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A Review of Crop Growth Simulation Models as Tools for Agricultural Meteorology

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Abstract

The Earth's land resources are finite, whereas the number of people that the land must support increases rapidly, this situation has been a great concern in the area of agriculture. Crop production must be increased to meet the rapidly growing food demands through sophisticated agricultural processes, while it is important to protect other natural resources and the environment. New agricultural research is needed to provide additional information to farmers, policy makers and other decision makers on how to accomplish sustainable agriculture over the wide variations in climate change around the world. Therefore many researchers have over the years shown interest in finding ways to estimate the yield of crops before harvest. This paper reviews some of the crop growth models that have been successfully developed and used over time. The applications of crop growth models in agricultural meteorology, the role that climate changes play in these models and few of the successfully used crop models in agro-meteorology are also discussed in detail.

Keywords

Simulate, Aggregation, Automated Stations, Solar Radiation, Policy Management

1. Introduction

Crop production is made up of an aggregation of individual plant species grown in a unit area with the aim of having an irreversible increase in the growth, sizes and volume of seeds or consumables from these plants, which are harvested for economic purposes. Ultimately, the breeders can anticipate future requirements based on the climate change by simulating the characteristics of the natural environmental system that studied in an abbreviated time scale through an appropriate model. A model is a schematic representation of the conception of a system or an act of mimicry or a set of equations which represent the behavior of a system, with the purpose of

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aiding, understanding and improving performance of the system.

Crop models can be used to understand the effects of climate change such as elevated carbon-dioxide, changes in temperature and rainfall on crop development, growth and yield. For example, a change in weather to warm and humid may lead to more rapid development of a plant disease, a loss in yield of a crop, and consequent financial adversity for individual farmers and for the people of the region. Most natural systems are complex and many do not have boundaries. It is a difficult task to produce a comprehensible, operational representation of a part of reality, which grasps the essential elements and mechanisms of that real world system and even more demanding, when the complex systems encountered in environmental management [1].

The bio-system is made up of a complex interaction among the soil, the atmosphere, and the plants that live in it. The alteration of one element may yield both a desirable and undesirable consequence. Minimizing the undesirable, while reaching the desired end result, is the principle aim of the agro-meteorologist. In any physics work related to agricultural meteorology, the use of mathematical modeling is essential. Of the different modeling techniques, mathematical modeling enables one to predict the behavior of design while keeping the expense at a minimum. Agricultural systems are basically a modified ecosystems and managing these systems is very difficult [1].

In ancient times, appearances in the air were called meteors [2]. In the first half of the 20th century, the upper soil layers were considered as part of meteorology [3]. Today meteorology is understood in a very general sense to be the science of the atmosphere [4]-[6] and includes also the mean states (climatology). Sometimes the definition of meteorology is very narrow, and only related to the physics of the atmosphere or weather prediction.

Micrometeorology is a branch of meteorology which deals with the atmospheric phenomena (observations) and processes at the lower end of the spectrum of atmospheric scales, which are variously characterized as micro scale, small-scale or local scale processes [7]. The scope of meteorology is limited to only phenomena which originate in and are dominated by the shallow layer of frictional influence adjoining the earth's atmosphere, commonly known as atmospheric boundary layer or planetary boundary layer. In particular, micrometeorology deals with the exchange of heat (energy), mass and momentum occurring continuously between the atmosphere and the earth's surface, including sub surface medium [7].

Meteorology is subdivided into branches [5] [6] [8] [9]. According to [2], the branches of micrometeorology are the theoretical meteorology, observational meteorology, and applied meteorology. Applied meteorology includes weather prediction and climatology and is sub divided into: hydro meteorology; technical meteorology which includes Construction meteorology, Traffic (Transport) meteorology, and Industrial meteorology; and bio meteorology which includes Agricultural meteorology (Phenology), Forest meteorology and Human meteorology.

This paper aims at reviewing some of the crop growth models that have been successfully developed and used over time and also providing additional information to farmers, policy makers and other decision makers on how to accomplish sustainable agriculture over the wide variations in climate change around the world.

