Crop Models in International Development : The Challenges Ahead

Matthias Langensiepen

Crop Science, University of Kiel, Olshausenstrasse 40, 24118 Kiel

Abstract

Crop models will play an increasing role in advancing international development. However, to become more reliable and widely acceptable, crop modeling has yet to meet a number of substantial challenges. The paper focuses on the most important process of plant growth, photosynthesis, and relates the underlying mechanisms to the soil and air environment. Common attributes of these mechanisms are flexibility and complexity.
Agricultural research will have to change its mode of thinking from descriptive research to scientific theorization (which is initialized by empiricism) if it wants to gain importance in providing model solutions for agricultural production. Proper solutions will be site-specific and require high degrees of abstraction and deduction.

Introduction

The intention of crop modeling is to simulate plant responses to their dynamically changing environment and to use this information to provide recommendations for crop management. This requires a basic understanding of the major processes affecting plant growth and yield (Landau et al. 1999; Monteith 1996; Passioura J.B. 1996) which have to be formulated in the explicit manner of computer languages.
Crop modeling is a science based operation, where research findings are made subject to discussion (Metselaar K. 1999), and differs from traditional agricultural research, which is based on empirical observation. Confusion exists about this fundamental difference which arise from uncertainties associated with mixing descriptive and analytical approaches.
Yet, the advantage of shifting management from an empirical basis (x kg water = y kg yield for instance) to a crop-simulation-based operation is its increasing time effectiveness of decision support, which is needed to synchronize agricultural crop production with accelerating market fluctuations. Food policy research has shown that markets in less developing countries are becoming vulnerable when opening themselves to world price signals (Islam 1996). Trade liberalization will force agricultural production to become more flexible to sustain stable food supply. Traditional agricultural research is probably not able to provide quick and suitable solutions, because it is based on long-term observations. Mimicking field experiments with crop simulation models will help to reduce the time required to establish different scenarios of production and to target agriculture practice with flexible management or policy options.
Interactions between production, ecology and economy are highly complex. Most of the underlying mechanisms are either yet to be quantified or even not known. The lack of corresponding knowledge forces modelers to build idealistic representations of true system behaviors. (According to Webster's dictionary, an "ideal" is something existing in fancy or imagination and is broadly lacking practicality). An usually unstated assumption is that such models can be transferred between different environments. Their empirical nature often does, however, not allow such extrapolations (Langensiepen et al.1999). Basing management or policy decisions on corresponding simulations means to take the incalculable risk of wasting production resources, which are precious, particularly in the dry areas.
There is increasing concern whether crop modeling is ready for application in less developing countries (Mutsaers H.J.W. and Z. Wang 1999). If crop simulation wants to become more

reliable to reach a stage of widespread application, a number of substantial challenges have yet to be meet. The complexity of issues lying ahead scale with increasing levels of organization. Mechanisms like membrane transport, cell metabolism, stomatal hydraulics, micro-pore flow, gas diffusion and others are principally well understood. When scaling to soil aggregates, single leaves or their boundary layers, an increasing number of mechanisms, which are mutually influencing each other, still require quantification. How these mechanisms integrate to form plant life and how they influence crop function is far from being well understood. In contrast, it is also known that higher levels of organization can lead to more balanced regulation. It seems in fact, that there exist many regulation principles which act similarly. For example, it is possible to predict biomass production by relating relative growth rates to specific leaf weight without necessarily knowing all the underlying processes and interactions at the cellular scale (Schulze et al. 1994 although read Pereira 1994). However, such knowledge can only be transformed into models if it was generated following strict scientific principles. Agricultural research will have to change its mode of thinking from empiricism to scientific theorization (which is initialized by empirical observation) if it wants to gain importance in providing model solutions for agricultural production. Building a solid bridge between natural sciences and agriculture is a pre-requisite to reach this goal. Ecophysiology, a branch of biological sciences describing physiological mechanisms underlying ecological observations, is a prime candidate for this purpose. Recent literature provides extensive and detailed insight into many of the underlying principles and leaves considerable room for improving currently available models. The purpose of this paper is to name some challenges which have the potential to improve the quality of simulating cropping systems. Such a list must be subjective and incomplete, of course, and it is not intended to deceive (the meaning of to "simulate") but to stimulate further discussion on the topic. A further aim is to request for the development of more science-based crop models.

