14 The crop model record: promise or poor show?

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'...model building is an enjoyable if arduous task whereas model testing can be heartbreak­ing. Perhaps this is why so many crop models are published without being tested...’ (Whisler et al., 1986)

'A recurring observation as one reviews the literature of computer-based medical decision making is that essentially none of the systems has been effectively utilized outside of a research environment, even when its performance has been shown to be excellent.' (Short-liffe et al., 1979)

14.1 Introduction

At a symposium held on the occasion of the 50th anniversary of agricultural research in Israel, Professor C.T. de Wit gave a survey of achievements in worldwide agricultural research. He maintained that 500 years was a more appropriate period to review, because the last major contribution was Liebig's Chemistry in its Application to Agriculture and Physiology published in 1840. Many would contest this thesis, but whatever other minor achievements there may have been in the interim, can Theoretical Production Ecology be relegated to the same bleak category? Or should we regard de Wit's contribution as the remodelling and development of an age-old discipline traceable to Joseph’s long-term yield predictions that were based on esoteric theory and flimsy data but were successfully applied to guide strategic food-security planning? More recently in 1735, Réaumur had the idea of relating day-degrees to phenological development and so conceived one of the more robust 'summary models' (or 'conservative relations' sensu Monteith, Chapter 1) that lives on to this day (Alm et al., 1988; Hesketh et al., 1988). Within this ancient discipline, the year 1958 could mark the beginning of the modern era (if not the revival) of theoretical production ecology when de Wit, in Transpiration and Crop Yields first defined the now well-known 'conservative relationship' underlying the mass of empirical data accumulated by Briggs & Shantz (1913) and others. This was soon followed by Photosynthesis of Leaf Canopies in 1965 which ushered in the computer as the instrument for simulating crop growth.

In the following years, crop models proliferated in a worldwide endeavour to describe the growth processes and explain the behaviour and yield potential of crops. At first, the motivation was probably scientific curiosity and a desire to exploit the possibilities offered by the modern computer. This was soon followed by the expectation (or rationalization?) that comprehensive explanatory analysis of growth processes would contribute to better research, plant breeding, crop
management and agricultural education. But already in 1973, John Passioura ridiculed the excessive enthusiasm then prevalent for complex crop models. Eight years later Monteith (1981) echoed the same sentiments. This evaluation is still very widespread even if not published explicitly. The function of crop models in research is indeed barely perceptible in the flood of professional literature that fills the agricultural libraries, and their impact on the farm planning and farm management scene is probably even less. Yet crop models are still proliferating and their merits are still being extolled, especially by the practitioners themselves (Whisler et al., 1986; de Wit & Penning de Vries, 1985; van Keulen, 1983; Loomis et al., 1979). The popular texts on simulation modelling published by de Wit & Goudriaan (1978) have been followed by others more specifically directed at crop modelling (van Keulen & Wolf, 1986; Penning de Vries & van Laar, 1982). This is an appropriate moment to look back and try to see whether crop models have lived up to expectations and to guess what promise there is for the future of this branch of theoretical production ecology. The answers are necessary not only to counter the critics, but especially to clarify some of the issues that face agricultural research at a critical crossroads when the traditionally generous government support is, in many countries, becoming a thing of the past (Brown, 1987; de Wit et al., 1987).

14.2 The crop model rationale

Mathematical models are the foundation of modern physical science. Biology submits reluctantly to the rigours of mathematics, but it must rely on it for describing and structuring many quantitative aspects of biological function (France & Thornley, 1984; Thornley, 1976). The integration of functions describing growth processes into a dynamic mathematical system has become a practical and exciting adjunct to experiments in crop photosynthesis, respiration and transpiration, and has made it possible to test assumptions about canopy growth processes in a consistent and comprehensive conceptual framework (de Wit et al., 1978; de Wit, 1970). Crop models have gone one step further in simulating a full cropping cycle from germination through to harvest maturity and analysing its response to a variable soil and aerial environment.

Crop modellers are keenly aware of the complexity of a crop and have recognized the simplistic nature of even a comprehensive model (Whisler et al., 1986; de Wit, 1970). The approach to defining the simplified system has varied widely not only with the varying objectives of different practitioners, but also with their preferences and capabilities. As a result, crop models range from very detailed process models like the cotton model GOSSYM (Whisler et al., 1986) and the soya bean model SOYMOMD (Meyer et al., 1979) to the relatively simple 'summary' models like the cotton crop models developed by Wallach et al. (1980). At least 14 crops have been modelled by different groups in various countries (Whisler et al., 1986) and there are numerous published models of different crops. Among them, more than 12 wheat models have appeared (including van Keulen
& Seligman, 1987; Angus & Moncur, 1985; O'Leary et al., 1985; Stapper, 1984; Weir et al., 1984; Hochman, 1982).