Types of Models

There are different types of models that have been developed over the years, and they can be classified into various groups or types, ranging from empirical models to explanatory models. Empirical models are based on the direct descriptions of observed data and are generally expressed as regression equations (with one or a few factors) and are used to estimate the final yield. This approach primarily examines the data, decides on an equation or set of equations and fits them to data. These models give no information on the mechanisms that give rise to the response. Examples of such models include those in agricultural experiment such as the response of crop yield to fertilizer application, the relationship between leaf area and leaf size in a given plant species and the relationship between stalk height alone or coupled with stalk number, diameter and final yield [1].

Mechanistic models, explain not only the relationship between weather parameters and yield, but also the mechanism of these models (explains the relationship of influencing dependent variables). These models are based on physical selection. Static and dynamic models do not contain time as a variable even if the end products of cropping systems are accumulated over time. In contrast dynamic models explicitly incorporate time as a variable and most dynamic models are first expressed as differential equations. Deterministic models estimate the exact value of the yield or dependent variable with defined coefficients [1].

In Stochastic models, a probability element is attached to each output. For each set of inputs different outputs are given along with probabilities. These models define yield or state of dependent variable at a given rate. Simulation models involve Computer models with a mathematical representation of a real world system. One of the main goals of crop simulation models is to estimate agricultural production as a function of weather and soil conditions as well as crop management. These models use one or more sets of differential equations, and calculate both rate and state variables over time, normally from planting until harvest maturity or final harvest [1].

Optimizing models have the specific objective of devising the best option in terms of management inputs for practical operation of the system. For deriving solutions, they use decision rules that are consistent with some optimizing algorithms. This forces some rigidity into their structure resulting in restrictions in representing stochastic and dynamic aspects of agricultural systems. Descriptive model defines the behavior of a system in a simple manner. The model reflects little or none of the mechanisms that are the causes of phenomena. It consists of one or more mathematical equations. An example of such an equation is the one derived from successively measured weights of a crop. The equation is helpful to determine quickly the weight of the crop where no observation is made [1].

Finally, explanatory models consist of quantitative description of the mechanisms and processes that cause the behavior of the system. To create this model, a system is analyzed and its processes and mechanisms are quantified separately. The model is built by integrating these descriptions for the entire system. It contains descriptions of distinct processes such as leaf area expansion [1].

2. Applications and Uses of Crop Growth Models in Agricultural Meteorology

Crop growth models are developed to solve problems of crop yield variations in agricultural meteorology. When the farmers have the difficult task of managing their crops on poor soils in harsh and risky climates, scientists and research managers need tools that can assist them in taking an integrated approach to finding solutions to the complex problem of weather, soil and crop management [8].

Some growth models allow evaluation of one or more options that are available with respect to one or more agronomic management decisions like the determination of optimum planting date, determine best choice of cultivars and the evaluation of weather risk and investment decisions.

A model can calculate probabilities of grain yield levels for a given soil type based on rainfall [9] [10]. showed that for maize, both simulated and measured mean yields with weeds are 86% of the weed-free yields. Also, investment decisions like the purchase of irrigation systems [11] can be taken even when these equipments are acquired for long term usage, through the predictions from growth models.

In agro-meteorological research, the crop models basically helps in testing scientific hypothesis, highlight where information is missing, organizing data and integrating across disciplines. The crop growth models can be used to predict crop performance in regions where the crop has not been grown before or not grown under optimal conditions. Such applications are of value for regional development and agricultural planning in developing countries [12]. It can be developed at various levels of complexity. The level of complexity required depends on the objective of the modeling exercise.

The top-down approach to model design [13] [14] is appropriate for models aimed at yield prediction. In this approach, complexity is kept to a minimum by commencing with a simple framework and only incorporating additional phenomena or processes if they improve the predictive ability of the model. [15]-[17] have adopted this method in developing models of soybean, maize and sorghum respectively.

