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A dynamic knowledge model for water management in maize

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Abstract Farmland irrigation management and model establishment are always core and difficult contents in crop simulation. This research was focused on exerting the establishment theory of knowledge model, and applying the systematic analysis method and mathematic modeling technology to knowledge expression system of maize water management. Based on soil water balance, a dynamic knowledge model with systematic and wide-application characteristics for maize water management was developed, after periodically quantifying the relationship of irrigation ration between cultivars' characteristics and environmental factors. Cases were studied on the knowledge model with the data sets of normal year in different eco-sites and those of different rain years in the same eco-sites. The results showed that there was no difference in water saving in normal years under different eco-sites, irrigation schedule changes with eco-sites greatly; but a more obvious difference in different rain years of the same eco-sites existing, with 8.6% and 31.9% of water saving in both more rainfall and normal rainfall years, respectively. Additionally, irrigation in the seedling stage did not change with year types, but it did in Knurling and filling stages. This can be concluded that the irrigation regime designed by the model is well coherent to the actual planting system, which indicated that the model had good decision-making and applicability.

Keywords maize, knowledge model, water management

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1 Introduction

Farmland irrigation management and model establishment are always core and difficult contents in crop simulation (Cui, 2000). With further researches on water saving agriculture, many crop-water production functions and models were established all over the world based on the relationship of water requirement in crop yielding (Hille, 1983; Shen et al., 1995). Such modeling researches in foreign countries can be traced back to 1913, including Briggs and Shantz's primary model through whole growing stages (1914); Jensen, Minhas and Rao's multiple model of phase water deficit (1968); Blank, Stewart and Singh's addition model of phase water deficit (1975); Feddes and Morgan's dynamic model of water production function (1978) and so on (Blank, 1975; Feddes, 1978; Morgan, 1980; Jensen, 1986). Chinese researchers mainly cited and improved the foreign models to make them more applicable and convenient in a particular environment (Mao, et al., 1994; Guo and Lei, 1996; Wang et al., 1999). In sum, those models can be divided into two types: one is water-crop yield model, based on variable crop water consumption to find the relationship of variable degree water deficit in crop yielding at different growth stages, this kind of models are always experientially or half-experientially deduced from experimental data; the other is dynamic yield model, based on the relationship of different soil water content with dry matter accumulation in the process of development, this kind of model has real-time operation, which can be trailed along with the whole growth period, connecting the crop yield to soil moisture content directly. Currently, many studies focus on the decision of irrigation time and demand with the latter based on water production function and system optimizing theory such as the foreign crop water management systems—CROPWAT (Smith, 1992) and ISAREG (Teiceira and Pereira, 1992). However, because of the poor integrated parameter demarcation and the absence of the corresponding decision functions, those functions are hardly used for decision-making in practice. National crop water management systems such as expert systems (Wang et al., 2001) and decision-making support systems (Zhou et al., 2000; Cui et al., 2006), which enhance the informational level, and improve the management efficiency greatly, still have the problems of site-specific, narrow-applicability, huge

knowledge base, difficult data timing collection and so on. Cao and Zhu (2004), using the integrated knowledge engineering and system modeling technology, have set up a spatial and temporal dynamic knowledge model, which is expected to overcome the traditional shortcomings of management modules such as poor decision and narrow applicability, and to design the module cultivation project on the basis of production system in special environments and conditions.

This research was focused on the establishment of a theory of knowledge model, and the application of the systematic analysis method as well as mathematic modeling technology to the knowledge express system of maize water management. Based on soil water balance, a dynamic knowledge model with systematic and wide-applicable characteristics for maize water management was developed after periodically quantifying the relationship of irrigation between cultivars' characters and environmental factors so as to provide a basis for intelligent and mathematic cultivation decision-making system of maize irrigation management.

2 Materials and methods

2.1 Modeling

For the purpose of modeling system, after collecting and analyzing the latest knowledge and the experts' experience of irrigation management in maize, and applying the system analysis method and mathematic modeling technology, the dynamic relationship between maize water requirement characteristics and management indexes to environmental factors was quantified. Finally, cases were studied on the system to validate its correctness and certain parameters in the model system were adjusted and modified through analyzing the feedback information.

2.2 Validation of model

Cases were studied on the knowledge model with the data sets of typical cultivar, many years' weather data in different eco-sites, such as Changping, Tai'an and Shenyang. The characteristics of typical cultivar 108 were obtained from experimental results, journals and internet. The normal weather data in different eco-sites were the average of seven years from 1994 to 2000. The weather data of more rainfall year in Changping were the average of the years of 1994 and 1996, the normal were average of 1995 and 1998, and the less were average of 1999 and 2000. All the data included the daily highest and the lowest temperatures, rainfall and gross radiation every day, all of which were model input values.

