Developments in modelling crop growth, cropping systems and production systems in the Wageningen School

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Introduction

Until the 1960s, agricultural research almost completely relied upon experimental and empirical work, combined with statistical analysis. Though progress had been impressive, constraints and limitations to this type of research became more and more evident: location- and time-specific results were difficult to generalize and extrapolate, and processes were often described rather than explained in terms of underlying processes, i.e., research was analytical rather than synthetic. Following pioneering work by C.T. De Wit, scientists at the Department of Theoretical Production Ecology[1] of Wageningen Agricultural University and the DLO Research Institute for Agrobiology and Soil Fertility[2] developed systems analysis and simulation modelling in agricultural research.

In systems analysis a system is studied by defining its borders, by distinguishing its major components, characterizing the changes in them, e.g. by mathematical equa-

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tions, and then interconnecting these representations to obtain a model of the original system (Leffelaar, 1999). Developing the model is the system synthesis phase. The behaviour of the model may now be studied and compared with experimental results obtained from the system. This research method is called systems analysis and simulation.

These new methods did not replace existing methodology but rather complemented experiments and statistics. Systems analysis and mathematical modelling supported design and analysis of specific experiments, to test new hypotheses. Following this phase of theory development and model testing, the models were increasingly applied for extrapolating knowledge and results in time and space. Over the years, modelling and empirical research have become more and more integrated, mutually supportive research activities. Moreover, systems analysis and mathematical modelling proved to be powerful tools in education, at undergraduate, as well as at graduate and PhD level.

History

Since the 1960s, Wageningen has built a tradition in developing and applying crop models in its agro-ecological research programme. Aims and scope of the work have evolved over the years (Bouman *et al.*, 1996).

In the 1960s and 1970s, the main aim of the modelling activities was to obtain understanding at the system scale, based on the underlying processes. Modelling and experimentation revolved around BACROS (BAsic CROp growth Simulator) and its components (De Wit *et al.*, 1978; Goudriaan, 1977; Van Keulen, 1975; Penning De Vries, 1974).

In the 1980s, a wide range of scientists in Wageningen became involved in the development and application of crop models. The generic crop model SUCROS (Simple Universal CROp growth Simulator) for the potential production situation was developed, which formed the basis for most recent Wageningen crop models such as WOFOST (WOrld FOod STudies), MACROS (Models of an Annual CROp Simulator), and ORYZA (a crop growth model for rice). A simplified approach (with respect to simulation of dry matter accumulation) was developed by Spitters & Schapendonk (1990), based on the light use efficiency approach (LUE) introduced by Monteith (1977): the model LINTUL (Light INTerception and UtiLization). For water- and nitrogen-limited production situations, model components were added to the SUCROS framework resulting in models such as ARID CROP (a crop growth model for arid conditions), SAHEL (Soils in semi-Arid Habitats that Easily Leach) and PAPRAN (Production of Arid Pastures limited by Rainfall And Nitrogen). Modelling efforts expanded to perennial species in forest systems, and the effects of yield-reducing factors, such as weeds, pests and diseases (Rabbinge, 1976; Kropff *et al.*, 1995).

In the 1990s, emphasis shifted to modelling applications in research, agronomic practice and policy making. In a major project (Simulation and systems Analysis for Rice Production – SARP) of Wageningen, the International Rice Research Institute and 15 national agricultural research stations in Asia, interdisciplinary teams of Asian scientists were trained in the development and application of simulation models.

Within this and other projects, a wide range of issues was studied using crop models, such as: mixed cropping, relay cropping in upland rice, effects of climate change, breeding applications, yield gap analyses, and water and nitrogen management.

Crop models also found their application in studies at higher levels of integration, i.e., farm and regional scale. In a research programme in Mali (Production Soudano-Sahélienne – PSS) optimization of land use based on detailed quantitative descriptions of cropping systems became subject of research (Breman & Sissoko, 1998). Studies on designing environmentally friendly farming systems were conducted, also enabling analysis of trade-offs between economic and environmental objectives. Also land use studies were conducted with a focus on interactive exploration of different strategies for the European Union, Costa Rica and Southeast Asia (e.g. Rabbinge & Van Latesteijn, 1992). Finally, crop models were used to explore limits for food production capabilities at global scale.