The EPIC, ALAMANC, CROPSYST, WOFOST, ADEL models are being successfully used to simulate maize crop growth and yield. The SORKAM, SorModel, SORGF and ALMANAC models are being used to address specific tasks of sorghum crop management. CERES-pearl millet model, CROPSYST, PmModels are being used to study the suitability and yield simulation of pearl millet genotypes across the globe. Similarly, the two most common growth models used in application for cotton are the GOSSYM and COTONS models. On the same analogy the PNUTGRO for groundnut, CHIKPGRO for chick pea, WTGROWS for wheat, SOYGRO for soybean, QSUN for sunflower are in use to meet the requirements of farmers, scientists, decision makers, etc., at present.

[18] successfully assessed nitrogen requirements by maize across agro-ecological zones in Nigeria using CERES-maize model. [19] using local weather and soil information correlated peanut yields with estimates from PEANUTGRO, a model in the CERES family and gave a regression with high coefficient (r^2 = 0.93) of variation. The construction of contemporary crop models entails the combination of many algorithms for physiologi-

cal processes and impact of environmental factors on process rates [20]. This clearly indicates that in the development of models and their application for solving problems at field level on agro-meteorological aspects are given due weight age.

[21] emphasized that simulation models contribute to our understanding of the real system which in-turn helps to bridge areas and levels of knowledge. It is believed that in conversion of conceptual models into mathematical simulation models the agro-meteorologists can understand the gaps in their knowledge. So, the interdisciplinary nature of simulation modeling efforts leads to increased research efficacy and improved research direction through direct feedback. In this direction [22] developed BAsic CROp growth Simulator (BACROS) which was used as a reference model for developing other models and as a basis for developing summary models. Also [23] described the potential of simulation models in assessing trait benefits of winter cereals and their capacity to survive and reproduce in stress-prone environment. Crop growth models have been used in plant breeding to simulate the effects of changes in the morphological and physiological characteristics of crops which aid in identification of ideotypes for different environments [24] [25].

3. Successfully Used Models in Agro Meteorology

In the beginning, models were meant to increase the understanding of crop behavior by explaining crop growth and development in terms of the understanding of their physiological mechanisms. Over the years new insights and different research questions motivated the further development of simulation models. In addition to their explanatory function, the applicability of well-tested models for extrapolation and prediction was quickly recognized and more application oriented models were developed. For instance demands for advisory systems for farmers and scenario studies for policy makers resulted in the evolution of models, geared towards tactical and strategic decision support respectively. Now, crop growth modeling and simulation have become accepted tools for agricultural research. The two popular models that frequently used in agro-meteorological studies are the de Wit School of models and the IBSNAT and DSSAT Models [26].

3.1. The de Wit School of Models

In the sixties, the first attempt to model photosynthetic rates of crop canopies was made [20]. The results obtained from this model were used among others, to estimate potential food production for some areas of the world and to provide indications for crop management and breeding [27] [28]. This was followed by the construction of an ELementary CROp growth Simulator (ELCROS) by [29] (de Wit *et. al.*, 1970). This model included the static photosynthesis model and crop respiration was taken as a fixed fraction per day of the biomass, plus an amount proportional to the growth rate. In addition, a functional equilibrium between root and shoot growth was added [30]. The introduction of micrometeorology in the models [31] and quantification of canopy resistance to gas exchanges allowed the models to improve the simulation of transpiration and evolve into the BAsic CROp growth Simulator (BACROS) [22].

3.2. IBSNAT and DSSAT Models

Since agriculture is the primary economic activity in many countries of the world and great numbers of the people depend on agriculture for their livelihood or to meet their daily needs, such as food. To meet these requirements, IBSNAT (International Benchmark Sites Network for Agro-technology Transfer) began in 1982. This was under a contract from the U.S. Agency for International Development to the University of Hawaii at Manoa, USA. IBSNAT was an attempt to demonstrate the effectiveness of understanding options through systems analysis and simulation for ultimate benefit of farm households across the globe. The purposes defined for the IBSNAT project by its technical advisory committee were to: 1) Understand ecosystem processes and mechanisms; 2) Synthesize from an understanding of processes and mechanisms, a capacity to predict outcomes and 3) Enable IBSNAT clientele to apply the predictive capability to control outcomes [1].

