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Simulation of Winter Wheat Yield and Water Use Efficiency on the Loess Plateau of China Using WAVES

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Abstract

Water availability is a major factor limiting crop yields on the Loess Plateau of China. As competition for water intensifies, it is essential to develop alternative irrigation schedules that maximise crop yield and water use efficiency (WUE) for a given level of water supply. A field experiment with winter wheat (*Triticum aestivum* L.) from 1995 to 1998 calibrated and tested a biophysically based model (WAVES) in terms of grain yield and WUE prediction. The data collected include water and energy balance components, biomass and grain yield. Comparisons between the measurements and the model predictions were made with three years of field data. Modelled grain yield and WUE based on biomass and harvest index were in better agreement with the measurements than those based on transpiration and harvest index. The model was sensitive to different irrigation treatments, and in reasonable agreement with field measured data. The highest irrigation treatment resulted in the greatest evapotranspiration but not the highest yield, so WUE was relatively low. Appropriately limited irrigation could improve the grain yield and WUE. Aiming only for maximum grain yield or for maximum WUE could lead to uneconomical irrigation management.

水分供应是黄土高原粮食产量的主要限制因素。由于用水竞争的加剧，选择能够在某一设定供水水平上，产量最高，水分利用效率（WUE）最高的灌溉方式就很重要。1995-98年间进行的冬小麦田间试验，在作物产量和WUE方面校正、检测了基于生物物理原理的 WAVES 模型。收集了水分能量

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平衡组分、生物量和粮食产量的数据，作了测量值和模型预测值的比较。以生物量和收获指数为基础预测的产量及 WUE 与实测值的吻合程度高于以蒸腾与产量指数为基础的数值。该模型对不同灌溉条件敏感性高，与实测值的吻合令人满意。灌溉最多，则蒸发最多，但产量不是最高，所以 WUE 相对较低，适当的有限灌溉能提高产量和 WUE。仅仅追求最大产量或最高 WUE 可能导致灌溉的经济效益不高。

THE LOESS Plateau, located in the middle reaches of the Yellow River, is one of the main agricultural regions in China. The Overview provides background information on this area; Figure 1 of the Overview shows its location. Winter wheat (*Triticum aestivum* L.) and summer corn (*Zea mays*) are the main crops in the area. Average annual rainfall ranges from 300 to 600 mm, with over 60% occurring from July to September. As rainfall is low and variable, water is the most important factor limiting agricultural production in the region. Crops are irrigated with water pumped from the Yellow River or from collected rainfall. However, the amount of available water in the Yellow River has declined rapidly in recent years, so there is an urgent need to reduce irrigation in order to sustain agriculture in this area (Kang and Li 1997). A challenge is to develop management techniques that increase water use efficiency (WUE) while optimising crop production. Chapter 4 discusses this in more detail.

When available water becomes limited, water deficits are unavoidable in some periods of the crop growing season. Irrigation scheduling then becomes more important and complex because irrigation decisions need to be based on the relationship between water use and grain yield and on WUE. This requires people to evaluate alternative irrigation schedules and choose a schedule that optimises crop yield and WUE for a given level of water supply. There are few detailed investigations on water use–grain yield

relationships and WUE under different water supply conditions in the region, although many irrigation practices involve soil water deficit control.

In order to develop guidelines for farmers and/or decision makers to manage crop production, many irrigation practices under various conditions must be evaluated in terms of their effect on yield and WUE. Process-based models can provide useful information about different irrigation practices. For example, Hook (1994) and Kang et al. (1992) have used models to determine the best irrigation strategies. Models can also add value to decision making by transferring results from extensive field experiments to other areas (Cheeroo-Nayamuth et al. 2000; Cabelguenne et al. 1999; Jagtap et al. 1999; Sankaran et al. 2000; Alagarswamy et al. 2000).