Description of the major summary and comprehensive modular approaches

The Wageningen School of agro-ecological modelling is unified in its final aim of gaining quantitative insight, but highly diverse in its products. We use three criteria to characterize the various models: production situation, complexity and application domain. In production situations we shall distinguish the models on the basis of the production situations, i.e., those for potential, water/nutrient limited and actual production levels (Van Ittersum & Rabbinge, 1997). Within each production level, we discuss models on the basis of their complexity, i.e., (1) (relatively) comprehensive models, designed for research purposes; (2) summary-type models, being less mechanistic but often more suitable for application and predictive purposes. These models may have three application domains: research, education and decision support and learning.

Production factors can be classified into growth-defining, growth-limiting and growth-reducing factors. Growth-defining factors determine the potential (of maximum) production and include radiation intensity, temperature, carbon dioxide concentration in the air and crop characteristics. Growth-limiting factors determine the production level within a given physical environment without the presence of pests, diseases, weeds and pollutants and contaminants. They include water and nutrients and their level is partly or entirely influenced by the farmer. Growth-reducing factors impede, hamper or reduce the production and include biotic stresses and abiotic stresses other than nutrient and water shortage.

Potential production

Present crop modelling approaches for potential production follow two approaches, the Light Use Efficiency (LUE) approach as adopted in the LINTUL models, and the photosynthesis approach in the SUCROS family models.

For many crop species grown under well-watered conditions and ample nutrient supply, in the absence of pests, diseases and weeds, biomass production has been shown to be linearly related to the amount of radiation intercepted (captured) by the crop canopy (Monteith, 1977). This relationship sets a finite limit on yield potential, which thus can be modelled without going into detailed descriptions of the processes of photosynthesis and respiration. Spitters & Schapendonk (1990) developed the model LINTUL with a module for the calculation of crop growth based on the LUE concept. As this module calculates total (aboveground) dry matter production, (economic) yield is then obtained by applying the concept of the Harvest Index (HI) or dry matter partitioning functions. The model has been applied in various situations where calculation of yield potential was the main purpose.

In the SUCROS models, the daily rate of canopy CO_2 assimilation is calculated from daily incoming radiation, temperature and leaf area index. The model contains a set of subroutines that calculate the daily totals by integrating instantaneous rates of leaf CO_2 assimilation. The calculation is based on the time course of radiation over the day in proportion to the sine of solar height and on exponential light extinction within the canopy. Sunlit and shaded leaves are considered separately. On the basis of the photosynthesis characteristics of single leaves – which in some versions depend on their N concentration, the photosynthesis light response curve and the light extinction profile – the photosynthesis profile in the canopy is obtained. Integration over the day and over the leaf area of the canopy with depth, yields daily CO_2 assimilation. After subtraction of respiration requirements, net daily growth rate is obtained. The dry matter produced is partitioned among the various plant organs.

The LINTUL and SUCROS models follow the daily calculation scheme for the rates of dry matter production of the plant organs, and the rate of phenological development. Phenological development rate is tracked in both models as a function of daily average ambient temperature and/or photoperiod. By integrating these rates over time, dry matter production of the crop is simulated throughout the growing season.

Water- and nutrient-limited conditions

Most of the Wageningen crop models for water- and/or nutrient-limited production use soil water balances based on the 'tipping bucket' principle (Van Keulen, 1975). Some use the 'Richards' approach for water transport (Richards, 1931), in which water potential gradients are the driving force. Potential evapotranspiration is computed using equations based on Penman, Makkink or Priestley-Taylor (Van Kraalingen & Stol, 1997). The direct effect of drought stress on crop growth is a function of the ratio between actual and potential transpiration. In addition, water stress is assumed to affect dry matter allocation in favour of root biomass and reduced leaf area formation. Some models use the water-use efficiency approach.