Extension of simulation models to the crop level has been undertaken for a variety of reasons that typically include: hypothesis generation and hypothesis testing, sensitivity analysis, finding ‘gaps in knowledge about the system’ as a guide for further research, interdisciplinary integration, improved crop management strategies, regional planning, identification and evaluation of plant characteristics that can help to define plant breeding aims. Other spin-off objectives include better communication between research workers in different fields and better understanding of complex crop responses. We can discuss these objectives under the headings: research, yield prediction and agricultural planning, farm management, and education. Some of the representative models can serve as indicators of the state of the art.

14.3 Research

The canopy photosynthesis model of de Wit (1965) and the subsequent comprehensive models of assimilation, respiration and transpiration (de Wit et al., 1978) set out to explain some quantitative aspects of crop growth in terms of the underlying processes. These models and others that were developed at the time (e.g. Loomis et al., 1967) dealt mainly with the question of potential growth and established what today appear to be the biological limits for agricultural production (Loomis & Williams, 1963). They set benchmarks for measuring agricultural achievement and defined production goals that were soon shown to be approachable technologically. They were used as vehicles for speculative thinking about crop behaviour and put previously qualitative questions like leaf angle effects on canopy photosynthesis into a quantitative context (Loomis et al., 1967; de Wit, 1965).

Later studies on respiration widened the scope of the photosynthesis models (Penning de Vries, 1974; 1975). Detailed crop micrometeorology models (Goudriaan, 1977) coupled with photosynthesis and transpiration models (de Wit et al., 1978) gave rise to process-based summary models (Goudriaan, 1986; Goudriaan & van Laar, 1978) and more elegant plant environment models (Chen, 1984). All these contributed to the refinement of specific crop models, that included both comprehensive models (Ng & Loomis, 1984; Fick et al., 1973) as well as summary models of plant growth and soil water processes. One of the first of these was ARID CROP, a model of annual grassland production (van Keulen et al., 1981; van Keulen, 1975).

Some of the achievements of the modelling activity of this period were quite impressive. An example is the study of growth in semi-arid conditions where in many years, potential production was shown to be limited by nutrient deficiency rather than by lack of water (van Keulen, 1975). These findings set the stage for comprehensive research projects on primary production in Israel and in the Sahel (Penning de Vries & Djitêye, 1982; van Keulen et al., 1982). The Sahel project was
subsequently awarded a special prize of merit by the Dutch Ministry of the Environment.

Whereas the first wave of plant growth simulation models produced demonstrably valuable insights into the quantitative aspects of plant growth, in the second stage the achievements tended to be more diffuse. In many cases, the added complexity of plant development, ontogeny and assimilate allocation to different plant organs, on the one hand, and the convergence on finer and more specific performance criteria, on the other, made it increasingly difficult to clearly demonstrate new findings or insights. So, for example, a well-validated model was used to examine possible reasons for the decline in cotton yields in the U.S.A. since 1965 after a threefold increase between 1935 and 1965 (Reddy et al., 1987). The model showed that impairment of root function, possibly as a result of herbicide effects, could have accounted for yield decline. This may have helped to draw attention to the problem even though herbicide damage to roots and consequent yield reduction had been demonstrated experimentally 20 years previously.

One of the applications of crop models is to examine the sensitivity of crop response to changes in plant characteristics so as to define breeding aims. However, there are very few examples of a breeding programme that was inspired by a crop model. Whisler et al. (1986) discuss a simulation analysis to determine the effect on cotton crop performance of different water use strategies where leaves were either 'water-savers' or 'water-spenders'. This characteristic was identified experimentally as a possible means of manipulating water use efficiency under certain conditions (Roark & Quisenberry, 1977). It was later found that a water-saving strategy indeed led to higher yields under dry conditions (Quisenberry et al., 1985). The simulation model GOSSYM 'confirmed' the result. But '...the use of physical/physiological process orientated crop simulation models in crop system design, including breeding, is still in its infancy...' (Whisler et al., 1986). Consequently, the 'acceptability' of simulation models among plant breeders is very uncommon. In fact, most crop simulation models have had very limited transferability to any other discipline, and at best have served the immediate purposes of the scientist or team that assembled them.