Modelling crop yield and WUE is an important facet of crop water management and requires a good understanding of crop–water relationships. WAVES (water, atmosphere, vegetation, energy and soil) is an integrated energy and water balance model based on the biophysical processes in the soil–plant–atmosphere continuum (Zhang et al. 1996). A detailed description of WAVES can be found in Zhang and Dawes (1998) and in Chapter 1 of this volume. The model was successfully applied to the Loess Plateau to model the processes of water dynamics, crop evapotranspiration, and biomass accumulation (Huang et al. 2001), but was not tested for crop yield prediction.

The objective of this chapter is twofold: to evaluate two different methods for predicting crop yield and WUE within the WAVES model, and to evaluate optimal water management practices for improving crop yield and WUE under limited water supply on the Loess Plateau.

Field Experiments and Data

Site description

We conducted field experiments in Changwu, Shaanxi Province, during 1995–98. The Overview provides background information about the area; Figure 4 of the Overview shows its location. The study site has an elevation of 1206 m and has a semiarid to warm temperate climate with an average annual rainfall of 542 mm, concentrated from July to September. Annual averages are 2226 hours for sunshine duration, 9°C for temperature and 1552 mm for potential evaporation. The groundwater table is 50–80 m below the surface. The soil is a dark loess soil with a loam texture; it has been intensively cultivated over many centuries. Table 1 shows the major physical properties of the soil. The top 30 cm contains 1.55% total organic matter, 0.106% nitrogen (Bremner and Mulvaney 1982) and 0.095% available phosphate (Olsen and Sommers 1982). The lysimeters were 3 m × 2 m in area and 3 m deep, separated by waterproof concrete walls buried up to the soil surface.

The soil was irrigated, fertilised and well mixed in the top 30 cm before sowing. In each plot, an aluminium tube, 2 m long, was installed for moisture measurements. A mobile plastic rain shelter was installed above the lysimeters to control

soil water status. Winter wheat (cultivar Changwu 89-134¹) was sown in late September. Seedling density was controlled at 200 plants/m². There were seven treatments of irrigation deficit each year with three randomly designed replicates (Table 2). All plants were harvested in early July in the year following planting.

Measurements and statistical treatment

A neutron moisture meter (CPN503, United States) was used to measure water content every 10 cm to a depth of 2 m, with measurements taken weekly. In controlling soil water deficit, average soil water content for the top 40 cm and 60 cm was monitored using a time-domain reflectometer (Trase system, Soil Moisture Equipment Corporation, United States). When soil water content dropped to the lower limit of the designated range (see Table 2), the plot was irrigated to its field capacity. The amount of irrigation water in each lysimeter was recorded and used to calculate total water consumption. At the end of the winter growing season, plants were harvested and the dry mass and final grain yield calculated. All data were statistically analysed and treatments were compared using Duncan's multiple range test.

Meteorological data were recorded by a standard weather station located at the experimental site. Daily values of maximum and minimum temperature, maximum vapour pressure deficit and average wind speed were recorded.

¹ This cultivar is widely used by farmers in the region.

Table 1. The particle composition and hydraulic properties of soils at Changwu.

Size (mm)	Particle composition						θ_s	θ_F	θ_{wilt}	γ_d
	>0.25	0.25–0.05	0.05–0.01	0.01–0.005	0.005–0.001	<0.001 mm				
%	1.1	2.4	57.0	8.6	17.7	13.2	0.486	0.255	0.1	1.21

θ_s = saturated soil water content (cm³/cm³); θ_F = field capacity (cm³/cm³); θ_{wilt} = water content at permanent wilting point (cm³/cm³); and γ_d = mean bulk density (g/cm³)

Table 2. Controlled minimum soil water content of different treatments in the winter wheat growing season.

No.	Treatment ^a	Minimum soil water content maintained (% of field capacity)				
		Seeding to before winter freezing	Regrowth to stem elongation	Booting to heading	Flowering to milk ripeness	Maturity to harvest
1	LLLLL	45	45	45	45	45
2	LLLHM	45	45	45	70	55
3	LHMLL	45	70	55	45	45
4	LMHMH	45	55	70	55	70
5	MMHHL	55	55	70	70	45
6	HMHHM	70	55	70	70	55
7	HHHHH	70	70	70	70	70

^a The growing season was divided into five periods and soil water content in the top 60 cm (40 cm before the jointing stage) was maintained during different stages at one of three levels: high soil moisture content (H) (no soil water deficit); medium (M) (mild soil water deficit); or low (L) (severe soil water deficit). When soil water content approached the minimum values, water was supplied up to field capacity.