2.   Outline of a typical crop simulation model

The objective of many crop models is to predict the timing and rate of growth, the partitioning of assimilates into economic yield components and to quantify the requirements of essential resources (water and nitrogen). A common backbone of such models is the relation between air temperature and phasic development. Heat units, expressed in growing degree-days (McMaster and Wilhelm 1997), serve as input to characterize plant ontogenetic development which may be modulated by photoperiodism and vernalization requirements (Ritchie et al.1998). The duration of phases and yield component characteristics are determined experimentally under optimum growth conditions. They constitute the yield potential at a certain geographic location (genetic parameters). Biomass growth is generally calculated following the radiation use efficiency approach (Monteith 1977). The partitioning of biomass into leaves, economic yield components, stems and roots is related to the stage of growth, genetic sink requirements and possible stress. Components of the soil water budget are estimated either following a cascade approach (Ritchie et al. 1988) or some numerical solution (Hillel 1998) of the Richards equation (Richards 1931). The curve number concept of the USDA-Soil Conservation Service (USDA 1988) is frequently used to estimate surface runoff. Infiltration and re-distribution of soil water directly impact the mobile fraction of soil nitrogen. Mineralization and immobilization of nitrogen is often simulated on the grounds of the PAPRAN model (Seligmann and van Keulen 1981), which divides soil organic matter into straw-root (fresh organic matter) and stable humus fractions assuming fixed rates of their decay. Nitrification rates are estimated using simulated concentrations of available ammonium and temperature as well as soil pH. Plant N-demand and supply are determined separately and the lesser of the two is then chosen to determine actual uptake. Estimations of N-demand and redistribution are related to empirically determined sink strengths. In the case

of cereals, the critical N-concentration is often based upon ZADOK's growth scale. The choice of method for determining crop water uptake depends on the type of soil water model being used. One method is to calculate root water uptake from pressure differences along the soil-plant water transport pathway using a canopy conductance factor (Stockle et al. 1994). This is not possible in case of the cascade approach where an empirical soil water content driven function is used to determine root water uptake (Jones and Kiniry 1986). Both approaches use empirical distributions of root length density. Crop water requirements (e.g. evapotranspiration) are frequently estimated following the Priestly-Taylor approach (Priestly and Taylor 1972) which assumes a state of thermal equilibrium between the crop canopy and the atmosphere. The FAO24-approach (Doorenbos and Pruitt 1977) is sometimes suggested as an alternative. The ratio between root water uptake and actual transpiration determines the state of plant water stress and affects biomass production and sink distribution.

3.   Challenges

The major disadvantage of many crop models is that they capture complex physiological interactions in a rather crude way by relating sink requirements with environmental variables using empirical routines for carboyhdrate partitioning, N-dynamics and organ growth and assume optimum growth conditions. If crop modeling wants to become an acceptable tool in providing practical solutions for agriculture it must consider the complexity associated with sub-optimal production conditions, which are more the rule than an exemption in the less developed countries. The following paragraph focuses on the most important process of plant growth, photosynthesis, relates the underlying mechanisms to the soil and air environment and points at the challenges lying ahead to improve the simulation of this system

