DOUBTFUL USEFULNESS OF CROP WATER PRODUCTION FUNCTIONS DERIVED FOR USE ON CANADIAN PRAIRIES

Y. W. JAME

Agriculture Canada Research Station
Swift Current, Saskatchewan

INTRODUCTION

In the semi-arid region of the Canadian prairies, water is the most limiting factor for crop production. Climatic demand for evapotranspiration during the growing season is often three or four times the amount of rainfall received. The importance of managing the limited precious water resources on the Canadian prairies is well recognized since the survival of our agricultural communities is dependent on how well we achieve this. Solutions to problems are continually being sought by farmers, extension personnel, researchers, and politicians for better management strategies that can be used to maximize efficient use of available water for crop production.

In order to apply any economic maximization technique to soil water management for crop production, a knowledge of the functional form of the relationship between crop yield and some measure of water use by the crop is required. This information is generally referred to as crop water production function. This paper will review the work done in the past regarding crop yield reponse to water and discuss different approaches for future research.

CONVENTIONAL FIELD EXPERIMENTATIONS: CORRELATION AND REGRESSIONAL ANALYSIS

Traditionally, on the Canadian prairies the crop water production functions were derived based on some simple assumptions that plant growth is directly related either to spring soil water content, growing season rainfall, total water use, irrigation amount, evapotranspiration deficit, or to many different combinations of these variables. Crop yields were generally expressed as polynomial or exponential functions of variables, with regression coefficients obtained through linear or nonlinear curve fitting procedures from a set of observed values. Usually, there was little consideration given to the physical and physiological processes involved.

There are myriad number of those crop water production functions being published for use on the Canadian Prairies. In many cases, crop yields were simply related to the sum of available spring soil moisture and growing season precipitation (Staple and Lahane 1954; Lahane and Staple 1965; de Jong and Rennie 1969). Some crop water functions were developed based on the

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assumption that plant growth is directly related to evapotranspiration (ET) or total water used (Henry et al 1986; Campbell et al. 1988). The water balance equation is often the basis for calculation of ET or total water use and is given as:

$$ET = I + P + S - R - D$$

where I is irrigation, P is precipitation, S is the change in soil water storage, R is runoff, and D is drainage below the root zone. The components of the above equation were either measured or estimated to obtain the value of ET.

Numerous functional forms have been proposed to describe relationships between crop yield and ET. Some of these are:

$$Y = a + b (ET)$$

$$Y = a + b (ET) + c (ET)^2$$

$$Y = a + b (ET) + c (ET)^2 + d (ET)^3$$

$$Y = a + b (ET) + c (ET)^{0.5}$$

$$Y = a (ET)^b$$

where Y is crop yield and a, b, c, d are regression coefficients. However, in all cases, the results were not satisfactory (Figures 1, 2). The scattered data indicate that the variation of crop yield with ET is very obvious.
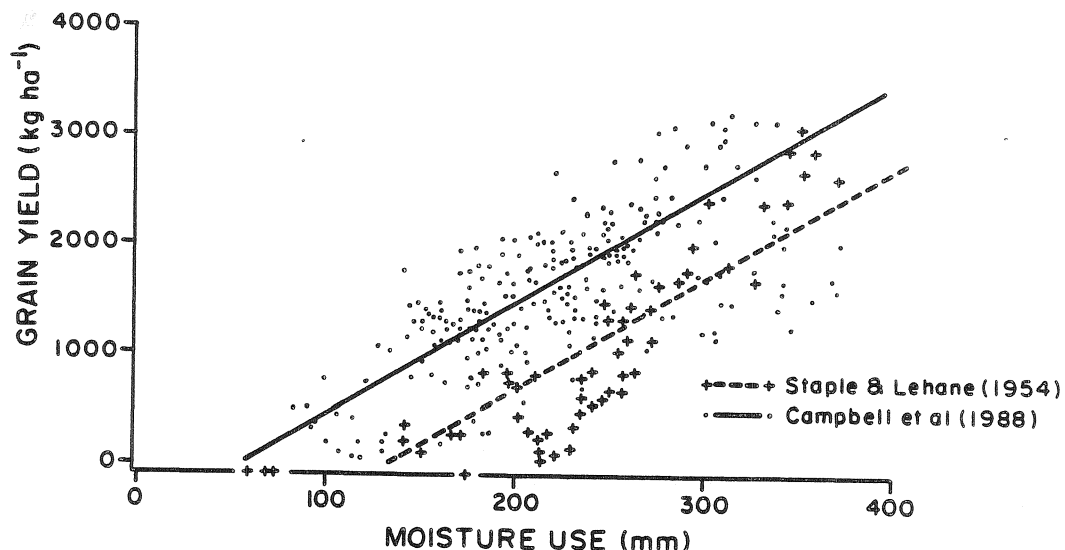