The models developed by IBSNAT were simply the means by which the scientists have and could be placed in the hands of users. In this regard, IBSNAT was a project on systems analysis and simulation as a way to provide users with options for change. In this project many research institutions, universities, and researchers across the globe spent enormous amount of time and resources and focused on the Production of a "decision support system" capable of simulating the risks and consequences of alternative choices, through multi-institute and multidisciplinary approaches, the definition of minimum amount of data required for running simulations and assessing outcomes and the testing and application of the product on global agricultural problems requiring site-specific yield simulations [1].

The major product of IBSNAT was a Decision Support System for Agro- Technology Transfer (DSSAT). The network members lead by J. W. Jones, Gainesville, USA developed this. The DSSAT is being used as a research and teaching tool. As a research tool its role to derive recommendations concerning crop management and to investigate environmental and sustainability issues is unparalleled. The DSSAT products enable users to match the biological requirements of crops to the physical characteristics of land to provide them with management options for improved land use planning. The DSSAT is being used as a business tool to enhance profitability and to improve input marketing [1].

The traditional experimentation is time consuming and costly. So, systems analysis and simulation have an important role to play in fostering this understanding of options. The information science is rapidly changing. The computer technology is blossoming. So, DSSAT has the potential to reduce substantially the time and cost of field experimentation necessary for adequate evaluation of new cultivars and new management systems. Several crop growth and yield models built on a framework similar in structure were developed as part of DSSAT package. The package consists of : 1) data base management system for soil, weather, genetic coefficients, and management inputs, 2) Crop simulation models, 3) series of utility programs, 4) series of weather generation programs, 5) strategy evaluation program to evaluate options including choice of variety, planting date, plant population density, row spacing, soil type, irrigation, fertilizer application, initial conditions on yields, water stress in the vegetative or reproductive stages of development, and net returns [1].

4. Role of Climate Change in Crop Modeling

The earth is warmed more than expected due to the presence of atmospheric gases like carbon dioxide, methane and other tropospheric gases. The shortwave radiation can pass through the atmosphere easily, but the resultant outgoing terrestrial radiation cannot escape because atmosphere is opaque to this radiation and this act to conserve heat. The increased concentration of carbon dioxide and other green house gases are expected to increase the temperature of earth. Crop production is highly dependent on variation in weather and therefore any change in global climate will have major effects on crop yields and productivity. Elevated temperature and carbon dioxide affects the biological processes like respiration, photosynthesis, plant growth, reproduction, water use etc [1].

However, in tropics and sub-tropics the possible increase in temperatures may offset the beneficial effects of carbon dioxide and results in significant yield losses and water requirements.

Proper understanding of the effects of climate change helps scientists to guide farmers to make crop management decisions such as selection of crops, cultivars, sowing dates and irrigation scheduling to minimize the risks. In recent years there has been a growing concern that changes in climate will lead to significant damage to both market and non-market sectors. The climate change will have a negative effect in many countries. The farmer's adaptation to climate change, through changes in farming practices, cropping patterns, and use of new technologies will help to ease the impact. The variability of our climate and especially the associated weather extremes is currently one of the concerns of the general community [1].

The application of crop models to study the potential impact of climate change and climate variability provides a direct link between models, agro-meteorology and the concerns of the society. As climate change deals with future issues, the use of General Circulation Models (GCMs) and crop simulation models provide a more scientific approach to study the impact of climate change on agricultural production and world food security compared to other surveys. Cropgro (DSSAT) is one of the first packages that modified weather simulation generators and it introduced a package to evaluate the performance of models for climate change situations. Irrespective of the limitations of GCMs it would be in the larger interest of farming community of the world that these DSSAT modelers look at GCMs for more accurate and acceptable weather generators for use in models. This will help in finding solutions to crop production under climate changes conditions, especially in underdeveloped and developing countries [1].

5. Crop Model Limitations

Crop models are not able to give accurate projections because of inadequate understanding of natural processes and computer power limitation. As a result, the assessments of possible effects of climate changes, in particular, are based on estimations. Moreover, most models are not able to provide reliable projections of changes in climate variability on local scale, or in frequency of exceptional events such as storms and droughts [32]. General Circulatory Models (GCMs) have so far not been able to produce reliable projections of changes in climate variability, such as alterations in the frequencies of drought and storms, even though these could significantly affect crop yields [1].