3.1   Soil Environment

Soils are heterogenous, poly-phasic, particulate, disperse and porous systems (Hillel 1998). Their physical composition can be divided into three phases : (1) The solid phase contains particles which vary in chemical composition, size, shape and orientation. If soils contain more than 15 % of clay (Horn 1994) or other amorphous substances, such as organic matter, they tend to form aggregates. (2) The liquid phase consists of water and substances dissolved therein. It affects soil physical properties, determines its thermal regime and influences various plant physiological mechanisms. (3) Respirative soil processes require diffusion of air to allow the exchange of oxygen and carbon-dioxide. The magnitude of atmospheric fraction depends on pore volume and soil water content.
Soil hydraulic properties include a water retention curve (the relation between volumetric water content and pressure head), hydraulic conductivity (the ratio of flux to potential gradient) and diffusivity of water (the ratio of hydraulic conductivity to specific water capacity). The soil water retention curve is essentially a pore size distribution curve (Arya et al. 1999), which is often assumed to be a fixed soil property (Klute 1986) . This assumption may be partly valid for sandy soils. However, as the clay content rises the soil tends to swell and shrink with changing moisture states. This and other mechanical effects influence the pore-size distribution, which in turn determines the volumetric soil water content. Assuming a fixed pore-size distribution will lead to errors in the determination of soil water content which may reach levels as high as 5 percent. It is a challenge to find methods which overcome this problem and which are concurrently applicable. Gräsle (1999), for example, proposes to carry out simultaneous measurements of probe volume and gravimetric water content at known levels of suction and compaction.
It is often assumed that once initial water permeation into the soil has reached a constant rate, water infiltration takes place under steady state conditions. However, biological activity and a

number of mechanical effects, cause soil water to follow distinct pathways. It is another challenge to characterize these preferential flow conditions. While biological activity is certainly difficult to be assessed and quantified this should not be the case with swelling and shrinking processes which are the major cause for preferential flow.

Accurate prediction of carbon and nitrogen turnover is essential for optimizing nitrogen use efficiency in cropping systems (Gabrielle et al. 1998; Honeycutt 1999). Nitrogen processes include mineralization, ammonium immobilization, ammonium adsorption, ammonium volatilization, nitrification, denitrification, leaching and plant uptake. About 95 percent of nitrogen present in the upper soil horizon is incorporated in organic substances which are closely related to soil carbon content (Zech and Kögel-Knaber 1994). Organic matter transformations are mediated by microbial activity and are influenced by temperature regime, available water and nutrients (N and P). A realistic simulation of soil heat transfer is particular important in this context. Current available methods (see reviews of Hillel 1998 and Hanks 1992) need to be improved and set into a plausible relation to the systems energy budget. The intensity of microbial transformations also depend on the quality and quantity of their primary resources (leaf and root residues) as well as on the composition of the microbe community. Complex bio-chemical reactions evolve from these interrelations and they are far from being linear, as assumed in many soil models. Better experimental bases and models are needed to understand and quantify these relations.

Water redistribution in soils have recently been reported to be affected by the plant root system. Data available from 30 species show that root systems can induce water transfer from deep and moist layers to the dry surface layer, a phenomen termed as „hydraulic lift" (Caldwell et al. 1998). A better understanding of this and more fundamental mechanisms of soil water uptake by plant roots (Thornley 1996) is certainly needed to improve the reliability of soil model routines.

It is still a challenge to accurately describe the heterogenity of pressure-flow distribution within the soil and its effect on rooting densities and the partitioning of hydraulic resistances.

3.2   Plant Functioning

One of the major drawbacks of current crop models is an incomplete or simplified description of root development and growth. Roots are fundamental for the acquisition and storage of resources despite their importance in mechanically stabilizing plant shoots. Root growth must be seen in close relation to plant carbon metabolism which is affected by external factors such as temperature or nutrients. Soil nitrogen availability regulates carbon allocation to shoot and root growth (Stitt and Schulze 1994). Root respiration accounts for 8 to 52 percent of total carbon assimilated when nutrition availability is free and limiting, respectively (van der Werf et al. 1994). Since roots are linked to the shoot system through an array of complex physiological pathways, accurately defining root functioning will remain a considerable challenge.