Figure 1. The relationship between wheat yield and total water use in Swift Current, Saskatchewan.

When crop yield was regressed with ET, some of the variation were

attributable to yearly changes of other climatic variables, such as temperature or solar radiation. To improve the reliability of prediction, the relationship between crop yield and evapotranspiration deficit (ETd) was suggested. For example:

$$Y = f (ETd)$$

or $$Y / Ym = f (ETd)$$

where ETd = 1 - ET/ETp, Y is actual crop yield, Ym is maximum crop yield when water is not a limiting factor, ETp is potential seasonal ET, and ET actual seasonal evapotranspiration. The relationships between the relative yield (Y / Ym) and the relative seasonal evapotranspiration (ET / ETp) were summarized for some major crops grown on the Canadian Prairies in the UMA report (1982). Figure 3 illustrates the type of variability encountered when data from different sources, experiments and years are combined.
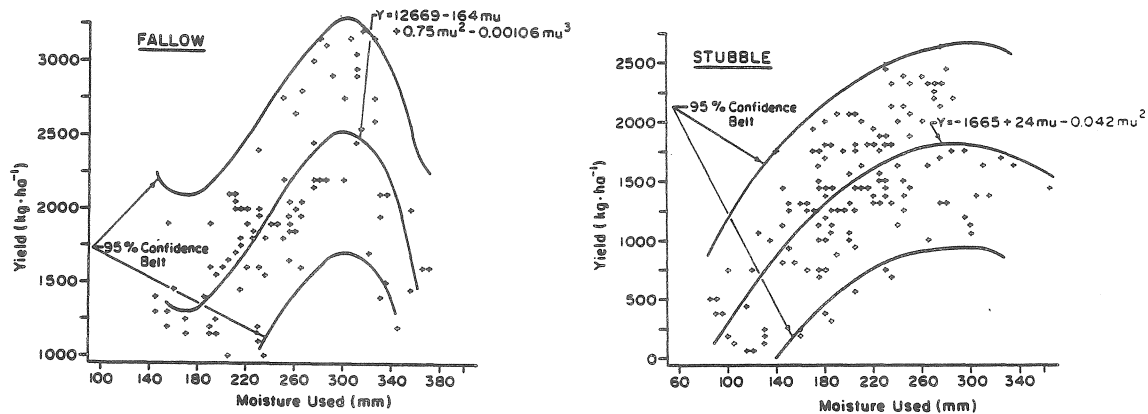

Figure 2. The relationships between yield and total water use for fallow-seeded (left) and stubble-seeded wheat (right) (Adopted from Campbell et al., 1988).

The simple relationship accounting only for seasonal ET may not predict well for grain production. This is because the components of grain yield (e.g. plant population, number of heads per plant, number of kernels per head, and kernel weight) are developing over different parts of the growing season and moisture stress may affect grain yield differently depending on the stage of growth at which it occurs. Thus the following crop water production functions were introduced to account growth stage effect:

$$Y/Y_m = \prod_{i=1}^{n} [1 - (1 - ET/ET_p)_i^2]^{\lambda_i}$$

$$Y/Y_m = \sum_{i=1}^{n} \lambda_i [1 - (1 - ET/ET_p)_i^2]$$

$$Y/Y_m = \prod_{i=1}^{n} (ET/ET_p)_i^{\lambda_i}$$

$$Y/Y_m = \sum_{i=1}^{n} \lambda_i (1-ET/ET_p)_i (Y_m - Y_i / Y_m)$$

$$Y/Y_m = \sum_{i=1}^{n} \lambda_i (ET_p - ET)_i / ET_p)$$

where i is an integer representing the number of growth sub-periods, and
Σ represents summation, Π multiplication,   and λ is a sensitivity
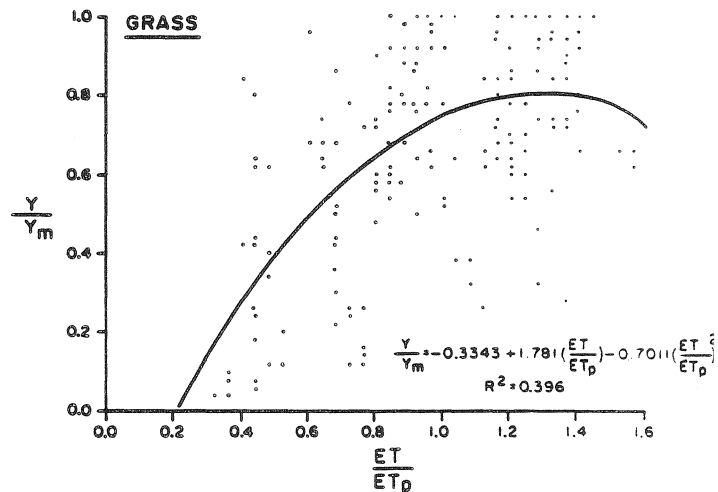factor of crop yield to water stress during growth sub-period i.
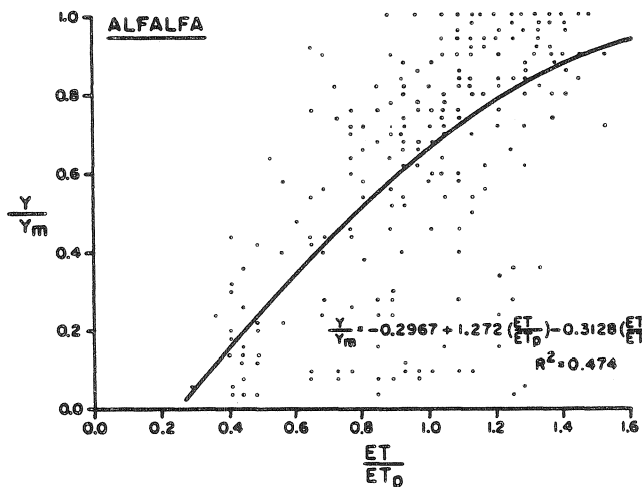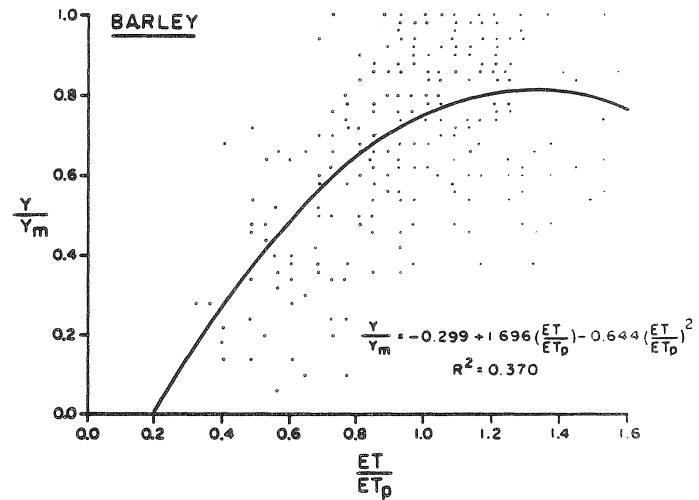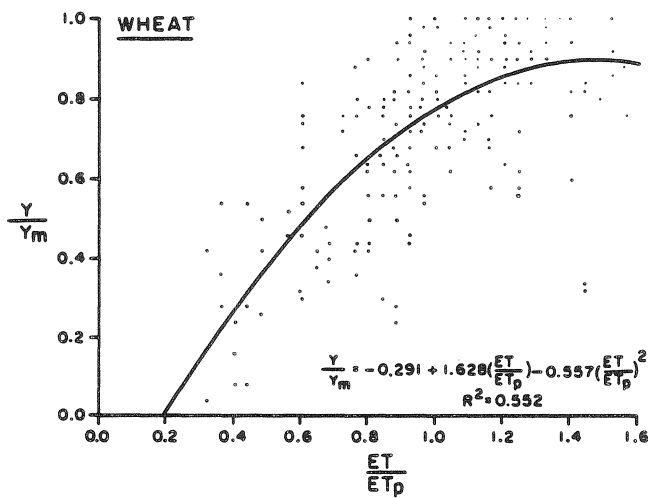