The successful research model could well be a model that fails – but for the right reasons – even though models that succeed, even if for the wrong reasons, are generally more popular (Klemes, 1986). In a study of water stress in wheat, growth could not be simulated adequately for certain stress conditions (Hochman, 1982). On closer analysis, it appeared that the assumption that stomatal response would be unimpaired after stress had been removed, was an oversimplification for such conditions. While the simulation identified a problem, it also proved (again) that under stress conditions, the responses of the plant can bring elusive processes into play. As such conditions are common for most crops, the crop model often treads dangerous ground.

In many cases, the insights gained from crop model analysis tend to be trivial or highly equivocal. As in so many areas of research, it is much easier to find good
answers than to formulate good questions. But the search goes on and the use of simulation models as 'research models' has continued and still raises expectations (Whisler et al., 1986). Some of the insights have been anything but trivial. The analysis of effects of CO₂ control of stomatal opening on assimilation and transpiration is probably one of the better examples (de Wit et al., 1978).

### 14.4 Yield prediction and farm planning

Comprehensive crop models have not excelled as yield predictors, mainly because of the large data base they require and the heterogeneity of large areas for which yield predictions are necessary. As a rule, yield prediction has depended on statistical regression models, sometimes improved by accounting for the soil moisture balance (Baier & Robertson, 1968) or by calculating crop transpiration with simplified procedures (Zaban, 1981). In order to overcome some of the unforeseen vagaries of weather and crop, models have been developed which use field data for repeated updating. A tulip bulb model uses intermediate harvests to update the yield prediction (Benschop, 1985) but the model has not been applied in practice.

A study of the use of remote sensing to update crop models for yield prediction indicated that updating the initialization of a simple crop model with the accumulated interim remote sensing data gives more stable estimates of final grain yield than updating based on the most recent measurement of crop status (Maas, 1988). There are cases where leaf area estimates with remote sensing appear to be more accurate than those derived from leaf area models, but routine application is hampered by problems of consistency in interpretation of data, mainly because of the effect of canopy architecture and variable optical characteristics of the crop on the reflected radiation, as well as by problems of cloud cover, long repeat cycles, cost and availability of satellite data (Kanemasu et al., 1985). Yield predictors for alfalfa based on a simple model have been proposed by Fick (1984), and numerous attempts have been made to use crop models for yield prediction in greenhouse crops. These have ranged from simple regression models (Liebig, 1981) to comprehensive crop models (Shina, 1988). Routine use of such models has not yet been implemented on a commercial scale.

Crop models have been used for estimating expected yields in areas where the crop has not been grown before (Fukai & Hammer, 1987). Passiouura (1973) felt that an expert in the crop of interest would make a more reliable estimate. That is usually an untested hypothesis – perhaps fortunately – for the modeller or for the expert. Crop models based on relatively simple biological relationships are being used in routines for planning optimum farm management strategies in collaboration with extension services (Kingwell & Pannell, 1987). These are still being actively developed.
14.5 Management

‘Will computer software replace the coffee shop?’ (Wink, 1988a). The considerable effort being invested in the development of crop models for farm management applications has been documented by Doyle & Edwards, 1986; Whisler et al., 1986; Fishman et al., 1985; Nordblom et al., 1985; Rotz, 1985; Savoie et al., 1985; Smith et al., 1985; Thanel et al., 1985; Wallach et al., 1980, and others. Some crop models have been incorporated into systems for optimum management of the greenhouse environment (Shina, 1988; Liebig, 1981; Challa & van de Vooren, 1980; Challa et al., 1980; Seginer, 1980). Some are part of pest management programmes (Barlow, 1985; Rabbinge & Rijsdijk, 1983; Hearn et al., 1981; Wallach et al., 1980). The ‘crop component’ in these management models can be anything from a full-blown comprehensive model (Whisler et al., 1986) to relatively simple summary models (Barlow 1985; Rabbinge & Rijsdijk, 1983; Wallach et al., 1980), some of which are embedded in advanced optimization routines (e.g. Chen, 1986). Those that have very simple constant biological relationships (e.g. Hepp, 1988) seem to be accepted more readily than more complex models. A revised version of the model ARID CROP (Ungar & van Keulen, 1982; van Keulen et al., 1981) has been used to evaluate the long-term overall stability of different grazing and feeding strategies in the semi-arid region (Ungar, 1985). The identification of large areas of high stability even under fluctuating growing conditions is of interest in itself even if the model is not being used directly for management.