Temperature effects on growth and development have been observed a long time ago and lead to the formulation of the concept of thermal time (Reaumur 1735 cited in Lambers 1et al. 1998). It implies that time, as sensed by plants, elapses more rapidly at high than at low temperature. Despite its wide and accepted application in different plant species, there is no physiological basis for the concept (Horie 1994). There exists confusion regarding what determines the rate of development (In case of cereals the phyllochron or plastochron ? Hay and Ellis 1997). Other than temperature, a second environmental factor influences development - light. It is not a simple stimulus, because it can vary and have influence in several ways, including its spectral distribution, quantity, direction, duration and periodicity. Leaves, stems, flowers and roots (!) respond to light in different ways (see review by Cosgrove 1994). The same is true for the distribution of temperature response (Granier and

Tardieu 1998), which depends on the partitioning of energy budget, a fact that is ignored in many crop models which use air-temperature instead. Other than temperature and light, there does not appear to be another decisive factor influencing the timing of physiological events. Doubling of air CO_2-concentrations, for example, does not influence phasic development or the rate of leaf appearance in wheat (Slafer and Rawson 1997).

Photosynthesis is the initial mechanism driving plant growth. It involves the uptake of carbon dioxide with a coupled release of vapor through transpiration. Leaf area and stems provide the supporting structure for plant gas exchange, heat dissipation and radiation absorption. Pre-investment into biochemical machinery and fixed elements is also needed to enable and induce the fixation of carbon dioxide. Ontogeny and genetic response to the environment (e.g. acclimation) play a regulating role in setting the general conditions for carbon fixation. The fixation process itself is very flexible and takes place on a timescale of milliseconds to seconds, depending on the type of reaction (Schreiber et al. 1994). The light reaction includes the absorption of photons at the pigment level and the primary reaction (splitting of water) to provide electrons for the thylakoid electron transport chain which drives the production of chemical energy (NADPH2 and ATP). There is a remarkable array of leaf mechanisms regulating the interception and heat dissipation of light energy, both in the short and long-term (see review of Björkmann and Demming-Adams 1994). The regulation also indirectly affects the dark reaction, because the photosynthetic carbon reduction cycle relies on the supply of NADPH2 and ATP. Ribulose-1,5-bisphosphate carboxylase/oxygenase (Rubisco) catalyzes the formation of phosphoglycerid acid (PGA) during the initial process of the Calvin cycle by binding CO_2 to its acceptor Ribulose-1,5-bisphosphate (RuPB). Further energy dependant steps lead to the export of sucrose and regeneration of RuBP. Since photosynthetic machinery accounts for more than half of the nitrogen in the leaf, photosynthesis is strongly affected by the availability of nitrogen (Lambers et al. 1998). Nitrogen distribution within the plant often correlates with light interception (de Pury and Farquhar 1997), because changes in irradiance alters the amount of photons absorbed and processed by the thylakoid proteins (Stitt et al. 1994) and activates Rubisco before it can develop catalytic activity (Pons et al. 1992). Photochemistry is also strongly affected by temperature. The latter results from the plants capability to partition radiative energy into sensible and latent heat (e.g. stomatal regulation). Summarizing what has been written so far we can conclude that photosynthesis is a process which responds with extreme flexibility to an array of environmental variables: Nitrogen,CO_2, light, heat, water and others. The concept of radiation-use-efficiency (Monteith 1977) is not capable of mimicking the underlying regulation principles of biomass accumulation despite being robust and applied in many crop models. This is also the reason why its application generally fails when environmental stresses limit plant growth. For example, when photosynthesis is in excess, assimilated carbon will be stored as starch in the leaf and does not contribute to growth. This is the case when there is an insufficient supply of assimilated nitrogen, which causes a preferential inhibition of shoot growth (Fichtner et al.1993). The consequence is a decrease of the shoot/root ratio (Studies of radiation use efficiency often focus on the shoot). Stitt et al. (1994) conclude that the rate of photosynthesis and availability of carbohydrates per se does not affect allocation to shoot or root growth. N-supply appears, therefore, to be fundamental in controlling the shoot/root ratio. It also controls the activity of genes responsible for the production of enzymes involved in the photosynthetic process. These genes respond to other environmental influences as well. The recognition and transduction of the corresponding signals is far from being well understood (Aducci P. 1997). Despite this regulation on the molecular level, there are other regulation mechanisms which are acting on a broader scale and which also require better quantification. Crucial branchpoints are the partitioning of primary carbohydrates into sugar and starch, the distribution of fixed carbon between carbohydrate and formation of amino-acids, the