Using the WAVES Model

WAVES can be used to predict crop yield and WUE. Crop yield is estimated from the carbon balance, determined by calculation of evaporation and transpiration demand for a given day. These fluxes are based on the soil conditions at the start of the day. A portion of the energy balance is used to estimate the stresses on the vegetation (Zhang and Dawes 1998), and carbon balance is then used to calculate assimilation based on those stresses. Finally, evaporative demand is calculated using a conductance based on the assimilation rate. In this way a complete cycle between the atmosphere, soil and vegetation can be made. The WAVES plant growth model is a generic algorithm using rate-based equations, physical principles and empirical results (Wu et al. 1994). WAVES does not attempt to model discrete phenological growth stages or to predict yield. The model treats a plant as three separate carbon sinks representing leaves, stems and roots. Each of these is assumed to occupy the conceptual site fully (i.e. leaves are evenly spread across each square metre, stem numbers are not determined but are uniformly spread and roots totally explore the depths to which root carbon is allocated).

Engineering estimates of crop yield can be made from knowledge of above-ground biomass and actual and potential transpiration, based on empirical relationships (Charles-Edwards 1982). The simplest equation uses the harvest index:

$$Y = HI \times DM \quad (1)$$

where Y is crop yield (kg/ha), HI is the harvest index, and DM is the total above-ground dry matter (kg/ha). Transpiration data can be used to make alternative yield estimates (de Wit 1958):

$$Y = HI \times m \frac{ET_a}{ET_p} \quad (2)$$

where m is a crop factor dependent on variety and species (kg/ha), ET_a is actual transpiration, and ET_p is average potential transpiration rate over the growing season. Within WAVES, the values of ET_a and ET_p are stored and can be used for these calculations with a user-specified harvest index and m parameter.

Harvest index is related to water supply level (Austin et al. 1980; Perry and D'Antuono 1989; Siddique et al. 1989). Based on Kang et al. (2000),

the harvest index for winter wheat was set to 0.25 (rainfed), 0.30 (limited irrigation), 0.40 (middle irrigation) or 0.35 (full irrigation). The crop factor m was set to 140 in all the simulations (Kang et al. 2000). Crop WUE was calculated as grain yield divided by seasonal evapotranspiration.

Calibration was done manually (i.e. without the use of software that optimises parameters for least squares or other error criteria). The calibration approach required a compromise between the degree to which a parameter could be adjusted for an individual plot, and the degree of parameter variation across plots. In order to obtain model parameters, the WAVES model was first run using the meteorological data between September 1995 and July 1996 and treatment 1 (full irrigation). Vegetation parameters for winter wheat were selected from the work of Zhang et al. (1996), with the accumulated temperatures and the maximum root depth adjusted according to local conditions. The soil in the experimental site has a fairly uniform profile and was assumed to have only one layer. The maximum rooting depth for winter wheat was set to 2 m under limited irrigation. The bottom of the soil column had a draining boundary with a maximum rate of 0.01 mm/day. This selection of the lower boundary condition is based on the specific characteristics of water balance with a winter wheat crop.

Results and Discussion

Grain yield prediction

Figure 1 shows a comparison of simulated and measured grain yield during the period 1995–98, using Equations 1 and 2 (Figs. 1a and 1b, respectively). Simulated grain yield using Equation 1 agreed well with the measurements. The best-fit slope through the origin was 0.97, with a correlation coefficient of 0.93. Grain yield simulated by Equation 2 also compared reasonably well with the measurements. The best-fit slope was 1.00 with a correlation coefficient of 0.82. These results indicate that grain yield can be approximated from estimates of above-ground dry matter and crop transpiration.

