, Li Y M (2007). Population and individual characteristics of growth and development and yield components of super-high-yielding winter wheat in Hebei Province. *Journal of Agricultural University of Hebei*, 30(3): 1–8 (in Chinese)
- Tong P Y, Cheng Y N (1997). *Model of Maize Growth and Yield*. Beijing: China Agricultural Technology Press (in Chinese)
- Wang G Y (1999). Simulation of crop yield–water relationship of wheat–maize system. Dissertation for the Master Degree. Baoding: Agricultural University of Hebei (in Chinese)
- Zhang F X, Zhou M Y, Xu H P, Guo K Q (2005). Effects of water and fertilizer coupling on growing and yield of winter wheat. *Journal of Water Resources and Architectural Engineering*, 3(2): 22–24 (in Chinese)
- Zhao G C, Liu L H, Yang Y S, Zhang Y, Yang Z S (2002). Effect of fertilizer application on population quality, root system distribution, grain yield and quality in super-high-yielding wheat. *Acta Agriculturae Boreall-sinica*, 17(4): 82–87 (in Chinese)