allocation of sugar to shoot and root, the partitioning of assimilated nitrogen to inorganic storage and organic compounds and the allotment of nitrogen to different plant organs. Biochemical reactions generally operate in a narrow range of optimum temperatures. Regulation of the plants heat-budget is therefore another process that needs thorough understanding to allow the establishment of causal links between plant growth and environment. Leaf stomatas play a decisive role in this regulatory process. They build a biological barrier between the biological environment of the plant and the physical environment of the atmosphere. They respond to a large number of plant internal and external factors. Light plays the dominant role in regulating stomatal gas diffusion, both quanititatively and qualitatively (see reviews by Zeiger 1994 and Sharkey and Orgava 1987). The water potential gradient between the liquid and gaseous phases of the plant-atmosphere interface is another important signal. Soils and roots are linked to this gradient by the plants sap conducting system and they also significantly influence stomatal opening. Moreshet et al. (1996) suspect that the plant hydraulic system undergoes a diurnal cycle of charge and discharge. CO_2 seems to be a controlling factor as well, but the underlying mechanisms are not yet known (Baldocchi D.D. 1991). Changes in assimilation capacity under saturation conditions appear to affect leaf conductance, but experimental evidence is weak (Schulze 1994). The complexity of stomatal regulation is further exacerbated by the fact that a single signal may use multiple osmoregulatory pathways (Talbott and Zeiger 1996). How different signals and stomatal responses are acting in an integrated manner is far from being understood (see reviews by Schulze 1994, Lange et al. 1971, Bunce 1997, Fuchs and Livingston 1996).

3.3 Atmospheric Environment

Plant geometry plays a decisive role in setting the general conditions for plant-atmospheric exchange processes. The exchange of heat, mass and energy is closely related to leaf area density, inclination and azimuth distributions. There is a need for tools which allow a more rapid assessment of these parameters (Langensiepen 1997). Estimations of leaf boundary layer characteristics can be traced back to flat-plate-medium theory of the airship industry (Schlichting and Truckenbrodt 1967) which fails to give a realistic description of exchange processes influenced by the flexibility and heterogenity of true leaf surfaces. Research seems to be at the very beginning here. Modelling of turbulent transfer is commonly based on the assumption that it is analogous to molecular diffusion (k-theory) and that it can be treated as a one-dimensional problem (flat, homogenic terrain) . However, in a strict sense, this is only possible, when the length of the eddies are much smaller than the scale over which the mean gradients change (Kaimal and Finniger 1993). Other methods like higher-order closure or Lagrangian models are becoming increasingly popular, but require extensive a priori information on the turbulence regime and sink-source distribution (Baldochii 1991; Schmid 1997). Aerodynamic phenomens, like the coupling between the elastic frequency of stalks and characteristic frequency of the energy-containing eddies (in Japanese "honami" - Finnigan 1979) let us foresee the complexity of issues lying ahead. This includes a proper description of aerodynamic processes on a regional scale, which is anything but homogenous (T.Oke 1987)

3.4 Other Challenges

Once a crop model has been developed it will be crucial how it is applied to practical situations. Data available to feed the model will always be limited and the usefulness of the model is therefore dependent on its minimum data requirements. There also has to be a common standard that allows exchange of information between different users. This, in turns, relies on an efficient design of the user interface. Linking models with the economic

environment is another challenge. Finally, it will also be crucial how the knowledge generated by crop models is transduced to the actual farm level considering the differences in cultural civilizations.

4 Outlook

Practical agriculture will only benefit from the application of crop models, if they are capable to provide accurate information for management decisions under a broad range of production conditions. Crop modelers, whether developing empirical or mechanistic models, must realize that the interaction between genotype, soil and air environment is site-specific. Proper solutions will require a high degree of abstraction and deduction. Holism, universability and complexity will be the coming key issues in modeling research.