The harvest index and crop factor must be known to predict grain yield using the above methods. For winter wheat on the Loess Plateau of China, the harvest index varies from 0.25 to 0.40, depending on water availability (Kang et al. 2000). In water-limited crops that rely predominantly on stored water, the harvest index is roughly proportional to the amount of water available after anthesis (Nix and Fitzpatrick 1969). This is not the case for crops that rely predominantly on current rainfall (Passioura 1986). In other words, the harvest index varies with available soil water and other factors; it cannot be considered as an independent variable. The success of grain yield predictions using

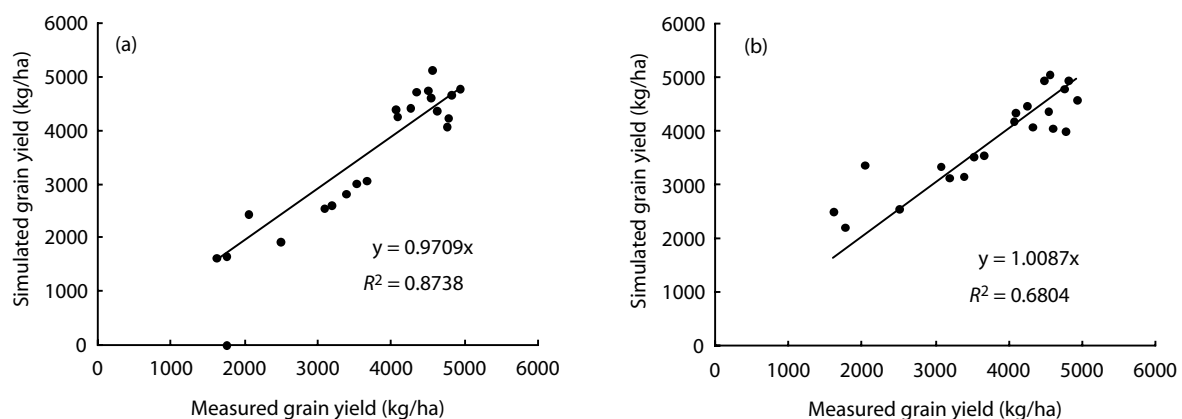


Figure 1. Effectiveness of WAVES in predicting grain yield for winter wheat, Changwu. (a) Prediction based on above-ground matter. (b) Prediction based on transpiration.

Equations 1 and 2 relies on accurate estimates of the harvest index. The results shown in Figure 1 support the findings of Zhang et al. (1999) and Wang et al. (2001), that the WAVES model can accurately simulate plant biomass under various soil moisture conditions.

The crop factor m is considered to be dependent only on variety and species (Hanks 1983). It can be applied to both water-limited and well-watered situations (de Wit 1958). We used a constant value in all simulations. Relationships represented by Equations 1 and 2 are attractive because they are simple; however, they are really useful only if we are able to estimate crop transpiration independently. This often means that a detailed model of a soil–crop–atmosphere system is required.

Water use efficiency

Figure 2 shows the comparison of the simulated WUE by the WAVES model and the measured values. The results obtained using Equation 1 agreed reasonably well with the measurements. The best-fit slope through the origin was 0.95, with a correlation coefficient of 0.75. The results using Equation 2 showed poor correlation with the measured values. Mathematically, WUE is estimated by dividing Equation 2 by actual

evapotranspiration and shows the variation in potential evapotranspiration. Since this quantity is independent of crop growth, little correlation can be expected. Where potential evapotranspiration, and therefore atmospheric demand, becomes the most limiting factor in crop growth, the relationship shown in Equation 2 may yield better estimates of WUE.

Figure 3 illustrates how evapotranspiration relates to simulated grain yield and WUE, using the WAVES model. Grain yield and evapotranspiration increased simultaneously when evapotranspiration was below a critical value; the slope increased as evapotranspiration decreased and became negative when evapotranspiration was larger than the critical value (about 500 mm). However, the maximum WUE was reached when evapotranspiration was at 440 mm and did not correspond to the maximum grain yield. When evapotranspiration was relatively low, an increase in water use by a crop could result in large increases in both grain yield and WUE. However, at maximum WUE, an increase in crop water use could still lead to an increase in grain yield, but could only reduce WUE.