Several approaches (at different degrees of detail) exist for modelling soil nitrogen and its limitations on crop growth. We discriminate between simple 'largely static approaches' and the comprehensive 'dynamic N-approach'. The 'largely static approach' aims to describe long-term changes in soil organic matter status and its consequences for systems functioning over many years, whereas 'dynamic approaches' include more detailed process-based nitrogen dynamics in the soil-crop system with short time steps. Relatively simple approaches to the description of *organic nitrogen* in the soil-plant-atmosphere system were developed in the framework of the Centre for World Food Studies (SOW being the Dutch acronym)[3] in the 1980's (Wolf & Van Keulen, 1989). They aim at analysis of long-term dynamics of soil organic nitrogen and their consequences for crop production. Two soil organic nitrogen pools ('stable' and 'labile') formed the core of that model, operating with time steps of one year. Flows between these pools, between the pools and inputs and outputs of the system and among the inputs and outputs were defined on the basis of so-called transfer coefficients. Organic soil nitrogen status, losses of nitrogen to the environment, and crop yields (based on nitrogen use efficiencies) are results of the model. A comparable approach was developed for soil phosphorus dynamics.

A simple approach to *soil organic matter* decomposition was developed by Janssen (1984), and taken further by Yang & Janssen (1997). They propose a first order approach with relative decomposition rate defined as a function of apparent age; different sources of organic matter are assumed to have different apparent initial ages.

The *static* QUEFTS approach (QUantitative Evaluation of the Fertility of Tropical Soils) can be used to quantify crop yields as a function of soil nutrient (nitrogen, phosphorus and potassium) status, characterized by standard soil analytical data (Smaling & Janssen, 1993).

In the more comprehensive *dynamic N-approach* the two aspects, i.e., availability and effects, were initially modelled separately: availability of mineral nitrogen to growing crops, and effects of crop nitrogen status on crop growth. The *availability* module comprises a soil organic matter balance with emphasis on soil microbiological aspects (developed in the Institute for Application of Nuclear Energy in Agriculture (ITAL)[4] research group, e.g. Van Veen & Frissel, 1981). In this module, differences in decomposition among organic input sources, characterized by their chemical composition were accounted for. In the *effects* module, influences of crop nitrogen status, expressed as the difference between optimal and actual nitrogen concentrations in the tissue, on phenological and physiological processes were described in detail (Van Keulen *et al.*, 1989).

Nitrogen dynamics in the soil, its availability to the crop and the effects of nitrogen deficiency on crop performance were combined in the model PAPRAN (Seligman & Van Keulen, 1981) and further elaborated in SWHEAT (a spring wheat crop model) (Van Keulen & Seligman, 1987) and ORYZA (Bouman *et al.*, 2001). This approach to simulation of nitrogen-limited production, that forms the basis for many current models, is referred to as the 'dynamic N-approach'.

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[3] An interdisciplinary group of scientists from Amsterdam's Free University and from Wageningen, the Department of Theoretical Production Ecology and the Centre for Agro-biological Research (CABO). The SOW Centre aimed at exploring the potentials and constraints for increased food security in developing countries, by integrating advanced knowledge from the (agro-)technical and the (socio-)economic disciplines, using a modelling approach.

[4] Presently part of Plant Research International, Wageningen University and Research Centre.

Pests, weeds and diseases

Pests, diseases and weeds continue to reduce crop yields, despite intensive crop protection measures. Ecophysiological models including the effects of these yield-reducing factors were first developed in the 1970s and early 1980s to increase insight into their harmful effects on crop production (e.g. Rabbinge & Rijsdijk, 1981). These models were then applied for formulation of more robust damage relationships to support rational decision making on the use of pesticides (e.g. Zadoks, 1988), followed by their use for strategic pest management decisions, such as guidance of breeding programmes and cropping systems design.

Weeds, unlike pests and diseases, represent the same trophic level as crops (this does not apply to parasitic weeds). This is reflected in the way their yield-reducing effects are modelled. In the first attempts to dynamically simulate crop-weed competition, the models comprised two individual growth modules (one for the crop and one for the weed) that were linked through additional modules accounting for distribution of resources over the competing species. For light, distribution is related to the vertical leaf area profile of competing species, which is dynamically simulated. For water and nutrients, competition is simulated through withdrawal of resources from a common pool. If supply is insufficient to meet the combined demand of the competing species, reductions in growth rate of both species are simulated similarly to the effects of water and/or nitrogen deficiency in monoculture models (Kropff & Van Laar, 1993).