Figure 3. The relationships between Y/Y_m and ET/ET_p for wheat, barley,
    alfalfa and grass grown in agro-climate areas of Saskatchewan
    river basin (adapted from UMA, 1982).

The above-mentioned crop water production functions are either additive or multiplicative in nature. Some fundamental differences in approach when defining the sensitivity of growth stages are obvious. Some researchers (Stewart et al. 1975; Campbell et al. 1981) noted that the degree of severity and the sequencing of water stress govern whether or not there is an especially sensitive stage; others have assumed that there is a "critical" growth stage irrespective of the degree of water stress and the sequence of stress occurrence. Bauer (1973) indicated that water stress at flowering stage was the most damaging to grain yields of wheat. Campbell et al. (1988) found that under certain circumstances such as stubble cropping in semi-arid climates, the water content for germination may be more critical because the seed may lie in relatively dry surface layer resulting poor germination. In UMA report (1982), the following equation was used to account the growth stage effects:

$$Y / Ym = a_0 + a_1 (ET/ETp)_5 + a_2 (ET/ETp)_6 + a_3 (ET/ETp)_7$$

$$+ a_4 (ET/ETp)_8 + a_5 (ET/ETp)_9 + a_6 (ET/ETp)_5 *$$

$$(ET/ETp)_s + a_7 (ET/ETp)_6 * (ET/ETp)_s +$$

$$a_8 (ET/ETp)_7 * (ET/ETP)_s + a_9 (ET/ETp)_8 * (ET/ETp)_s$$

$$+ a_{10} (ET/ETp)_9 * (ET/ETp)_s$$

where $(ET/ETp)_5$, $_6$, $_7$, ...are for month of May, June, July, ... and $(ET/ETp)_s$ for growing season.

Singh et al. (1987) assessed those crop production functions which consider growth stage effects. They concluded that some of the functions performed better than others under a particular set of conditions, however, none performed satisfactorily under all conditions. This emphasized that those functions should be used with caution. It is evident that the effects of water stress at different growth stages and the effect of inter-stage dependence, if any, will only be thoroughly understood as the physiological processes governing plant growth and development are themselves better understood.

There are many other functional forms describing crop yield response to water. For example, Bole and Pittman (1980) related barley yield to soil stored available moisture (Ws), growing season precipitation (GSP) and nitrogen fertilizer (N) in the form:

$$Y = a + b_1 Ws + b_2 Ws^2 + b_3 GSP + b_4 GSP^2 + b_5 N$$

$$+ b_6 N^2 + b_7 Ws * GSP + b_8 Ws * N + b_9 GSP * N$$

$$+ b_{10} Ws * GSP * N$$

and Williams et al. (1975) used sixteen variables including time trend, soil texture, topograph, available soil moisture at seeding, potential ET, and evapotranspiration deficit for each month of May, June, and July to predict

crop yields of wheat, oat and barley.

These correlation-based crop water production functions are widely used on the Canadian Prairies. There is no doubt that the application of this type of analysis has made contributions in increasing and stabilizing agricultural production, in converting unproductive or marginal areas into useful agricultural land, and in providing some qualitative understanding of some of the interactions that were involved in the processes. However, it is also well understood that considerable care is required in their applications because of their simplifications. They should only be applied for the conditions under which the relationships were established. Thus, their use is fairly local; accuracy will be reduced considerably if applied outside the range of calibration. The information obtained can only be rigorously applied to some other sites where the sequence of climate and crops are identical to those used in developing the original functions, and where the soil parameters of consequence to the crop are similar. The chances of such coincidence on the Canadian Prairies are rare and hence quantitative applicability of this type of information is remote. How does one extrapolate those results to an almost infinite array of soil, weather patterns, crop, new cultivars, and management practices that occur across space and time, over the Canadian Prairies? Dispite much emphasis on research efforts, problems of how to manage the precious soil water resources more efficiently for crop production remain, due to our collective tendency to overgeneralized specific experience obtained in given set of circumstances and to extend our conclusions to situations in which they do not necessarily apply.