For management and planning purposes, model formulation is more like an engineering project where problem specifications determine the level of resolution and efficiency required. Pragmatic rather than scientific criteria for success would be a more appropriate guide for evaluation in such situations. The successful projects that use crop models are on the whole aimed at improving disease and pest control decisions (Rabbinge & Rijsdijk, 1983; Hearn et al., 1981) and have become accepted relatively widely, although initial enthusiasm for some successful applications has not always been maintained over time (Daamen & van der Vliet, 1988). Others have been relatively simple models aimed at specific operations like timing of boll opening in cotton so as to improve scheduling of harvesting operations (Wallach et al., 1980). Some crop models developed for aiding pest control decisions have been difficult to maintain because of changes in the resistance and parameters of population dynamics of the pest, as well as unusual crop responses that were neither foreseen nor understood (E. Kletter, personal communication). It has been even more difficult to raise-end-user enthusiasm for the use of comprehensive crop models. ‘Perhaps the most extensive crop simulation evaluation effort to date is that of Marani & Baker (1981). They made several improvements in GOSSYM...were able to obtain good simulation of seasonal time courses...’ (Whisler et al., 1986). Whereas the model itself did not gain farmer acceptance in Israel, a summary model for irrigation scheduling was applied to a limited extent. In the U.S.A., a project has been
launched to use GOSSYM as part of an expert system in cotton extension (Whisler et al., 1986). In Australia, a cotton pest control model has attained relatively wide support and acceptance (Hearn et al., 1981).

The difficulties encountered in attaining acceptability of crop models of any level of complexity are apparently very common. In Michigan, U.S.A., a powerful, well-run, computerized farm accounting system is used mainly for income-tax accounting, even though individual enterprise analysis is available on request (Harsh et al., 1988). Budget-orientated software specially tailored for farmers' needs, based upon simple bio-economic crop models, have been developed for many farm decision situations. They have been used on farms only to a limited extent, and then mainly by extension and consulting agencies. Similar problems of acceptability occur in the field of medical decision aids (Shortliffe et al., 1979), and are possibly related to different ways of thinking appropriate to different types of activity. Practitioners often find abstract, hypothetical thought processes inappropriate or even inadequate for the multidimensional multiple-objective reality in which they must perforce operate. Whatever the reason, and despite the considerable effort invested in crop management models, their impact on farm practice has been very small. The new farm generation that has grown up with computers may find wider use for them, but that remains to be seen.

14.6 Education

Building a crop model or a version of a crop model can be a valuable heuristic experience. Not only is it necessary to become acquainted with a large body of literature, but the act of testing the adequacy of one's perception of the target system is generally very sobering. Most crop models that apply to new situations require 'adjustment' that can range from valid setting of boundary conditions, to model development that takes into account phenomena previously ignored (Penning de Vries et al., 1987; Steiner et al., 1987; Reddy et al., 1985). Unwarranted 'fiddling' with parameter values can make the simulation study '...the most cumbersome method of curve-fitting yet devised' (de Wit, 1970). Yet sometimes, 'fiddling' as part of a careful sensitivity analysis can be a useful educational tool (Penning de Vries et al., 1987).

Crop models have been the subject of a number of doctoral and masters theses (e.g. Shina, 1988; Stapper, 1984; Dayan, 1978; Morgan, 1976; van Keulen, 1975) and have been part of simulation courses that have been given 'to spread the gospel' (van Keulen & Wolf, 1986; Penning de Vries & van Laar, 1982). An interesting project on the simulation of rice cultivation problems in Southeast Asia involved an international group of crop, soil and plant protection scientists who, after the course, went home again and prepared case studies on disease and pest problems, nitrogen nutrition, sowing dates, planting density, iron toxicity effects, genotype variation, etc. (Penning de Vries et al., 1988). The results of these studies were presented at a concluding symposium about 8 months later (Penning de Vries et al., 1987). The course raised much enthusiasm among the participants.
and the majority felt that they had gained a valuable research ability. The results of the case studies indicate that ‘transfer of the technology’ is feasible, especially with the increasing availability of powerful PCs. On the other hand, the results of the case studies highlight some of the chronic problems encountered when using crop models in practice. Even though the course participants could draw upon the expertise of the course supervisors and worked on a model that had been prepared by experienced scientists, the results of the case studies tended to reveal the inadequacies of the model for the specific problem chosen, even after adjustment. Most conclude with a statement that ‘...more research is necessary...’. (Unequivocal results were obtained only in a long-term problem where there was no opportunity to validate the model!) These case studies were admittedly prepared by novices in the field and so should not be judged too harshly. The point is that even after much preparatory work, the application of crop models in specific situations still requires much experience and effort. Even so, the exercise certainly encouraged interdisciplinary activity, gave the participants a clearer picture of the sensitivity of the systems they study, and indicated areas where they thought more research would be useful.