Literature

Aducci P. (1997) Signal transduction in plants. Birkhäuser, Basel

Arya L.M., Leij F.J., van Genuchten M.T. and P. Shouse (1999) Scaling parameter to predict the soil water characteristic from particle-size distribution data. Soil Science 63: 510-519

Baldocchi D.D. (1991) Discerning the forest from the trees: an essay on scaling stomatal conductance. Agric. For. Met. 54: 197 - 226

Björkmann O. and B. Demming-Adams (1994) Regulation of photosynthetic light energy capture, conversation and dissipation in leaves of higher plants. In Schulze E.D. and M.M. Caldwell (eds.) Ecophysiology of photosynthesis. Ecological Studies 100. Springer, Berlin.

Bunce J.A. (1997) Does transpiration control stomatal responses to water vapor pressure deficit ? Plant, Cell and Environment 19: 131-135

Caldwell M. M., Dawson T.E., and J.H. Richards (1998) Hydraulic lift: Consequences of water efflux from the roots of plants. Oecologia 131: 151-161

Cosgrove D.J. (1994) Photomodulation of growth. In Kendrik R.E. and G.H.M. Kronenberg (1994) Photomorphogenesis in plants. Kluwer, Dordrecht

Finnigan J.J. (1979) Turbulence in waving wheat. I. Mean statistics and honami. Boundary Layer Meteorology 16: 181-211

Fuchs E.E. and N.J. Livingston (1996) Hydraulic control of stomatal conductance in Douglas fir (Pseudotsuga menziesii (Mirb.) Franco) and alder (alnis runra(Bong)) seedlings. Plant, Cell and Environment 19(9): 1091 - 1098

Horie T. (1994) Crop ontogeny and development. In Boote K.J., Bennet J.M., Sinclair T.R. and G.M. Paulsen (eds.) Physiology and determination of crop yield. ASAE, Madison, Wisconsin

de Pury D.G.G. and G.D. Farquhar (1997) Simple scaling of photosynthesis models from leaves to canopies without the errors of big-leaf models. Plant, Cell and Environment 20: 537-557

Doorenbos J. and W.O Pruitt (1977) Guidelines for predicting crop water requirements. Irrigation and Drainage Paper 24. FAO, Rome

Fichtner K., Quick W.P., Schulze E.D., Mooney H.A., Rodermel S.R., Bogorad L. and M. Stitt (1993) Decreases ribulose-1,5-bisphosphate carboxylase-oxygenase in transgenic tobacco transformed with „antisense" rBcS. V. Relationship between photosynthetic rate, storage strategy, biomass allocation and vegetative plant growth at three different nitrogen supplies. Planta 190: 1-9

Gabrielle B. and L. Kengni (1998) Analysis and field-evaluation of the CERES Models' Soil Components: Nitrogen Transfer and Transformations. Soil Sci. Soc. Am. J. 60: 142-149

Gräsle W. (1999) Numerical simulation of mechanical, hydraulic and coupled soil processes using the finite element method (in German with English summary). Schriftenreihe Nr. 48. Institute of plant nutrition and soil science. University of Kiel. ISSN 0933-680-X

Granier C. and F. Tardieu (1998) Is thermal time adequate for expressing the effects of temperature on sunflower leaf development ? Plant, Cell and Environment 21: 695-703

Hanks R.J. (1992) Applied soil physics. Springer, Berlin

Hay R.K.M. and R.P. Ellis (1997) The control of flowering in wheat and barley: What recent advances in molecular genetic can reveal. Annals of Botany 82: 541 - 554

Hillel D. (1998) Environmental soil physics. Academic press, San Diego

Honeycutt C.W. (1999) Nitrogen mineralization from soil organic carbon and crop residues: Field evaluation of laboratory predictions. Soil Sc. Soc. Am. J. 63: 134-141

Horn R. (1994) The effect of aggregation of soils on water, gas and heat transport. In: Schulze E.D. (ed.) Flux control in biological systems. Academic Press, San Diego.