Simulation of effects of pests and diseases starts with identification of damage mechanisms that may act at the process level, e.g. reduction of leaf photosynthetic rate due to a foliar pathogen, or at the state variable level, e.g. consumption of leaves by an insect. Quantitative relations between pest intensity (e.g. the number of insects or disease severity) and the degree to which the identified processes are affected, are incorporated in the crop growth model. Pest progress over time is often simply introduced as a forcing function, though in principle, population models of pests and diseases might be connected to a crop growth model. Schematically, effects of pests and diseases can be classified into effects on light capture and effects on light use efficiency. If only light interception is affected, the degree of damage is proportional to the reduction in light capture, and a LINTUL-type of model will be appropriate (Rossing *et al.*, 1992). If light use efficiency is affected a model that contains more detail on photosynthesis and respiration, i.e., a SUCROS-type model, is often used. In some systems, such as that of the stem borer in rice, specific organs important for yield formation are affected and additional routines that explicitly simulate processes such as tillering and kernel formation are required (Bastiaans, 1993).

Major Wageningen crop models

Operational versions of the generic LINTUL and SUCROS models are available for several crops, consisting of a module for potential production with or without modules to account for water and/or nitrogen limitation. The model WOrld FOod STudies (WOFOST) was developed within the framework of SOW, and uses the SUCROS approach for potential production conditions. Water-limited versions of LINTUL, SUCROS and WOFOST all use a tipping bucket approach for the soil-water balance with 3 to 4 compartments. Limitation by nitrogen (using the dynamic N-approach) has been implemented in LINTUL only for some crops, but in several SUCROS-based models (e.g. SWHEAT and ORYZA). In WOFOST, nutrient-limited yields are calculated through the QUEFTS procedure, following the dynamic calculation of potential and water-limited yields.

The ORYZA2000 suite of models is operational for potential, water-limited and nitrogen-limited production of rice crops (Bouman *et al.*, 2001). The model components for potential production are based on the SUCROS concept. Different options for the water balance have been designed for upland, lowland, aerobic and paddy rice systems. The nitrogen-limited version uses the dynamic N-approach.

The eco-physiological model INTERCOM (a model to simulate INTERplant COMpetition) for dynamic simulation of crop-weed interactions consists of a number (equal to the number of competing species) of coupled crop growth (SUCROS-type) models, a water balance using the tipping bucket approach, and a nitrogen-limitation module using the dynamic N-approach.

For a more comprehensive overview of the Wageningen agro-ecological models, see Van Ittersum *et al.* (2003).

Epilogue

The philosophy of the Wageningen modelling group has been based on open exchange of information. To facilitate this, models were published in books and reports, describing the scientific basis and including full codes, allowing use of this scientific knowledge by the international modelling community. The citation intensity of these publications is witness to the value of such a publication medium, in addition to publishing short articles in refereed international scientific journals.

In contrast to the attention on single crops in many different modules and models, there has not been a strong drive towards modelling cropping systems (rotations) nor development of an integrated framework for agro-ecological modelling for implementation and application purposes. Major challenges will be to continually increase our understanding of production systems, particularly under conditions of resource limitations, and to operationalize this knowledge in easy-to-use, well-documented and robust crop and cropping system models. This requires more focus, co-ordination and a sound and clear funding situation, not depending on individual projects. In addition, systems thinking and simulation must continue to form a prominent part of the academic curricula, so as to generate a continuous reservoir of critical users. Meeting these challenges requires action in a European or even global perspective.

Note

This paper is based on, and partly an excerpt from a comprehensive review paper 'On approaches and applications of the Wageningen crop models' by M.K. Van Ittersum, P.A. Leffelaar, H. Van Keulen, M.J. Kropff, L. Bastiaans & J. Goudriaan, published in European Journal of Agronomy 17 (2003); see Van Ittersum *et al.* (2003).

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