As different users possess varying degrees of expertise in the modeling field, misuse of models may occur. Since crop models are not universal, the user has to choose the most appropriate model according to his objectives. As a result, the assessments of possible effects of climate changes are based on estimations. Moreover, most models are not able to provide reliable projections of changes in climate variability on local scale, or in frequency of exceptional events such as storms and droughts [32]. General Circulatory Models (GCMs) have so far not been able to produce reliable projections of changes in climate variability, such as alterations in the frequencies of drought and storms, even [33] though these could significantly affect crop yields. GCMs do a reasonable job in simulating global values of surface air temperature and precipitation, but do poorly at the regional scale [34].

Furthermore, biological and agricultural models are reflections of systems for which the behavior of some components is not fully understood and differences between model output and real systems cannot be fully accounted for. Crop models are therefore not able to give accurate projections because of inadequate understanding of natural processes and computer power limitation. Again, methodology of model validation is still rudimentary. The main reason is that, unlike the case of disciplinary or traditional experiments, a large set of hypotheses is being tested simultaneously in a model [1].

The validation of models at present is further complicated by the fact that field data are rarely so definite that validation can be conclusive. This results from the fact that model parameters and driving variables are derived from site-specific situations that ideally should be measurable and available. However, in practice, plant, soil and meteorological data are rarely precise and may come from nearby sites. At times, parameters that were not routinely measured may turn out to be important and they are then arbitrarily estimated [1].

Measured parameters also vary due to inherent soil heterogeneity over relatively small distances and to variations arising from the effects of husbandry practices on soil properties. Crop data reflect soil heterogeneity as well as variation in environmental factors over the growing period.

Model performance is limited to the quality of input data. It is common in cropping systems to have large volumes of data relating to the above-ground crop growth and development, but data relating to root growth and soil characteristics are generally not as extensive. Most simulation models require that meteorological data be reliable and complete. Finally, sampling errors also contribute to inaccuracies in the observed data [1].

An ultimate crop model would be one that physically and physiologically defines all relations between variables the model reproduces and universally real world behavior. However, such a model cannot be developed because the biological system is too complex and many processes involved in the system are not fully understood (Jame and Cutforth, 1996). Even if an ideal crop model could be produced, the collection of the highly precise system parameters and of the input data for the crop environment would be a formidable task in itself. Thus, the level of detail involved in a crop model is closely linked to the end use of the model and the precision required. Even when a judicious choice is made, it is important that aspects of model limitations be borne in mind such that modeling studies are put in the proper perspective and successful applications are achieved.

6. Conclusions

Various kinds of models such as Statistical, Mechanistic, Deterministic, Stochastic, Dynamic, Static, Simulations are in use for assessing and predicting crop growth and yield. Crop growth model is a very effective tool for predicting possible impacts of climatic change on crop growth and yield. These models are useful for solving various practical problems in agriculture. Adequate human resource capacity has to be improved and validate simulation models have to be developed across the globe.

As a research tool, model development and application can contribute to identifying gaps in our knowledge, thus enabling more efficient and targeted research planning. Models that are based on sound physiological data are capable of supporting extrapolation to alternative cropping cycles and locations, thus permitting the quantification of temporal and spatial variability. Most models are virtually untested or poorly tested, and hence their usefulness is unproven. Indeed, it is easier to formulate models than to validate them. Many agronomists have been confused by the situation. They are discouraged by the complexity of the models, the lack of model testing, and the inevitable inaccuracies that arise when such testing is done.

Consequently, they have seriously doubted the usefulness of crop models in agronomy. Unfortunately, this confusion is caused partly by those who are naively optimistic that crop modeling is the panacea for agricultural problems and apply crop models indiscriminately. Because most agronomists do not fully understand the concept of crop growth modeling and systems-approach research, training in this area is required. An intensely calibrated and evaluated model can be used to effectively conduct research that would in the end save time and money and significantly contribute to developing sustainable agriculture that meets the world's needs for food.