Islam N. (1996) Implementing the Uruguay Round: Increased Food Price Stability by 2020 ? 2020 Vision Brief 34, June 1996. www.cgiar.org/ifpri2020/briefs/number34.html

Jones C.A. and J.R. Kiniry (1986) CERES-Maize: A simulation model of maize growth and development. Texas University Press

Kaimal J.C. and J.J. Finniger (1993) Atmospheric Boundary Flows. Their Structure and Measurement. Oxford Univ. Press, New York,

Klute A. (1986) Water retention: Laboratory methods. In Klute A. (ed.) Methods of soil analysis part 1: Physical and mineralogical methods. Am. Soc. Agron. Monograph 9, Madison, Wisconsin, USA

Lambers H., Chapin III F.S. and T.L. Pons (1998) Plant physiological ecology. Springer, Berlin

Landau S., Mitchell R.A.C., Barnett V., Colls J.J., Craigon J. and R.W. Payne (1999) Response to ∀Comments on ! Testing winter wheat simulation models predictions against observed UK grain yields by Landau et al. [Agric. For. Meterol. 89 (1998) 85-99]! by Jamieson et al. [Agric. For. Meteorol. 96 (1999) 157-161]∀. Agric. For. Met. 96: 163-164

Lang O.L., Lösch R., Schulze E.D. and L. Kappen (1971) Response of stomata to air humidity. Planta 100: 76-86

Langensiepen M. (1997) Improving agricultural system management using meteorological network data: Case studies in Brazil, Germany and Israel on corn. Tropenlandwirt Beiheft. No. 59. ISBN 3-88122-928-0

Langensiepen, M., Fuchs, M., Bergamaschi H., Gräsle W. and J. Scholberg, 1999 : Are crop models universally applicable ? International Symposium on Modelling Cropping Systems. June 21-23, 1999. Lleida, Spain. Proceedings

McMaster G.S. and W.W. Wilhelm (1997) Growing degree-days: one equation, two interpretations. Agric. For. Met. 87(4): 289-298

Metselaar K. (1999) Auditing predictive models: A case study in crop growth. Doctoral thesis Wageningen Agricultural University.- With ref.- With summary in Dutch. ISBN 90-5485-977-6

Monteith J.L. (1977) Climate and the efficiency of crop production in Britain. Phil. Trans. R. Soc. Lond. B. 281: 277 - 294

Monteith J.L. and M. Unsworth (1994) Principles of enviromental physics. Arnold, London

Monteith J.L. (1996) The quest for balance in crop modeling. Agron. J. 88: 695-697

Moreshet S., Fuchs M. Cohen Y, Cohen Y. and M. Langensiepen (1996) Water transport characteristics of cotton as affected by drip irrigation layout. Agron. J. 88 (5): 717 - 722

Mutsaers H.J.W. and Z. Wang (1999) Are simulation models ready for agricultural research in developing countries ? Agron. J. 91: 1-4

Oke T.R (1987) Boundary layer climates. Routledge, London

Passioura J.B. (1996) Simulation Models: Science, snake oil, education, or engineering ? Agron. J. 88: 690-694

Pereira H.S. (1994) Gas exchange and growth. In Schulze E.D. and M.M. Caldwell (eds.) Ecophysiology of photosynthesis. Springer, Berlin.

Pons T.L., Pearcy R.W. and J.R. Seemann (1992) Photosynthesis in flashing light in soybean leaves grown in different conditions. I. Photosynthetic induction state and regulation of ribulose -1,5-bisposphate carboxylase activity. Plant, Cell and Environment 15: 569 - 576

Priestly C.H.B. and R.J. Taylor (1972) On the assessment of the surface flux and evaporation using large scale parameters. Monthly weather review 100: 81-92