Simply aiming for maximum grain yield under limited irrigation will require too much water. However, aiming for maximum WUE will result in

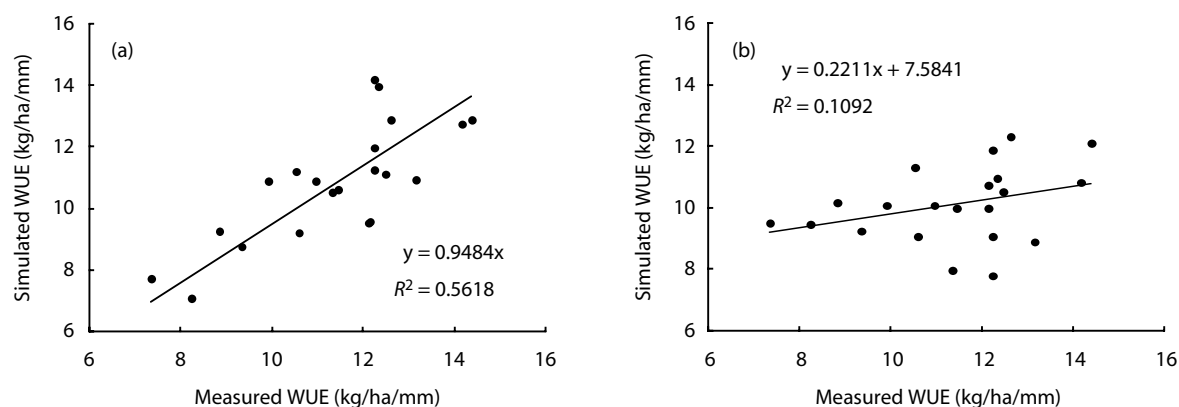


Figure 2. Effectiveness of WAVES in predicting water use efficiency (WUE) for winter wheat, Changwu. (a) Prediction based on above-ground matter. (b) Prediction based on transpiration.

a lower grain yield. Thus, it is necessary to consider both yield and WUE when irrigating. The association of high WUE with high yields has important implications for efficient use of water resources on the semiarid Loess Plateau of China.

Table 3 shows total evapotranspiration, grain yield, biomass and WUE calculated by summation of daily output from simulations over the whole growing season from 20 September to 2 July for three years, together with irrigation water use and rainfall. Simulated seasonal evapotranspiration varied between 234 and 526 mm. Simulated biomass was between 8800 and 12,600 kg per hectare (kg/ha). The simulated grain yield was 1600–5140 kg/ha, and 2200–5040 kg/ha, using Equations 1 and 2 respectively. Crop WUE was 6.16–12.87 kg/ha/mm and 7.78–12.33 kg/ha/mm for yield simulated by Equations 1 and 2 respectively.

Clearly, evapotranspiration, biomass and grain yield were lower under rainfed conditions than under irrigation. Evapotranspiration and yield depend on applied irrigation. Both evapotranspiration and biomass were maximised by full irrigation treatment, and were correspondingly lower without irrigation. However, the maximum grain yield occurred in treatment 5, in which applied irrigation water was 300 mm, reduced by one-third compared with the full irrigation treatment, with the deficit of evapotranspiration between 7% and 13%. The simulated results indicated that WUE of winter wheat could be improved by limited irrigation. Table 3 also indicates that the maximum WUE usually occurred in treatment 4. It suggests that the limited irrigation scheme has practical value for winter wheat production in this semiarid area.