3 Results and analysis

3.1 Description of model algorithm

Maize field water demand is the total field evapotranspiration. It is affected by cultivar characters, environments and

crop management levels, and equals to the summation of irrigation water, rainfall and under-ground water through leaf transpiration. This model, based on the field water balance equation (Cao and Luo, 2003), can calculate the optimal irrigation amount (OIA , m^3/hm^2) in a particular growth stage as follows

$$OIA = [(ETO - ERAIN)] + (W_b - W_a) \times ID \times 0.1 \times 10 \quad (1)$$

where ETO stands for field evapotranspiration in the whole growth stage of maize (mm), which can be calculated by Eq. (2) to (5); $ERAIN$ (mm) is efficient rainfall; W_b (%) represents soil water contents around maize root in telophase; W_a (%) represents soil moisture content around maize root in the initial stage (W_b and W_a are closely related to farmers' irrigation practice); ID is the depth of irrigation management (20 cm); and 0.1 and 10 are units of transfer coefficients.

In Eqs. (2)–(5), ETO can be calculated with equation of Priestly-Taylor (Cao and Luo, 2003), where EEQ represents balanced evaporation (mm/day), Q is daily solar radiation energy (kJ/m^2), obtained from weather database (Zuo et al., 1991), T_{day} represents daily average temperature ($^{\circ}C$), $CALB$ represents reflectivity of solar radiation opposite to leaf layers (%), LAI represents leaf area index, and $SALB$ represents reflectivity of solar radiation opposite to naked field (%), ranging from 0.08 to 0.24 with a ratio of sand in soil ascending (Cao and Luo, 2003).

$$ETO =$$

$$\begin{cases} EEQ \times 1.1 & 5^{\circ}C \leq T_{max} \leq 24^{\circ}C \\ EEQ \times ((T_{max} - 24) \times 0.05 + 1.1) & T_{max} > 24^{\circ}C \\ EEQ \times 0.01 \times e^{(0.18 \times (T_{max} + 20))} & T_{max} < 5^{\circ}C \end{cases} \quad (2)$$

$$EEQ = Q \times (2.44 \times 10^{-3} - 1.83 \times 10^{-3} \times CALB) \times (T_{day} + 29) \quad (3)$$

$$T_{day} = 0.6 \times T_{max} + 0.4 \times T_{min} \quad (4)$$

$$CALB = \begin{cases} 0.23 - (0.23 - SALB) \times e^{(-0.75LAI)} & LAI \leq 4 \\ 0.23 + \frac{(LAI - 4)^2}{160} & LAI > 4 \end{cases} \quad (5)$$

The trend of LAI at growth phases is given in Table 1. According to equation of Monsi, $OLAIM$ in Eq. (6) is the optimal maximal leaf area index in silking phase, which is influenced by cultivar type, sunlight intensity and normal illumination of bottom leaf (Ling, 2000; Cao and Luo, 2003). I_0 is natural light intensity above the crops (around 60 000 lx), I_s is compensated light intensity of bottom leaf in colony (3 000–4 000 lx), K is sunlight eliminated coefficient, ranging from 0.5 to 0.7 with cultivar type tighten ascending; and \ln is spontaneous logarithm.

$$OLAIM = -(\ln I_s/I_0) \times 1/K \quad (6)$$

The amount of efficient precipitation refers to the part of rainfall that permeates in the crop root system to supply for

Table 1 Trend of *LAI* with growth phases

Growth phase		<i>LAI</i>	
		Sowing in spring	Sowing in summer
Seedling to Tasseling	Three leaves	0.07*OLAIM	0.07*OLAIM
	Knurling	0.17*OLAIM	0.20*OLAIM
	Trumping	0.58*OLAIM	0.60*OLAIM
Tasseling to maturity	Tasseling	OLAIM	OLAIM
	Filling	0.86*OLAIM	0.70*OLAIM
	Maturity	0.50*OLAIM	0.35*OLAIM

Note: * is multiply operation symbol.

effective use. It is a complex and dynamic process, which is connected with the quantity of rainfall, soil traits, maize leaf layer and root depth (Zuo et al., 1991; Cao and Luo, 2003). Because of many difficulties in collecting the data of rainfall and soil traits, here we use an experiential rainfall coefficient α to calculate the efficient rainfall during the whole growth phases (Eq. (7)). Pd is daily rainfall (mm).

$$ERAIN = \sum GSV P \tag{7}$$

$$GSVP = \sum Pd \times \alpha \tag{8}$$

$$\alpha = \begin{cases} 0 & Pd < 3.5 \\ 1.0 & 3.5 \leq Pd < 15 \\ 1.0 - 0.8 & 15 \leq Pd < 50 \\ 0.8 - 0.7 & 50 \leq Pd \leq 100 \\ 0.7 & Pd > 100 \end{cases} \tag{9}$$