References

[1] Murthy, V.R.K. (2002) Basic Principles of Agricultural Meteorology. Book Syndicate Publishers, Koti, Hyderabad.

[2] Foken, T. (2008) Micrometeorology. Springer-Verlag, Berlin Heidelberg, 306 p.

[3] Hann, J.F. and Süring, R. (1939) Lehrbuch der Meteorologie. Verlag von Willibald Keller, Leipzig, 480 p.

[4] Dutton, J.A. (2002) The Ceaseless Wind: An Introduction to the Theory of Atmospheric Motion. Dover Publications, Mineola, 640 p.

[5] Glickman, T.S., Ed. (2000) Glossary of Meteorology. American Meteorological Society, Boston, 855 p.

[6] Kraus, H. (2004) Die Atmosphäre der Erde. Springer, Berlin Heidelberg, 422 p.

[7] Arya, S.P. (2001) Introduction to Micrometeorology. Academic Press, San Diego, 415 p.

[8] Houghton, D.D. (1985) Handbook of applied meteorology. Wiley, New York, 1461 p.

[9] Hupfer, P. and Kuttler, W., Eds. (2005) Witterung und Klima, begründet von Ernst Heyer. B. G. Teubner, Stuttgart, Leipzig, 554 p. http://dx.doi.org/10.1007/978-3-322-96749-7

[10] Kraus, H. (2004) Die Atmosphäre der Erde. Springer, Berlin Heidelberg, 422 p.

[11] Sivakumar, M.V.K. and Glinni, A.F. (2002) Applications of Crop Growth Models in the Semiarid Regions. In: Ahuja, L.R., Ma, L. and Howell, T.A., Eds., *Agricultural System Models in Field Research and Technology Transfer*, Lewis Publishers, CRC Press Company, Boca Raton, 177-205. http://dx.doi.org/10.1201/9781420032413.ch9

[12] Kiniry, J.R. and Bockholt, A.J. (1998) Maize and Sorghum Simulation in Diverse Texas Environments. *Agronomy Journal*, **90**, 682-687. http://dx.doi.org/10.2134/agronj1998.00021962009000050018x

[13] Kiniry, J.R., Rosenthal, W.D., Jackson, B.S. and Hoogenboom, G. (1991) Predicting Leaf Development of Crop Plants. In: Hodges, T., Ed., *Predicting Crop Phenology*, CRC Press, Boca Raton, 29-42.

[14] Boggess, W.G. and Amerling, C.B. (1983) A Bioeconomic Simulation Analysis of Irrigation Environments. *S.J. Agric. Econ*, **15**, 85-91.

[15] Van Keulen, H. and Wolf, J. (Eds.) (1986) Modelling of Agricultural Production: Weather, Soils and Crops. Simulation Monographs. PUDOC, Wageningen.

[16] Hammer, G.L., Hoizworth, D.P., Mulo, S. and Wade, L.J. (1989) Modeling Adaptation and Risk of Production of Grain Sorghum in Australia. In: Foale, M.A., Hare, B.W. and Henzell, R.G., Eds., *Proceedings of the Australian Sorghum Workshop*, Toowoomba, 28 February-1 March 1989, Australian Institute of Agricultural Science, Brisbane, 257-267.

[17] Shorter, R., Lawn, R.J. and Hammer, G.L. (1991) Improving Genotypic Adaptation in Crops—A Role for Breeders, Physiologists and Modelers. *Experimental Agriculture*, **27**, 155-175. http://dx.doi.org/10.1017/S0014479700018810

[18] Sinclair, T.R. (1986) Water and Nitrogen Limitations in Soybean Grain Production. I. Model development. *Field Crops Research*, **15**, 125-141. http://dx.doi.org/10.1016/0378-4290(86)90082-1

[19] Muchow, R.C., Sinclair, T.R. and Bennett, J.M. (1990) Temperature and Solar Radiation Effects on Potential Maize Yield across Locations. *Agronomy Journal*, **82**, 338-343. http://dx.doi.org/10.2134/agronj1990.00021962008200020033x

