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Результаты научных исследований, представленные на конференции, связаны с решением целого ряда фундаментальных проблем: 1. Выявление взаимосвязей и изучение функционирования почвенно – растительных комплексов и агроэкосистем в условиях техногенного воздействия, глобальных и региональных климатических изменений; 2. Применение математического моделирования и информационных технологии в земледелии и агроэкологии; 3. Разработка фундаментальных основ мониторинга состояния агроэкосистем и управления продукционным процессом; 4. Применение современных методов в селекции растений.

В сборнике представлены научные труды, посвященные широкому спектру проблем, решаемых в области агрофизики, почвоведения, растениеводства, микробиологии, генетики и селекции растений, физиологии, биохимии, математического моделирования и информационных технологий.

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FROM CROP GROWTH MODELS TO MODEL-BASED DSS FOR SUSTAINABLE AGRICULTURE AND LAND USE – TRENDS AND PERSPECTIVES

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A brief description of the history of crop growth modelling worldwide beginning from the first regional modelling schools of de Wit (Netherlands), of Ritchie (United States), of Unger/Claus and Müncheberg (Germany) and of Poluektov (SU and Russia) up to the recent international modelling community under the global umbrella of AgMIP (Agricultural Model Intercomparison and Improvement) is given. Possibilities and problems of crop growth models are discussed. For model-based solving of actual problems in agricultural practice different model types are necessary. This requires integrated system modelling approaches and new types of cooperation in research. To exemplify this, the decision support systems LandCaRe-DSSfor adaptation of agriculture to climate change and the irrigation scheduling system WEB-BEREST are introduced briefly. Finally, the trends and perspectives in agricultural crop growth modelling are outlined.

Introduction

The world has become more complex in recent years due to many factors, including the growing population and its demands for more food, water, and energy, the limited arable land for expanding food production, and increasing pressures on natural resources. Over the past century, enormous progress has been achieved worldwide in improving human welfare. Agricultural production more than tripled between 1960 and 2015, owing in part to productivity-enhancing Green Revolution technologies and a significant expansion in the use of land, water and other natural resources for agricultural purposes (FAO, 2017). Expanding food production and economic growth in the most of cases are possible only at the expense of the natural environment. The negative trends in the environment are accelerating in pace and intensity, and agriculture is an important part of the problem. Looking ahead, the core question is: Can we achieve the required production increases, even as the pressures on already scarce land and water resources and the negative impacts of climate change intensify? Besides progress in the so called basic sciences (biology, soil science, physics and others) we therefore need progress in complex agricultural systems science at different scales. Integrated crop growth and land use model sare important tools to better understand changes in the past and to be able to predict the impacts of future developments (Jones et al., 2016).Agricultural system models play an increasingly important role in the development of sustainable land management across diverse agro-ecological and socioeconomic conditions because field and farm experiments require large amounts of resources and may still not provide sufficient information in space and time to identify appropriate and effective management practices (e.g., Teng and Penning de Vries, 1992). They are also an important prerequisite for the development of Integrated Decision Support Systems (DSSs) to support sustainable farm management, sustainable land use planning and development of sustainable climate adaptation strategies of agriculture (Wenkel et al., 2013).

In this paper referring to the results of the International Crop Modelling Symposium (iCROPM) which took place in Berlin in March 2016 (iCROPM, 2016), we give a short overview of the history of Crop Growth Modelling in West and East, we discuss the possibilities and problems relative to current and future needs and we draw conclusions for the further development of model systems. In the light of the pros and cons of dynamic crop growth models finally we analyze the possibilities and limits of dynamic models as integrated components of a DSS.

Brief history of crop growth modelling

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, i.e. research was more analytical.