The amount of irrigation and drainage at the growth phase of i can be calculated by Eq. (10), where $ERIR$ is efficiency ratio of irrigation ration, varying with different irrigation styles, 0.7 in trench irrigation, 0.9 in sprinkle, and 1 in drip-ping, respectively. In this study, $ERIR$ is equal to 0.7. W_{ai} is soil moisture content around maize root in the initial stage of i (%); W_{bi} is the soil water contents in telophase of i , which is equal to upper limit water content of i .

$$OIA_i = [(ETO_i - GSV P_i) \times 10 + (W_{bi} - W_{ai}) \times ID] / ERIR \tag{10}$$

When W_{ai} is below the drought limit index, the maize crops need to be irrigated, the quantity is OIA_i . When W_{ai} is above the upper limit index, the crops need drainage, the quantity of drainage is OIA_i too. If neither, a verdict model will be needed to analyze the economic efficiency before irrigation.

Maize expenditure, demand for water and response to water absence in different growth stages vary with the environments and plant growing statuses, and they follow a rule of little in prophase, much in metaphase and intermediate in anaphase (Kang et al., 1998; Ling, 2000). Here λ as a water-yield product coefficient (Wang and Wang, 1998) was used for economic benefit analysis before irrigation (Table 2). i is growth stage; Lim , Low , Opt , Hig are the drought limit, low limit, optimal and upper limit of soil water content index, respectively; and ID is irrigation depth (cm).

Table 2 References table of water-yield product coefficient, irrigation depth, indexes of soil water contents at different growth stages

Growth phase	i	λ	ID/cm	$Lim\%$	$Low\%$	$Opt\%$	$Hig\%$
Sowing to knurling	1	0.56	0–60	55	60	67.5	80
Knurling to trumping	2	1.17	0–60	60	65	72.5	85
Trumping to tasseling	3	1.38	0–80	65	70	77.5	85
Tasseling to filling	4	1.38	0–80	65	70	77.5	85
Filling to maturity	5	0.78	0–100	60	65	72.5	85

Note: Lim , Low , Opt and Hig are the ratios of actually soil water contents to most field available water contents.

In this article, we introduce the equation “gap between input and output” for analysis, the target functions are $R = \Delta Y_i P_y - OIA_i P_w - C$, and $\Delta Y_i = WUE \times \lambda_i \times ETO_i$, where R stands for irrigation benefit; ΔY_i is yield increment with irrigation; P_y is the price of maize; P_w is the price of water; C is the wastage of people or material resources; WUE represents the highest water utilization efficiency (1.4); λ_i stands for the coefficient of water and yield in different growth phases, the other parameters as the above. The total amount of irrigation can be calculated by Eq. (11). Water saving efficiency (WSE) can be calculated by Eq. (12), with 600 as experiential amount of irrigation per unit area at a given time (m^3/hm^2); $count()$ is function symbol, returns irrigation times.

$$W = \sum OIA_i \quad (R_{OIA_i} \geq 0, i = 1, 2, 3, 4) \tag{11}$$

$$WSE = \frac{600 \times count(\sum OIA_i) - W}{600 \times count(\sum OIA_i)} \times 100\% \tag{12}$$

3.2 Model verification

Cases were studied on knowledge model for water management in maize with the data sets of typical cultivars and normal year in different eco-sites (Table 3). The result indicated that under the condition of suitable sowing time in a normal year, the trend of field evapotranspiration in different eco-sites was identical. The field evapotranspiration showed large in seedling, minishing with the accretion of *LAI* until tasseling, then increasing with the declining of *LAI*, which tallied with other current research theories. At the same time, temporal and dynamic variation of field evapotranspiration and rainfall in different eco-sites was good. Rainfall was rich in Jinan, which got along well with the maize requirement rule except irrigating once at seedling. It was the same in Beijing, except irrigating twice in seedling and knurling phases. Rainfall was rare in Shenyang and irrigation would last the whole developing phases, so water saving irrigation agriculture should be developed to realize the high yield of crops. Results in Table 3 are accordant with current experimental irrigation ration and water distribution in different stages (Shandong Academy of Agriculture Science, 1983; Chen and Li, 1994; Sun et al., 1996). Furthermore, the irrigation ration in Shenyang was more than that of Beijing

Table 3 Water management of typical cultivar under suitable sowing dates designed by knowledge model for different eco-sites in normal climatic years