Beside the fact that the experiences obtained at one site are not readily transferable to other sites, the end result in term of accuracy for most of the correlation-based equations, even applied to the same site, is often not satisfactory. There is considerable body of experimental evidence showing that the relationship between crop yield and total water use is linear or curvilinear with correlation coefficient up to 0.8 - 0.9 when data were collected at the same site in a short term study. However, due to unavoidable variability associated with weather and field work, it generally takes a lengthy time (10 or 20 years) to develop relationships in order for meaningful interpretation to be obtained. Statistical evidence based on longer term studies on Candian prairies shows that from 30 to 40% of the total variation is usually associated with experimental error. An example of the relationship between wheat yield and total water use, along with five prediction equations commonly used in southern Saskatchewan are given in Figure 4. The data were obtained in the Brown and Dark Brown soil zones on Topographic Class 3 soils under the Innovative Acres Research and Development Project, which was initiated in 1982 (Rennie and deYong 1989). The scattered data indicate that the variation of grain yield with total water use is obvious. The correlation-based equations only result in a statistical "average". With such a large variation, statistical "average" provide little valuable information on identifying better management strategies that can be applied to maximize efficient use of the limited water available for crop production.

On the Canadian Prairies, risk related to variable and unpredictable climate is the most serious impediment to profitable and stable agriculture. Sensible farming decisions to maximize profit when opportunity exists and to

minimize loss when facing inclement weather are important strategies which farmers must make in order to survive on the Canadian prairies. Because the correlation and regression analysis only results in a statistical "average", it is a fundamental error to expect that this type of information will assist farmers in making those important decisions. Thus, searching for more efficient agricultural water management on the Canadian prairies, we need emphasis on three important areas that are related to climatic risk:

1. Development of prediction model and their use to improve quantification of risk;
2. Crop and soil management that reduces or buffers climatic risk;
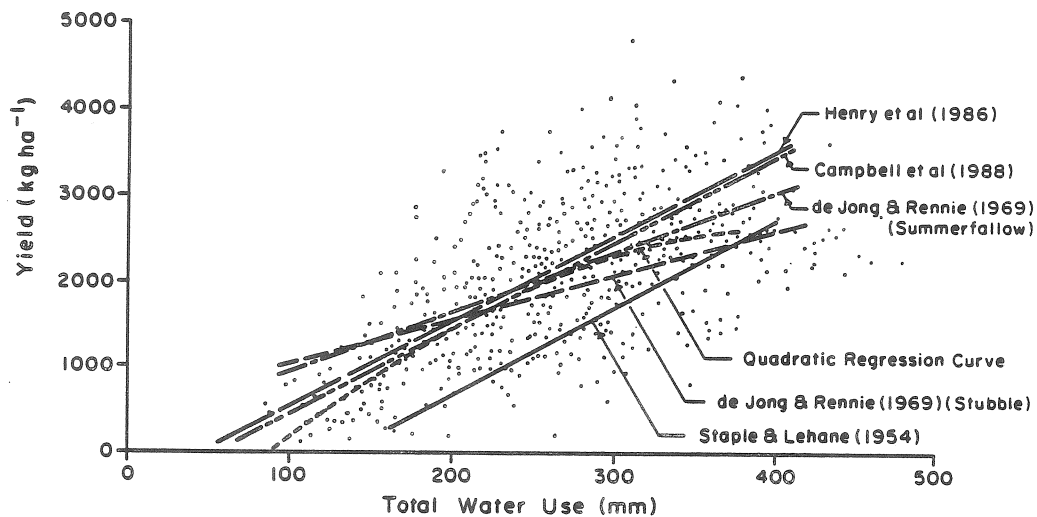3. Long range (i.e. growing season) weather forecasting that can enhance farm management

Figure 4. The relationships between wheat yeild and total water use in southern Saskatchewan. Observed data (.) were collected during 1982-1986 from Brown and Dark Brown soil zones on Topographic Class 3 soil under the Innovative Acres Research and Development project (Rennie and de Yong 1989).