The Wageningen School of agro-ecological modelling

Following pioneering work by C. T. De Wit, scientists at the Department of Theoretical Production Ecology of Wageningen Agricultural University and the DLO

Research Institute for Agrobiology and Soil Fertility (Netherlands) were the first, which developed systems analysis and simulation modelling in agricultural research. Since the 1960s, Wageningen has built a tradition in developing and applying crop models. Rather than focusing on a few models, diversity is its trademark. The origin and philosophy of this school are traced from de Wit's classical publication on modelling photosynthesis of leaf canopies in 1965. 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) with especially designed equipment and field experiments. These modelling approaches have served as the basis and inspiration for modelling groups around the world.

In the 1980s the generic crop model SUCROS (Simple Universal Crop growth Simulator) for the potential production situation was developed in Wageningen, which formed the basis for most recent Wageningen crop models such as WOFOST (Van Keulen and Wolf, 1986; Boogaardet al., 1998; Supit et al., 1994), MACROS (Penning de Vries et al.,1989) and ORYZA (Bouman et al., 2001). For water- and nitrogen-limited production situations, model components were added to the SUCROSframework resulting in models such as ARID CROP, SAHEL and PAPRAN (Van Keulen et al., 1981; Seligmanand Van Keulen, 1981). Modelling efforts expanded to perennial species in forest systems, and the effects of yield-reducing factors, such as weeds, pests and diseases (Rabbinge, 1976; Kropffan Van Laar, 1993). In the 1990s the Wageningen group focused more on applications in research, agronomic practice and policy making. A wide range of issues was studied using crop models, such as: mixed cropping (e.g. Baumann et al., 2001), effects of climate change (Nonhebel,1993; Wolf, 1993; Goudriaan, 1996; Rodriguez et al., 1999), breeding applications (Kropff et al., 1995; Bindraban, 1997; Aggarwal et al., 1997; Yin et al., 2000), yield gap analyses (e.g. Casanova, 1998), and water and nitrogen management (e.g. Ten Berge et al., 1997; Farre et al., 2000). In the 1990s crop models also found their application in studies at the higher levels of integration, i.e. farm and regional scale. Finally, crop models were used to explore limits for food production capabilities at global scale (Penning de Vries et al., 1995). The philosophy of the Wageningen modelling group has been based on open exchange of information and a strong linkage with teaching. To facilitate this, models were published in books and reports with full programming code and describing the scientific basis, allowing use of this scientific knowledge by the international modelling community.

Crop growth modelling in USSR/Russia

Due to political constraints on the professional interaction in the time period of the Cold War (1945–1990) till now in the Western countries only a few is known about the history and state of the art in agro-ecosystem modelling and its use in agricultural management in the former Soviet Union and in East Germany. In the 1960s analog to the Wageningen School of agro-ecological modelling the history of crop modelling and simulation in the former USSR started with the almost simultaneous development of two competitive versions (radiation and CO2). The first approach had been developed by Budagovsky et al. (1964) and the second one was presented by Budyko (1964) and Budyko and Gandin (1964). In Russia these papers were the basis for a quantitative theory of crop growth and crop production, resulting in the change from a static to a dynamic presentation of crop-environment relationships. The academic literature on simulating photosynthesis and photorespiration and other processes is quite voluminous - the subject is discussed in practically all monographs on mathematical simulation (Tooming, 1977; Bikhele et al., 1980; Sirotenko, 1981; Poluektov, 1991) and proves the high theoretical standard in this field in the Russian science. During the next 30 years up to the 1990th, extensive and very effective activities on developing crop simulation models in the former USSR have been carried out within the framework of the scientific society WYM (Weather-Yield-Mathematics) and other research programs (Sirotenko, 2001). As a result, more than 20 monographs and some hundred papers were published (Sirotenko, 1977; Poluektov, 1977; Sirotenko, 1996; Sirotenko, 2001). Unfortunately, the information contained in the majority of these publications remains unknown to the Western scientific community. In general, in Russia has been evolved two schools in crop/yield/agro-ecosystem modelling: the school of Sirotenko (All-Russian Research Institute of Agricultural Meteorology Obninsk) and the school of Poluektov (Agrophysical Research Institute St. Petersburg (ARI)). Prominent examples for the developed models are WEATHER-YIELD (Sirotenko, 2001) and AGROTOOL (Poluektov,1984; Poluektov et al.,2002; Poluektov and Terleev, 2007). Today the school of Poluektov is moving forward by the initiatives of A. G. Topaj from ARI St. Petersburg. They bring together all recent Russian-wide existing modelling groups in this field and founded a special modelling workshop cycle, which is open also for all international crop modelers (Barnaul, 2012; AFI, 2014). The AGROTOOL model is incorporated in the APEX system, a tool for computer-based multi-variant simulation experiments for agricultural for cop growth (Medvedev and Topaj, 2011; Topaj et al, 2016).