Eco-sites	Growth phase	Items			
		ETO_i /mm	$ERAIN_i$ /mm	OIA_i /($m^3 \cdot hm^{-2}$)	W /($m^3 \cdot hm^{-2}$)
Jinan	Sowing to Knurling (6.1–6.21)	68.72	25.92	578.0	578.0
	Knurling to Trumping (6.22–7.60)	55.52	65.82	0	
	Trumping to Tasseling (7.7–7.23)	47.40	84.00	0	
	Tasseling to Filling (7.24–8.8)	43.78	140.32	-865.4	
	Filling to Maturity (8.9–9.18)	109.15	113.59	0	
Beijing	Sowing to Knurling (5.10–6.8)	82.13	30.05	670.8	1 245.5
	Knurling to Trumping (6.9–6.25)	52.58	23.20	574.7	
	Trumping to Tasseling (6.26–7.13)	56.81	48.72		
	Tasseling to Filling (7.14–7.31)	44.17	111.68	-575.1	
	Filling to Maturity (8.1–9.10)	86.06	178.08	-1 020.2	
Shenyang	Sowing to Knurling (4.20–6.7)	103.56	32.37	861.9	2 745.1
	Knurling to Trumping (6.8–6.29)	60.21	42.22	470.8	
	Trumping to Tasseling (6.30–7.19)	50.10	41.01		
	Tasseling to Filling (7.20–8.5)	207.62	154.08	635.4	
	Filling to Maturity (8.5–10.5)	196.06	108.30	777.0	

Note: The soil moisture content pre-sowing was supposed as 60%, and OIA_i was got after R verdict.

and that of Beijing more than Jinan, probably because less precipitation in Shenyang and Beijing benefited the rooting of maize downward into the deep soil, so that the maize plants could fully utilize the deep under-ground water. However, this model does not involve the effect of under-ground water on the water requirement and needs further modifications.

Cases were studied on the knowledge model with the data sets of different rainfall years in Beijing and typical cultivars under the condition of suitable sowing time (Table 4). The result indicated that irrigation in seeding does not change with year, but in knurling and filling they do. In more rainfall years, irrigation was done once in seedling, making drainage in filling anaphase; in modest year, irrigation was conducted twice in seedling and knurling, making drainage in killing anaphase; and in less rainfall year, irrigation was done three times in seedling, knurling and filling, respectively. Design of irrigation system in Table 4, which indicates a good decision-making and wide applicability, is coherent to the actual planting system well (Shandong Academy of Agriculture Science, 1983; Chen and Li, 1994; Sun et al., 1996).

4 Conclusion and discussion

The system analysis principle and mathematical modeling technique were applied to develop a systemic and dynamic knowledge model for irrigation management in maize, after integrated consideration of the environmental factors, soil physical and chemical traits, maize growth characteristics and irrigation economic benefits. Cases were studied with data sets from different eco-sites in normal years as well as the same eco-site in different rainfall years. The results showed no difference in water saving at different eco-sites in normal years, but more significant differences at the same eco-site in different rainfall years, with 8.6% of water saved in a rainier year and 31.9% in a normal rainy year, which indicated that

Table 4 Water management of typical maize cultivars under normal sowing dates designed by knowledge model for Beijing region in different climatic years

Year type	Developing phase	Items			
		ETO_i /mm	$ERAIN_i$ /mm	OIA_i /($m^3 \cdot hm^{-2}$)	W /($m^3 \cdot hm^{-2}$)
More rainfall	Sowing to knurling	83.47	21.84	766.3	766.3
	Knurling to trumping	46.41	120.40	0	
	Trumping to tasseling	37.78	5.60	0	
	Tasseling to filling	38.92	139.44	-905.2	
	Filling to maturity	65.42	148.56	-931.4	
Modest rainfall	Sowing to knurling	80.65	41.20	544.5	816.4
	Knurling to trumping	44.51	27.32	271.9	
	Trumping to tasseling	57.73	100.84	0	
	Tasseling to filling	43.39	122.72	-693.3	
	Filling to maturity	97.66	131.08	-434.2	
Less rainfall	Sowing to knurling	83.29	38.88	594.1	1 809.3
	Knurling to trumping	58.50	4.48	640.2	
	Trumping to tasseling	53.56	29.12	575.0	
	Tasseling to filling	56.50	43.44		
	Filling to maturity	100.99	121.12	0	

the model had good decision-making and applicability. Compared with other optimal irrigation models and management experts based on water-yield product function (Smith, 1992; Teiceira and Pereira, 1992; Wang et al., 2001; Cui et al., 2006), this model has the merits as follows.

First, input value of the model only needs conventional weather and soil data, which is brief, practical and easy to be collected. Results have indicated that the model is of good dynamic and wide-applicability.

Second, in view of economic and ecological benefits, water supply levels and water resource distribution among the main growth stages of maize in different environments and different rainfall years can be quantified dynamically, which makes water resource distribution in farming more scientific and normative. This model is bound to have a broad prospect

if connected to the climate forecast model (Chaves et al., 2005).

Finally, though the model is more advanced than others in dynamic and applicability, it still needs further research to make it perfect. For example, *LAI* trend decision among the growth stages was only involved in more experimental parameters; unconsidering the effect of fertilizer and deep underground water; lacking verification for different cultivars and so on.

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