In recent years, the development of explanatory crop growth simulation models has shown promise for increasing the opportunities of analyzing production potentials and developing appropriate techniques to achieve the above-listed items 1 and 2.

ALTERNATIVE APPROACH: PROCESS-BASED SIMULATION MODELS FOR FUTURE RESEARCH

In crop growth simulation models, attempts are made to consider all aspects of crop growth and water dynamics through the soil-plant-atmosphere system, based on firmly established Physical and physiological principles. A general overview description of a plant growth simulation model when water is the only limiting growth factor is given in Figure 5.

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Input Variables for Plant, Soil, Weather

t < t end — N → Stop

Y

Separation of potential Evaporation (Em) and Transpiration (Tm)

Calculation of Actual Evaporation (E)

Root Growth

Root Water Uptake and Actual Transpiration (T) ← (Hourly Time Step if Necessary)

Soil Water Flow ←

Calculation of Daily Photosynthetic

Growth Rate of Total Plant Biomass

Assimilate Distribution

Leaf Area Index

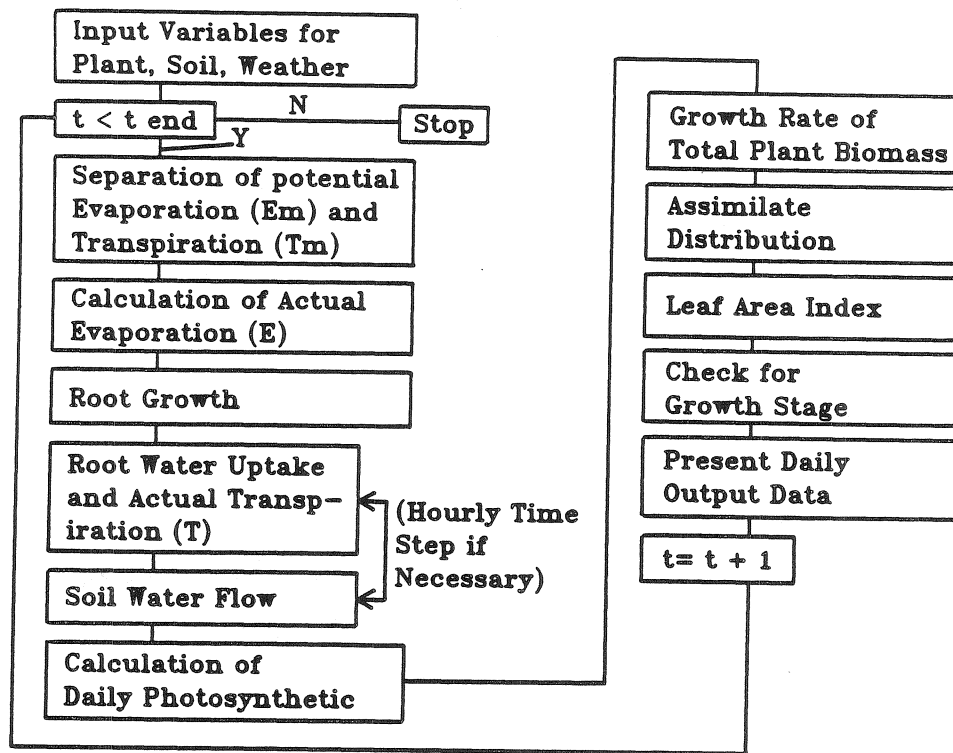Check for Growth Stage

Present Daily Output Data

t = t + 1

Figure 5. Flow diagram of dynamic plant growth simulation model.

In theory, a representation of all aspects of water dynamics in the soil-plant-atmosphere system and their influences on plant growth, based on soundly established physical and physiological understanding, should produce a crop water production model which would be applicable universally. Of course it is impossible at the present time to develop a model that embodies a perfect depiction of reality because not all the processes involving water flow in soil and plant and their influences on plant growth are fully understood. Thus, today's crop growth simulation models still are limitations of reality with some assumptions and simplifications. However, with continued research and increased understanding of such phenomena, those assumptions and simplifications will be gradually replaced by more physically and physiologically approaches when processes involved are understood. Although the advanced models become more complex, they are accompanied by increasing precision, generality, and explanatory power. This is a normal mode of progress.