Crop growth modelling in GDR/Germany

During the second part of the 1960s parallel to the Wageningen and the Russian agro-ecosystem modelling schools also in Germany the first crop growth model approaches were developed. In East Germany, the School of Unger and Claus from the Institute of plant breeding in Quedlinburg began to work on the model-based biophysical analysis of plant systems. This school brought together the hydro-meteorological, the bio-physical and the plant-physiological components in one crop growth model. The aim of this very complex and detailed model was to find out the sensitive crop-intern processes for a successful plant breeding focused on height crop yields (Unger and Ross, 1977; Claus, 1977; Claus and Unger, 1977).

In the 1970s on the basis of extensive field experiments for collecting of coherent data sets in the system soil-plant-atmosphere-management the Müncheberg crop growth modelling school was developed in the Research Centre for Soil Fertility. This school is existing till up to now in the Leibniz-Centre for Agricultural Landscape Research. Crop growth and agro-ecosystem models from Müncheberg were developed mainly for practical applications. In Müncheberg the crop growth model TRITSIM (Mirschel et al, 1986; Matthäus et al, 1986) for winter wheat and the agro-ecosystem model family AGROSIM for winter cereals, sugar beet and catch crops (Mirschel and Wenkel, 2007) were developed. In the 1980s together with the Institute for Plant Protection Eberswalde and the Institute for Cybernetics and Information Processes Berlin the computer-aided modelling and simulation system AGROSIM-W for integrated pest management of winter wheat was developed (AdLDDR, 1986). On the basis of the modelling language SONCHES (*S*imulation *O*f *N*onlinear *C*omplex *H*ierarchical *E*cological *S*ystems; Wenzel et al, 1986) this system brought together the model TRITSIM and three models for pests and diseases (Rossberg et al., 1986a and 1986b; Gutsche et al., 1986). AGROSIM-W was used for the assessment of complex infestation situations in practice (Ebert et al., 1986). The agro-ecosystem models HERMES (Kersebaum, 1995; Kersebaum, 2007) and MONICA (Nendel et al, 2011) are recent products of the Müncheberg crop growth modelling school. Both models active take part in the AgMIP (Agricultural Model Intercomparison and Improvement Project, http://www.agmip.org/) and MACSUR (Modelling European Agriculture with Climate Change for Food Security, http://macsur.eu/)networking. The development of the HERMES model starts in the 1990s. The HERMES model mainly focuses on biomass and yield production as well as on nitrogen cycling. The MONICA model was developed at the end of the 2000s, combines algorithms mainly from HERMES and some from AGROSIM, and the calculation of organic matter turn-over and C- and N-dynamics is based on the routines used in the DAISY model (Hansen et al., 1991). Both, the HERMES and the MONICA models are generic agro-ecosystem models taking into account a lot of different agricultural crops and give the possibility to simulate whole crop rotations.