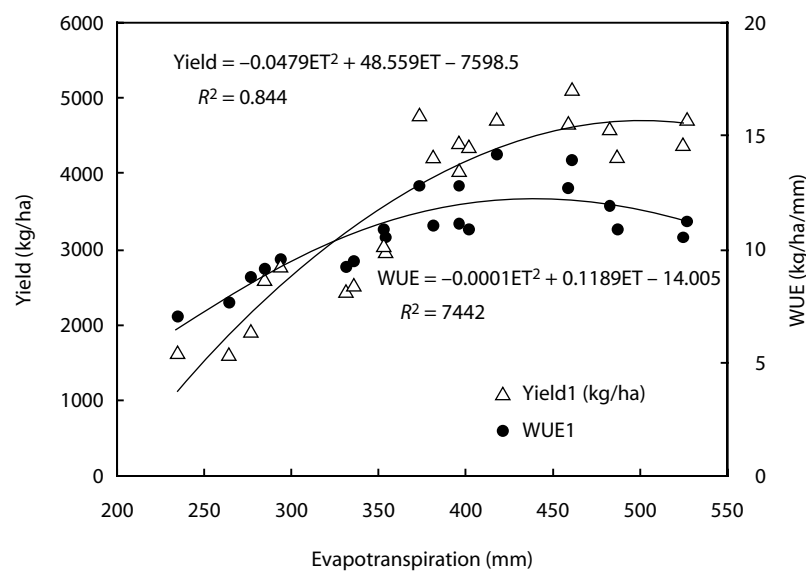


Figure 3. Effectiveness of WAVES in predicting the relationship between seasonal evapotranspiration (ET), water use efficiency (WUE) and grain yield for winter wheat in Changwu.

Table 3. Winter wheat evapotranspiration, biomass and grain yield simulated by the WAVES model, Changwu, 1995–98.

Years	Treatment no.	Rainfall ^a (mm)	Irrigation water (mm)	No. of irrigations	ET ^a (mm)	Biomass (kg/ha)	Yield 1 (kg/ha) ^b	Yield 2 (kg/ha) ^c	WUE1 ^d (kg/ha/mm)	WUE2 ^e (kg/ha/mm)
1995–96	1	239.6	0	0	234	8840	1660	2210	7.1	9.46
	2		100	1	284	10,400	2610	3120	9.2	9.09
	3		100	2	294	10,500	2810	3150	9.57	10.73
	4		200	3	395	11,175	4430	4470	11.21	11.32
	5		300	4	372	11,475	4790	4590	12.87	12.33
	6		400	4	380	11,438	4233	4003	11.13	10.52
	7		450	5	402	11,563	4375	4047	10.9	10.08
1996–97	1	137.0	0	0	263	10,000	1620	2500	7.7	9.50
	2		100	1	330	11,200	2450	3360	9.28	10.18
	3		100	2	335	11,167	2550	3350	9.52	10.00
	4		200	3	395	11,975	4070	4790	12.86	12.11
	5		300	4	458	12,400	4680	4960	12.76	10.83
	6		400	4	487	12,406	4255	4342	10.93	8.91
	7		450	5	523	11,938	4408	4178	10.53	7.98
1997–98	1	267.4	0	0	276	10,240	1940	2560	78.78	9.26
	2		100	1	354	11,767	3000	3530	10.6	9.98
	3		100	2	353	11,833	3070	3550	10.88	10.06
	4		200	3	417	12,373	4740	4949	14.2	11.86
	5		300	4	460	12,600	5140	5040	13.96	10.95
	6		400	4	482	12,500	4617	4375	11.98	9.08
	7		450	5	526	11,686	4736	4090	11.25	7.78

^a ET and rainfall are evapotranspiration and rainfall in the growing season of winter wheat respectively

^b Yield 1 is the simulated grain yield by Equation 1

^c Yield 2 is the simulated grain yield by Equation 2

^d WUE1 is the water use efficiency based on yield 1

^e WUE2 is the water use efficiency based on yield 2

Conclusion

The WAVES model can be used to predict grain yield of winter wheat on the Loess Plateau. The simulated grain yield based on biomass and harvest index showed better agreement with the measurements than that based on transpiration and harvest index. The simulated WUE using grain yield from biomass and the harvest index agreed reasonably well with the measured values. However, when the grain yield obtained from crop transpiration and the harvest index was used to calculate WUE, the results estimated from the model showed poor correlation with the measurements. The model was very sensitive to different irrigation treatments. The harvest index is an important parameter for grain yield prediction. The model was developed with a constant harvest index for different irrigation treatments. However, the values of harvest index were similar but not constant for different irrigation treatments, and related water supply level.