There are many plant growth simulation models available (de Jong and Zentner 1985; Stewart and Dwyer 1985; Ritchie and Otter 1985; van Keulen and Seligman 1987; van Diepen et al. 1988; Willams et al. 1988; Walker 1989). They vary widely in aim, structure, and level of detail. Only few years ago, the literature was replete with a bewildering array of experimental studies not based on explicit theory, and their seemingly contradictory results could not be reconciled, owing to the absence of unifying concept.

However, due to the widespread availability of computer and analysis techniques capable of handling complex systems, nowadays it seemed that the opposite problem has appeared, namely, a plethora of theoretical models. Most models are virtually untested or poorly tested and hence unproven. It has become altogether easier to formulate models than to validate them.

Since not all the processes affecting plant growth and water flow in soil and plant are fully understood, all crop growth simulation models are approximations of reality with some assumptions and simplifications. A model needs extensive experimental calibration and validation. It should be tested not merely for its overall predictions but also for its component processes under widely differing sets of environmental conditions to assess whether the model is structurally sound, and as well, to assess the extent and limitations of it validity. Only after extensive and independent experimental validation, can a plant growth simulation model eventually become (no doubt after numerous modifications) an actually working tool capable of providing guidance in the practical management of agricultural systems.

When a complex crop growth simulation model is proven to be valid at an acceptable accuracy level, the possibilities inherent in the model are varied and numerous. The use of the crop growth simulation model to obtain the crop water production function, instead of using relationships derived exclusively from regression analysis of collected yield data, permits the extrapolation to other sites with different climatic and soil inputs. The model can also be used as a tool for quantifying the risk due to various climatic uncertainties; numerical experimentations in cases where field experiments are slow, expensive, or impossible; evaluating the possible impact of climatic changes or new agronomic practices on crop production; predicting the state of crop growing conditions and using the predictions for making sensible farming decisions; screening out which parameters affect most significantly the final output and identifying promising concept for plant breeding; and improving our understanding of the underlying processes and the importance of their interaction.

Many biophysical processes associated with plant growth are well known qualitatively. Many instruments for measuring water status of soil and plant are presently available. No longer are we constrained by computational capability. It may now be appropriate to restrict the number of correlation-based conventional experiments and replace some of them with completely instrumented and intensively monitored experiments to allow calibration and validation of process-based crop growth simulation models. With such information, a limited number of field trials would provide more quantitative, applicable, and less costly obtained information than the large number of uninstrumented trials now commonly employed.

CONCLUSIONS

The primary aim of establishing relationships between crop yield and water use is to identifying better management strategies that can be used to maximize efficient use of the limited available water for crop production on the Canadian Prairies. Traditionally, these relationships were derived from correlation-based regressional analysis. The ready-made correlation-

based solutions are specific and inflexible and will therefore rarely apply as new problems arise in varying circumstances.

With the ever-dwindling resources available for research, it is imperative that projects are focused on developing a better understanding of the physics of water dynamics in the soil-plant-atmosphere system and their influences on the physiology of plant growth with less emphasis on empirical correlation-based relationships. Research should build on the solid foundation of available knowledge, use the potential of the first-rate instruments that are available, and intergrate measurements with model development to assure validity of the process-based model.

The development of a process-based crop growth simulation model requires separate understanding of plant, soil and atmospheric factors which affect the soil water balance and plant growth. To reach the goal, we need close linkage among scientists of different disciplines; especially soil scientists, agrometeorologists, plant physiologists, plant breeders, engineers, and computer specialists. Multidisciplinary teams willing to work together in unison will be needed in order to develop optimun crop production systems to meet the challenge of managing our limited and unpredictable agricultural water resources more efficiently on the Canadian Prairies.

REFERENCES

Bauer, A. 1973. Effect of water supply and seasonal distribution on spring wheats. Agric. Experiment Station, North Dakota State Bulletin 490.