Crop growth modelling in the United States of America

Some of the earliest agricultural systems modeling in the United States of America were done by Earl Heady and his students to optimize decisions at a farm scale and evaluate the effects of policies on the economic benefits of rural development (Heady, 1957; Heady and Dillon, 1964). In 1964 the International Biological Program (IBP) was created. It left a legacy of thinking and conceptual and mathematical modelling that contributed strongly to the evolution of systems approaches for studying natural systems and their interactions with other components of more comprehensive managed systems(Coleman et al., 2004).After the global wheat crisis in 1974 in the USA new research programs were funded to create crop models that allow the USA to use them with newly available remote sensing information to predict the production of major crops that were grown anywhere in the world and traded internationally. This led to the development of the CERES-Wheat and CERES-Maize crop models by Joe Ritchie and his colleagues in Texas (Ritchie and Otter, 1985; Jones and Kiniry, 1986). These two models have continually evolved and are now contained in the DSSAT (Decision Support System for Agrotechnology Transfer) suite of crop models (Jones et al., 2003; Hoogenboom et al., 2012). Today DSSAT comprises crop growth models for over 42 crops. The models have been combined into one Cropping System Model (CSM) that has the same soil water, nitrogen, phosphorus and organic carbon balance simulations across all crops, but uses unique modules for the simulation of crop growth and development for each crop. The models have been used for a diverse range of studies, including plant breeding and genomics, irrigation and fertilizer management, climate variability and decision making, in-season yield forecasting, irrigation water use projections, nitrogen leaching and soil degradation, crop rotation and long-term soil fertility, climate change impact and adaptation, and food security. DSSAT's models has been in use for more than 20 years by researchers, educators, consultants, extension agents, growers, and policy and decision makers in over 100 countries worldwide (Hoogenboom et al., 2015). The CropSyst model developed in the Washington State University is a multi-year and multi-crop model and has been parameterized for a wide range of crops such as potatoes, lentils, tea and grapes (Stockle et al., 2003). The EPIC model developed in US consists a crop growth component (Williams et al., 1989).

Crop growth models in other countries of the world

Besides the crop growth models within DSSAT, the crop growth models from Netherlands, Germany and Russia several other models have been developed during the last years. Numerous models are now available, with different objectives, and many new models are still appearing. Actually, there is no universal model and it is necessary to adapt system definition, simulated processes and model formalizations to new agricultural crops or to specific environments. Examples for such models are: the French model STICS (Brisson et al., 2003), the Australian model APSIM (Keating et al., 2003), the Danish model DAISY (Hansen et al., 1991) and the New Zealand model SIRIUS (Jamieson et al., 1998). A very good overview of crop growth and agro-ecosystem models is given by the CAMASE model register (Plentinger and Penning de Vries, 2005) which lists more than 250crop growth and agro-ecosystem models and approaches.

Limitations of dynamic Crop Growth Models

Despite the progress in crop modelling and use in the last 40 years we should be aware, that all models have limitations. The accuracy of crop models depends on our current understanding of physiological processes and their interactions. The discrepancies among the models clearly indicate that this understanding is by no means complete. Model developers make assumptions about what components to include in the system, how these components interact, and how they respond to the environment and to management practices. The models themselves and their performances also depend heavily on the data used to develop and evaluate them. As a result, there is considerable uncertainty in results produced by the use of agricultural systems models (Jones et al., 2016). Most crop models contain a mixture of empiricism and mechanism. They combine the advantages of simplicity, such as a reduced parameter set, with explanations and reasonable accuracy and use a set of heuristic equations describing crop growth and development. Input parameters for these equations must be identified using standard or specially planned laboratory, greenhouse or field experiments (Poluektov and Topaj, 2001). Such parameter sets for all crops and locations are not or only restricted available. An optimal crop model would be one that physically and physiologically defines all relations between variables. 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. 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 (Jame and Cutforth, 1996). Since crop models are not universal, the user has to choose the most appropriate model according to his objectives. In most cases they require careful calibration and validation for local use.

Other limitations of the most existing models are, that they only simulate the major factors that affect crop performance, e.g. weather, water and soil nitrogen availability and are available only for the most important agricultural crops. Components to describe the effects of tillage, intercropping, pests, weeds, salinity, excess water, interplant competition and other factors on crop performance are missing. Therefore, the most models today have not the capabilities to compute yield loss associated with specific pests and diseases or insufficient soil fertility level (N, P, K, Mg, C_{org} …) and to diagnose the reasons for the gap between potential and actual yield (Keating and McCown, 2001). At present the existing models are parameterized for different crops but not or seldom for different crop varieties (alone for winter wheat in Germany there are more than 15 different varieties actual). This is one reason that calibration of models using field data is widely practiced to obtain genotype-specific parameters.