WUE in this region can be improved by irrigation scheduling. Evapotranspiration was the highest when most irrigation water was applied, but WUE was relatively low. Appropriately controlled irrigation could improve the grain yield and WUE. Aiming only for maximum grain yield or for maximum WUE could lead to uneconomical irrigation management.

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References

- Alagarswamy, G., Singh, P., Hoogenboom, G., Wani, S.P., Pathak, P. and Virmani, S.M. 2000. Evaluation and application of the CROPGRO-Soybean simulation model in a Vertic Inceptisol. *Agricultural Systems*, 63, 19–32.
- Austin, R.B., Bingham, J., Blackwell, R.D., Evans, L.T., Ford, M.A., Morgan, C.L. and Taylor, M. 1980. Genetic improvement in winter wheat yields since 1980 and associated physiological changes. *Journal of Agricultural Science*, 84, 675–689.
- Bremner, J.M. and Mulvaney, C.S. 1982. Nitrogen–total. In: Page, A.L., Miller, R.H. and Keeney, D.R., eds, *Methods of Soil Analysis, Part 2, Chemical and Microbiological Properties*. Madison, WI, American Society of Agronomy, 595–624.
- Cabelguenne, M., Debaeke, P. and Bouniols, A. 1999. EPICphase, a version of the EPIC model simulating the effects of water and nitrogen stress on biomass and yield, taking account of developmental stages: validation on maize, sunflower, sorghum, soybean and winter wheat. *Agricultural Systems*, 60, 175–196.
- Chang, Y.Y. and Corapcioglu, M.Y. 1997. Effect of roots on water flow in unsaturated soils. *Journal of Irrigation and Drainage Engineering*, 123, 202–209.
- Charles-Edwards, D.A. 1982. *Physiological Determinants of Crop Growth*. Sydney, Academic Press.
- Cheeroo-Nayamuth, F.C., Robertson, M.J., Wegener, M.K. and Nayamuth, A.R.H. 2000. Using a simulation model to assess potential and attainable sugar cane yield in Mauritius. *Field Crops Research*, 66, 225–243.
- Dawes, W.R., Zhang, L., Hatton, T.J., Reece, P.H., Beale, G. and Packer, I. 1997. Evaluation of a distributed parameter eco-hydrological model (TOPOG-IRM) on a small cropping rotation catchment. *Journal of Hydrology*, 191, 64–86.
- de Wit, C.T. 1958. Transpiration and crop yields. *Veersl. Landbouwk. Onderz.* 64.6 Institute of Biological and Chemical Research on Field Crops and Herbage, Wageningen, The Netherlands.
- Feedes, R.A., Bresler, E. and Neuman, S.P. 1974. Field test of a modified numerical model for water uptake by root systems. *Water Resources Research*, 10, 1199–1206.
- Feedes, R.A., Kowalik, P.J. and Zaradny, H. 1979. Simulation of field water use and crop yield. Wageningen, The Netherlands.
- Hanks, R.J. 1983. Yield and water-use relationships: an overview. In: Taylor, H.M., Jordan, W.R. and Sinclair, T.R., eds, *Limitations to efficient water use in crop production*. American Society of Agronomy, Crop Science Society of America, Soil Science Society of America.
- Hook, J.E. 1994. Using crop models to plant water withdrawals for irrigation in drought years. *Agricultural Systems*, 45, 271–289.
- Huang Mingbin, Shao Mingan and Li Yushan. 2001. Comparison of a modified statistical–dynamic water balance model with the numerical model WAVES and field measurements. *Agricultural Water Management*, 48(1), 21–25.
- Jagtap, S.S., Abamu, F.J. and Kling, J.G. 1999. Long-term assessment of nitrogen and variety technologies on attainable maize yields in Nigeria using CERES-maize. *Agricultural Systems*, 60, 77–86.
- Jones, H.G. and Tardieu, F. 1998. Modelling water relations of horticultural crops: a review. *Scientia Horticulturae*, 74, 21–46.