[20] Hammer, G.L. and Muchow, R.C. (1994) Assessing Climatic Risks to Sorghum Production in Water Limited Subtropical Environment. I. Development and Testing of a Simulation Model. *Field Crops Research*, **36**, 221-234. http://dx.doi.org/10.1016/0378-4290(94)90114-7

[21] Amissah-Arthur, A. and Jagtap, S.S. (1995) Application of Models and Geographic Information System Based Decision Support System in Analysis the Effect of Rainfall on Maize Yield Stability. *Sustain Africa*, **3**, 2-15.

[22] Hammer, G.L., Sinclair, T.R., Boote, K.J., Wright, G.C., Meinke, H. and Bell, M.J. (1995) A Peanut Simulation Model: I. Model Development and Testing.

[23] Monteith, J.L. (2000) Agricultural Meteorology: Evolution and Application. *Agricultural and Forest Meteorology*, **103**,

5-9. http://dx.doi.org/10.1016/s0168-1923(00)00114-3

[24] de Wit, C.T. (1967) Photosynthesis: Its Relationship to Overpopulation. In: San Pietro, A., Green, F.A. and Army, T.J., Eds., *Harvesting the Sun*, Academic Press, New York, 315-320.

[25] de Wit, C.T. and Goudriaan, J. (1978) Simulation of Assimilation, Respiration and Transpiration of Crops. Simulation Monograph. PUDOC, Wageningen.

[26] O'Toole, J.C. and Stockle, C.O. (1987) The Role of Conceptual and Simulation Modelling in Plant Breeding. *Presented at the International Symposium on Improving Winter Cereals under Temperature and Soil Salinity Stresses*, Cordoba, 26-29 October 1987, 9.

[27] Hunt, L.A. (1993) Designing Improved Plant Types: A Breeders View Point. In: de Vries, F.P., Teng, P. and Metselaar, K., Eds., *Systems Approaches for Agricultural Development*, Springer, Dordrecht, 3-17.

[28] Kropff, M.J., Haverkort, A.J., Aggarwal, P.K. and Kooman, P.L. (1995) Using Systems Approaches to Design and Evaluate Ideotypes for Specific Environments. In: Bouma, J., Kuyvenhoven, A., Bouman, B.A.M., Luyten, J.C. and Zandstra, H.G., Eds., *Eco-Regional Approaches for Sustainable Land Use and Food Production*, Kluwer Academic Publishers, Dordrecht, 417-435. http://dx.doi.org/10.1007/978-94-011-0121-9_21

[29] de Wit, C.T. (1965) Photosynthesis of Leaf Canopies. Agricultural Research Report No. 663. PUDOC, Wageningen.

[30] Kramm, G., Dlugi, R. and Mölders, N. (2002) Sublayer-Stanton Numbers of Heat and Matter for Aerodynamically Smooth Surfaces: Basic Considerations and Evaluations. *Meteorology and Atmospheric Physics*, **79**, 173-194. http://dx.doi.org/10.1007/s007030200002

[31] Linneman, H., Dehoogh, J., Keyzer, M.A. and van Heemst, H.D.J. (1979) Moira, Model of International Relations in Agriculture. North Holland Publishing Company, Amsterdam.

[32] de Wit, C.T., Brouwer, R. and Penning de Vries, F.W.T. (1970) The Simulation of Photosynthetic Systems. In: Setlik, I., Ed., *Prediction and Measurement of Photosynthetic Productivity*, *Proceedings of International Biological Program/Plant Production Technical Meeting*, Trebon, PUDOC, Wageningen, 47-70.

[33] Penning de Vries, F.W.T., Brunsting, A.B. and van Laar, H.H. (1974) Products, Requirements and Efficiency of Biological Synthesis, a Quantitative Approach. *Journal of Theoretical Biology*, **45**, 339-377. http://dx.doi.org/10.1016/0022-5193(74)90119-2

[34] Goudriaan, J. (1977) Crop Micrometeorology: A Simulation Study. Simulation Monograph. PUDOC, Wageningen.