Moreover, today most crop 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. To use crop models and system approaches for a more effective resource management simulation models for all major crops incorporated into crop rotations are needed.

From crop growth models to model based Decision Support Systems

At present in agricultural and agro-landscape sciences and in practical agriculture it is common to use all possibilities to get information for a better decision making, for a better agro-management and for an optimal adaptation of agriculture and agro-landscape use to climate change for instance. Here models and especially crop growth models play an essential role. Such models are incorporated into decision support systems or scheduling systems for agriculture. Exemplary on two such systems are pointed out here briefly: the LandCaRe-DSS an interactive model-based knowledge and decision support system for climate change impact assessment and adaptation of agriculture to climate change (for detailed description see Wenkel et al., 2013) and the WEB-BEREST system for model-based operative field specific irrigation scheduling (Mirschel et al., 2014). Both systems were developed in the Institute of Landscape Systems Analysis of the ZALF Müncheberg, Germany. Into LandCaRe-DSS the process-based agro-ecosystem model MONICA (Nendel et al., 2014) for a detailed description of crop growth at field level, the model YIELDSTAT (Mirschel et al., 2014) for yield estimation at field and regional level and the model ONTO (Mirschel, 2010) for crop ontogenesis at field and regional level are integrated. The three models are parameterized for all relevant agricultural crops in German agriculture. LandCaRe-DSS was developed for a use in science, administration, advisory service and agricultural farms.

The system WEB-BEREST is a web-based irrigation scheduling system for an operative usage by irrigation advisory services or farmers itself. In WEB-BEREST for assessment of ontogenesis the ONTO model and a lot of crop-specific and ontogenesis-dependent parameters for more than 100 different agricultural crops, vegetables, fruits and specialized crops such as tobacco, hop and medical plants, are integrated. For estimation of effectiveness of each irrigation water amount in the system also a simple crop yield model for agricultural crops is used.

Perspectives for the further development of Crop Growth Models

Crop Growth and Agricultural system models have become important tools to provide predictive and assessment capability to a growing array of decision-makers in the private and public sectors. Despite ongoing research and model improvements, many of the agricultural models today are direct descendants of research investments initially made 30–40 years ago, and many of the major advances in data, information and communication technology (ICT) of the past decade have not been fully exploited (Antle et al., 2016). Agricultural system models already play an essential role in assessing the broader environmental consequences of agricultural technologies. These consequences include long-term on-farm impacts on soil productivity, as well as off-farm impacts on air, water quality and biodiversity.

However, the scientific challenge in making these assessments is great, and substantial improvements are needed so that agricultural system models, and the associated ICT platforms and knowledge products will be able to support the goal of a sustainable agricultural production. The next generation of agricultural system models therefore should combine weather, soil, genetic, and management components to simulate yield, resource use, and transfer of nutrients and chemicals to surrounding water, air and other eco-systems taking into account weed, pest and disease pressures.

Considering the results of the International Crop Modelling Symposium iCROPM2016 in Berlin (Germany) (iCROPM, 2016) in the following we have tried to provide a summary of the most important needs and challenges for the further development of crop growth models:

• Development and integration of new modules

User demands for information derived from models will grow for specific use-cases. Therefore, there is a need for developing of additional modules, such as agro-chemicals fate, impact of tillage on soil hydraulic properties etc. and their integration into crop/cropping system models.

• Incorporating pest and disease damage in crop models

The concept of damage mechanism has enabled much progress in modelling the effects of multiple harmful organisms on crops (pathogens, animal pests, and weeds). As a result, it is now possible to model yield losses caused by one or multiple injuries in a generic manner. However, the availability of injury functions, representing the time course of diseases (or pests) under actual field conditions, is a major obstacle to the use of such models. The shortage of field data is the main impediment in modelling crop pests and diseases, and their relations to crops.