Reaumur R.A.F. (1735) Observations du thermometre faites a Paris pendant l'annee 1735, comparees avec celles qui ont ete faites sous la ligne, a l'Isle de France a Algeres & en quelquesunes de nos Isles de l'Amerique. Historie de l'Academie Royale des Sciences, avec les Memories de Mathematique & de Physique pour la meme annee Paris, 545-580

Richards L.A. (1931) Capillary conduction of liquids through pore systems. Physics 1, 318-333

Ritchie J.T., Godwin D.C. and S. Otter-Nacke (1988) CERES-Wheat. Texas University Press

Ritchie J.T., Singh U., Godwin D.C. , Bowen W.T.. Tsuji G.Y., Hoogenboom G. And P.K. Thornton (1998) Cereal growth, development and yield. In Tsuji G.Y. and G. Hoogenboom (eds.) Understanding options for agricultural production. Kluwer, Dordrecht

Schlichting H. and E. Truckenbrodt (1969) Airodynamik des Flugzeuges. 2.Bd.Springer, Berlin

Schmid H.P (1997) Experimental Design for Flux Measurements: Matching Scales of Observations and Fluxes. Agric. For. Met. 87: 179-200

Schreiber U., Bilger W. and C. Neubauer (1994) Chlorophyll fluorescence as a nonintrusive indicator for rapid assessment of in vivo photosynthesis. In Schulze E.D. and M.M. Caldwell (eds.) Ecophysiology of photosynthesis. Ecological Studies 100. Springer, Berlin.

Schulze E.D. (1994) The regulation of plant transpiration: Interactions of feedforward, feedback and futile cycles. In: Schulze E.D. (ed.) Flux control in biological systems. Academic Press, San Diego.

Schulze E.D., Beck E., Steudle E., Stitt M. and H. Zwölfer (1994) Flux control in biological systems: A comparative view. In: Schulze E.D. (ed.) Flux control in biological systems. Academic Press, San Diego.

Seligman N.G. and H. van Keulen (1981) PAPRAN: A simulation model of annual pasture production limited by rainfall and nitrogen.p 192-221. In Frissel M.J. and J.A. van Veen (eds.) Simulation of nitrogen behaviour of soil-plant systems. Pudoc, Wageningen

Sharkey T.D. and T. Orgawa (1987) Stomatal response to light. In Zeiger E., Farquhar G.D. and I,R. Cowan (eds.) Stomatal function. Stanford University Press, Stanford

Slafer G. And H.M. Rawson (1997) CO2 effects on phasic development, leaf number and rate of leaf appearance in wheat. Annals of Botany 79: 75-81

Stitt M and E.D. Schulze (1994) Plant growth, storage and resource allocation: From flux control in a metabolic chain to the whole-plant level. In: Schulze E.D. (ed.) Flux control in biological systems. Academic Press, San Diego.

Stockle C.O. , Martin S.A. and G.S. Campbell (1994) CropSyst, a cropping system simulation model: Water/nitrogen budgets and crop yield. Agric. Syst. 46: 335-359

Talbott L.D. and E. Zeiger (1996) Central roles of potassium and sucrose in guard-cell osmoregulation. Plant Physiology 111 (4): 1051 - 1057

Thornley J.H.M. (1996) Modelling water in crops and plant systems. Ann. Bot. 77: 261-275

USDA (1988) National engineering handbook. Chapter hydrology. Section 4, 4-10. U.S. Government printing office: USDA, Washington

van der Werf A., Poorter H. and H. Lambers (1994) Respiration as dependent on a species' inherent growth rate and on the nitrogen supply to the plant. In Roy J. and E. Garnier (eds.) A whole-plant perspective of carbon-nitrogen interactions. SPB Academic Publishers, The Hague

Zech W. and I. Kögel-Knaber (1994) Patterns and regulation of organic matter transformation in soils: Litter decomposition and humification. In: Schulze E.D. (ed.) Flux control in biological systems. Academic Press, San Diego.

Zeiger E. (1994) The photobiology of stomatal movements. In Kendrick R.E. and G.H.M. Kronenberg (eds.) Photomorphogenesis in plants. Kluwer, Dordrecht