- Kang, S.Z., Liu, X.M., Gao, X.K. and Xiong, Y.Z. 1992. Simulation of water transportation in soil-plant-atmosphere continuum. *Journal of Hydraulic Engineering*, 3, 1–12 (in Chinese).
- Kang, S.Z., Liu, X.M. and Zhang, G.Y. 1993. Simulation of soil water and heat movement with crop canopy shading. *Journal of Hydraulic Engineering*, 3, 11–17 (in Chinese).
- Kang, S.Z., Liu, X.M. and Xiong, Y.Z. 1994. Theory of water transport in soil-plant-atmosphere continuum and its application. Water Resources and Hydro-Power Press of China, Beijing, 228 pp.
- Kang, S.Z. and Li, Y.J. 1997. Tendency and countermeasure of 21st century water-saving agriculture development in China. *Transactions of the Canadian Society of Association Executives*, 13, 1–7.
- Kang, S.Z., Zhang, L., Liang, Y.L. and Caia, H.J. 2000. Effects of limited irrigation on yield and water-use efficiency of winter wheat in the Loess Plateau of China. *Field Crops Research* (submitted).
- Leenhardt, D., Lafolie, F. and Bruckler, L. 1998. Evaluating irrigation strategies for lettuce by simulation: 1. Water flow simulations. *European Journal of Agronomy*, 8, 249–265.
- Nimah, M. N. and Hanks, R. J. 1973. Model for estimating soil water, plant and atmospheric interrelations: 2. Field test of model. *Soil Science Society of America Proceedings*, 37, 528–532.
- Nix, N.A. and Fitzpatrick, E.A. 1969. An index of crop water stress related to wheat and grain sorghum yields. *Agricultural Meteorology*, 6, 321–337.
- Olsen, S.R. and Sommers, L.E. 1982. Phosphorus. In: Page, A.L., Miller, R.H. and Keeney, D.R., eds, *Methods of Soil Analysis, Part 2, Chemical and Microbiological Properties*. Madison, WI, American Society of Agronomy, 403–448.
- Passioura, J.B. 1986. Resistance to drought and salinity: Avenues for improvement. *Australian Journal of Plant Physiology*, 13, 191–201.
- Perry, M.W. and D'Antuono, M.F. 1989. Yield improvement and associated characteristics of some Australian spring wheats introduced between 1860 and 1982. *Australian Journal of Agricultural Research*, 40, 458–472.
- Sankaran, V.M., Aggarwal, P.K. and Sinha, S.K. 2000. Improvement in wheat yields in northern India since 1965: measured and simulated trends. *Field Crops Research*, 66, 141–149.
- Siddique, K.H.M., Belford, R.K., Perry, M.W. and Tennant, D. 1989. Ear:stem ratio in old and modern wheat cultivars; relationship with improvement in number of grains per ear and yield. *Field Crops Research*, 21, 59–78.
- Wang, H.X., Zhang, L., Dawes, W.R. and Liu, C.M. 2001. Improving water use efficiency of irrigated crops in the North China Plain—measurements and modelling. *Agricultural Water Management*, 48, 151–167.
- Wu, H., Rykiel, E.J. Jr., Hatton, T. and Walker, J. 1994. An integrated rate methodology (IRM) for multi-factor growth rate modelling. *Ecological Modelling*, 73, 97–116.
- Zhang, L., Dawes, W.R. and Hatton, T.J. 1996. Modelling hydrologic processes using a biophysically based model—application of WAVES to FIFE and HAPEX-MOBILHY. *Journal of Hydrology*, 185, 147–169.
- Zhang, L. and Dawes, W. 1998. WAVES—An integrated energy and water balance model, CSIRO Land and Water Technical Report No. 31/98.
- Zhang, L., Dawes, W.R., Slavich, P.G., et al. 1999. Growth and ground water uptake responses of lucerne to changes in groundwater levels and salinity: lysimeter, isotope and modelling studies. *Agricultural Water Management*, 39, 267–284.