• Integrating crop physiology and modelling with genetic improvement

Crop physiology and modelling provide opportunities to improve breeding efficiency by either dissecting complex traits to more amenable targets for genetic prediction, or by trait evaluation via phenotypic prediction in target production regions to help assess breeding strategies. Next generation crop models must provide a better way to include gene effects (gene-based crop model). This requires a transdisciplinary approach that integrates physiology and modelling into quantitative genetic improvement systems, rather than a model-based focus on «genotypic coefficients» and «ideotypes». Although some existing crop models are modular, new modules are needed that are designed based on what we are now learning about genetic control of processes and so that new modules can be easily modified.

• Modularity and interoperability

The agricultural systems research community needs to have standards and protocols so that they can operate multiple models and decision support systems. We should not aim to find a way for only one "perfect" model. Instead, we should aim for component models that are structured as modules that can be used alone to address specific questions (such as when to apply a chemical or irrigation) and, more importantly, where those modules can be integrated into holistic biophysical and economic models to address more comprehensive problems. Modular models are needed to ensure efficient scientific progress as well as model longevity and maintainability (Jones et al., 2016).

• Need for broad, open and harmonized data

Open, discoverable, accessible, and usable data are essential for evaluating and improving or developing new models and robust simulations. These data will provide a foundation across all disciplines for next generation crop models.

• Broaden the scientific collaboration and transdisciplinarity

There is a need to broaden the scientific collaboration, such as exists for example among biophysical and economic modelers, in particular to include plant breeders, insect and disease researchers, modelers, etc. Prospects for developing next generation crop models are promising due to recent scientific progress, trends in interest among various users, and new efforts to create open data resources and to change the culture of researchers to enable them to contribute data for broad uses.

Projects like MACSUR and AgMIP that have already had major impacts on science are good examples for a new quality in international collaboration.

• Stronger consideration the information need of different stakeholders

The next generation of agricultural systems models must be driven by the information needs of diverse stakeholders. A key innovation envisaged for the next generation of models would be their linkage to a suite of knowledge products – which could take the form of mobile technology «apps», personal computer-based dashboards, and online analytical and communication tools – that would enable the use of the models by a much more diverse set of stakeholders and for a wider range of purposes than is now possible. The importance of the modelling adage «the right answer for the right reason» and Einstein's remark of «as simple as possible but no simpler», will become evident.

Summary and conclusions

Agricultural systems are very complex. If we want to manage our scarce agricultural resources or to estimate the effects of future climatic change on agriculture, we need integrated tools which can simulate the crop growth in a wide variety of environments and under a wide variety of management practices. Recent advances in computer technology have made it possible to represent the soil-plant-climate system quantitatively. This has convinced scientists that the use of process-oriented crop models and the systems approach to research is a worthwhile and important goal.

Crop modelling, the computerized simulation of dynamic crop systems, was born about 30–40 years ago. Since the first publication, crop modelling has gone through a number of developmental stages. Some of the earliest models proved to be among the most notable achievements to date. During the juvenile stage that followed, there was an impressive increase in complexity and computer sophistication. Greater expectations led to more and more detailed descriptions of the functioning of the biotic and abiotic components of cropping systems. It is amazing that despite the contacts between eastern European and western scientists were rare for a long period, the development of crop growth simulation models take place nearly in parallel.

The principle of crop growth modelling and its application to decision making are based on the understanding of natural processes and using this understanding to describe agricultural systems performance through systems analysis. This understanding is by no means complete. Thus, research projects need to be focused on further efforts toward increasing our knowledge and improving our understanding of soil – plant – atmosphere interactions. Recent trends in broader collaboration across institutions, across disciplines, and between the public and private sectors suggest that the stage is set for the major advances in agricultural systems science that are needed for the next generation of models, databases, knowledge products and decision support systems. Looking back teaches us, that there is no universal model that provides a solution for all problems. Therefore, models should continue to be developed and adapted to several particular situations. The professionals dealing with modelling should define their objectives prior to constructing their models, and the model users should choose one that has been developed to solve their particular needs.

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