Bole, J.B. and U.J. Pittman. 1980. Spring soil water, precipitation, nitrogen fertilizer: Effect on barley yield. Can. J. Soil Sci. 60:461-469.

Campbell, C.A., H.R. Davidson and G.E. Winkleman. 1981. Effect of nitrogen, temperature, growth stage and duration of moisture stress on yield components and protein content of Manitou spring wheat. Can. J. Plant Sci. 61:549-563.

Campbell, C.A., R.P. Zentner and P.J. Johnson. 1988. Effect of crop rotation and fertilization on the quantitative relationship between spring wheat yield and moisture use in southwestern Saskatchewan. Can. J. Soil Sci. 68:1 -16.

de Jong, E. and D.A. Rennie. 1969. Effect of soil profile type and fertilizer on moisture use by wheat grown on fallow or stubble land. Can. J. Soil Sci. 49:189-197.

de Jong, R. and R.P. Zentner. 1985. Assessment of the SPAW model for semi-arid growing conditions with minimal local calibration. Agric. Water management 10:31-46.

Henry, J.L., J.B. Bole and R.C. Mckenzie. 1986. Effect of nitrogen water interactions on yield and quality of wheat in western Canada. In:

Wheat Production in Canada - A Review (A.E. Slinkard and D.B. Fowler Ed.). Proc. Can. Wheat Production Symp. Univ. of Saskatchewan, Saskatoon. 165-191.

Lehane, J.J. and W.J. Staple. 1965. Influence of soil texture, depth of soil moisture storage, and rainfall distribution on wheat yields in southwestern Saskatchewan. Can. J. Soil Sci. 45:207-219.

Rennie D.A. and E. DeYong. 1989. Innovation acres: Maintaining productivity and soil quality. AgriScience. December 1989:5-7.

Ritchie, J.T. and S. Otter. 1985. Description and performance of CERES-wheat: A user-oriented wheat yield model. In: ARS wheat project. U. S. Dept. of Agric. ARS-38:159-175.

Singh, P., H. Wolkewitz and R. Kumar. 1987. Comparative performance of different crop production functions for wheat (Triticum aestivum L.). Irrig. Sci. 8:273-290.

Staple, W.J. and J.J. Lehane. 1954. Weather conditions influencing wheat yield in tanks and field plots. Can. J. Agric. Sci. 34:552-564.

Stewart, D.W. and L.M. Dwyer. 1985. A resistance model for water balance calculations and yield estimates of spring wheat. In: Advance in Evapotranspiration. Proc. National Conf. on Advances in Evapotranspiration. Am. Soc. Agric. Eng.:170-176.

Stewart, J.I., R.D. Misra, W.O. Pruitt, and R.M. Hagan. 1975. Irrigating corn and grain sorghum with a deficit water supply. Trans. ASAE 18:270-280.

UMA Report. 1982. South Saskatchewan river basin planning program: Agronomy component - Irrigation water requirement criteria study. Prepared for the Goverment of the province of Alberta Department of the Environment Planning Division by Underwood Mclellan Ltd.

Van Diepen, C.A., C. Rappoldt, J. Wolf, and H. van Kenlen. 1988. Crop growth simulation model WOFOST version 4-1. Documentation. SOW - 88-01. Center for World Food Studies, Wageningen.

Van Keulen, H. and N.G. Seligman. 1987. Simulation of water use, nitrogen nutrition and growth of a spring wheat crop. PUDOC Wageningen. 310 pp.

Walker, G.K. 1989. Model for operational forecasting of Western Canada wheat yield. Agric. Forest Meteorol. 44:339-351.

Williams, G.D.V., M.I. Joynt and P.A. McCormick. 1975. Regression analyses of Canadian Prairies crop-district cereal yields, 1961-1972, in relation to weather, soil and trend. Can. J. Soil Sci. 55:43-53.

Williams, G.D.V., R.A. Fautley, K.H. Jones, R.B. Stewart, and E. E. Wheaton. 1988. Estimating effects of climatic change on agriculture in Saskatchewan, Canada. In: The Impact of Climatic Variations on Agriculture (M.L. Parry, T.R. Carter, and N.T. Konijn Eds.). Kluwer Academic Publishers:220-320.