14.7 The balance of achievement

The principles guiding valid crop modelling were discussed by de Wit (1970) and the requirements for the acceptability of models in practice have been defined repeatedly (Harsh et al., 1988; Shortliffe & Clancey, 1984; Charlton & Street, 1975). Nevertheless, crop modelling has not matured over 25 years to a stage where its function and utility is no longer open to question. The objectives that were set for different crop models covered a wide range from research through to applications in management and agricultural development planning. The record is uneven, but probably stands up best to scrutiny in a research environment where, when used judiciously in conjunction with experimentation, it has inspired structured research programmes that have increased understanding of crop behaviour and, in particular, of potential production limits (Whisler et al., 1986; de Wit et al., 1978). Certainly, crop models provide an effective means for ‘falsifying’ hypotheses about crop growth (as any crop modeller soon learns!) and as long as they continue to do so, their role in the future of agricultural research could well be assured. They can also highlight the equivocal nature of many experimental ‘facts’ (van Keulen & Seligman, 1987).

The greater understanding gained from crop modelling, or, for that matter from other branches of agro-biological research, does not necessarily lead to significant application in the short run (Spedding, 1979). Crop plants and the production systems in which they operate exhibit a ‘conservatism’ that is the basis of the robust and generally predictable functioning on which the farmer depends. This conservatism sets limits that are more severe than those that face engineering technology. As a result, the eventual impact on farm practice of crop models developed in a research context is diffuse by the nature of things. It can be
expressed indirectly by various pathways, including better interdisciplinary communication and collaboration in research. Research models have had no noticeable effect on plant breeding aims and practice, possibly because breeding is concerned more with relatively unequivocal objectives like pest and disease resistance, increased tolerance to environmental constraints like heat, cold, drought and salinity, improvement of quality, appearance, product uniformity, shelf-life, etc. The importance of these objectives is self-evident and crop models seem to have little more to offer. Crop models that can estimate the importance of identifiable plant characteristics for determining long-term yield increase and yield stability should have been able to contribute to defining plant breeding aims, but this has not been evident.

Possibly the greater disappointment in crop model performance is in the field of farm management. There are surprisingly few examples of successful applications, even when the models have been specially tailored for use by farmers or extension personnel. Shortliffe & Clancey (1984) summarized a similar problem in the development of computer-aided medical diagnosis systems. They suggest that in addition to accuracy of decisions it should be shown that there is a demonstrated need for the system, that it performs at least as well as an expert and, among other characteristics, is cost-effective. They conclude that ‘...remarkably few [systems] have met...the criterion of need...’ This ‘need’ may also be difficult to demonstrate in the case of crop models for management purposes, partly because farm practice ‘...includes many non-scientific factors that make for some confusion as to just what science can contribute...’ (Spedding, 1979). This may be the reason why the coffee shop (Wink, 1988a), or the pub, is still a preferred venue for exchange of management information.

Consultants and extension personnel may well find that crop models already meet some of their needs and improve the service they can provide for the farmer. The field is still wide open and progress will probably come with experience and with better understanding of the role that biological and bio-economic models can play in farm management, planning and development.

14.8 Conclusion

Although the crop modelling record has chalked up many disappointing performances and dead ends, it achievements, especially in research and education have been impressive and, judging by the continuing interest and activity, the future of crop modelling has just begun. If ‘...the next generation of agricultural plants and animals is but a gleam in the eyes of molecular biologists...’ (Wink, 1988b), should crop modellers be any less optimistic? A central aim, if not the ultimate challenge of crop research, is to explain crop behaviour. Crop models are a powerful tool for testing our understanding of crop behaviour – as the frequent discrepancies between model and reality so eloquently testify! The valid use of models to falsify hypotheses in an integrated crop context and as part of a research programme, surely is reason enough not to ‘...declare a moratorium...’
on crop modelling (Monteith, 1981).

The crop simulation approach pioneered by de Wit and the Wageningen school of Theoretical Production Ecology has had a recognizable and increasing influence on agricultural science worldwide. It is a developing technique and the onus is on the ingenuity and perspicacity of agricultural scientists to find appropriate applications. Although the more ambitious expectations have yet to be fulfilled, this should not deter the new generation of crop modellers. It should be a source of encouragement to them that, even after de Wit, there are still major challenges ahead!

14.9 Acknowledgments

‘Fools rush in where angels fear to tread’ is the pervading feeling one has after attempting to evaluate the record of crop models, particularly after illuminating discussions on the subject with G. Stanhill, I. Noy-Meir, Z. Enoch, H. Talpaz, E.D. Ungar, I. Spharim, E. Kletter and H. van Keulen. If there is any substance to this review, then most of the credit goes to them.

14.10 References

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