2011

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Published in Agricultural Drought Indices: Proceedings of an Expert Meeting, June 2-4, 2010, Murcia, Spain, pp. 138-148, edited by M. V. K. Sivakumar, R. P. Motha, D. A. Wilhite, and D. A. Wood (Geneva: World Meteorological Organization, 2011).

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Abstract

Crop models can play a role in this agricultural management decision making process to cope with drought and other natural disasters. Crop simulation models are designed to imitate the behavior of a plant system. These models separate yield prospects into components due to changing weather trends, genetic improvements, and improved technology. Simulation modeling is increasingly being applied in research, teaching, farm and resource management, policy analysis, and production forecasts. Crop simulation models can be used to simulate the drought-reduced crop yields, but a number of issues limit operational applications.

Introduction

Agricultural producers face a number of risks in their operations. The United States Department of Agriculture's Risk Management Agency has defined five primary categories of risk: production, marketing, finance, legal, and human risk (Harwood et al. 1999). Seasonal climate variability is a major source of production risks. In fact, the majority of crop failures in the United States are associated with either a lack of moisture or excess rainfall (Ibarra and Hewitt 1999). Climate variability is also greatly associated with marketing risks. Drought conditions, extreme wetness and flooding, spring freezes, and similar conditions leading to crop failure can dramatically affect crop and livestock prices. A good market plan requires an analysis of supply and demand projections throughout the cropping season. Expectations early in the season are highly uncertain. Commodity markets respond decisively to these early projections, and seasonal climate variability plays an important role in modifying the balance between supply and demand. In order to accomplish the ultimate goal of providing useful information to the agricultural decision maker that will help to reduce the variety of risks, an integration of monitoring, modeling, and forecasting tools needs to be readily available in a management toolkit.

Background

Some of the most important decisions in agricultural production, such as what crops to grow and how much land to allocate, depend on the existing knowledge base of current and future physical conditions like soil and climate, and yields and prices. Modeling of the various processes in the system helps us to understand its flow and intricacies. Weather and climate continually alter some of these major decisions as natural disasters and extreme events disrupt agricultural activities. Agricultural drought is one of the major disruptive events affecting crop productivity at the farm level, and sustainable agriculture and food security around the world.

Impacts on agriculture can be addressed at various levels, including crop yields, farm and village level outputs and income, regional and national production, and global production and prices. Each level requires different sets of criteria, including methods and input data. However, there is a multi-tier relationship between various scales. For example, the data inputs of the crop response can be fed into the farm level model. The output of the farm level model can then be used as input to the regional scale. The output from the regional scale can be used as input into the national assessment, and the resulting output can be used for global crop production assessments.

The characterization of agricultural drought is entirely different from other types of droughts. The deficiency of water in sensitive growth stages can reduce production in some crops severely. The effect of one drought event may continue to affect an area for several growing seasons or even several years; thus, there is the need to analyze agricultural drought events on the basis of continuous weather data. The analysis of agricultural drought is also complicated by the fact that the beginning and end of any drought is often difficult to determine. Furthermore, the impact of drought often accumulates slowly over a considerable period of time. The impact of drought may linger long after the termination of the event. The absence of a precise and universally accepted definition of drought has added to the complexity. Therefore, any realistic definition of drought must be region and application specific.

Agricultural drought links various characteristics of meteorological drought to agricultural impacts, focusing on precipitation shortages, differences between actual and potential evapotranspiration, and soil moisture deficits. Any realistic definition of agricultural drought should account for the susceptibility of crops at different stages of crop development. The crop simulation-based analysis of drought may serve to identify crop losses due to agricultural drought because of the water loss accounting procedures. Crop simulation models can be very useful tools for the characterization of drought by calculating the water deficiency due to deficient rainfall, runoff (slope effect), deep percolation (soil effect), and evapotranspiration (temperature effect). Crop simulation models then can be used to simulate the drought-reduced crop yields. However, there are many issues to contend with regarding crop modeling. Some of these will be discussed in this chapter.

Crop Modeling

Models are mathematical equations depicting the relationships between crop growth, development, yields, technology, and climate. For example, crop yield is a function of complex interactions of biotic and abiotic factors, including crop management (e.g., fertility, variety, and seeding rate), soil and field characteristics (e.g., drainage, topography, and soil water holding capacity), and weather conditions (e.g., temperature, precipitation, and light use efficiency). Crop production varies not only spatially but also temporally. The agricultural system is complex and, although it is nearly impossible to represent the system in mathematical terms, crop models can provide some sense of reality in terms of phenological development or response to climate extremes or other environmental or biological parameters affecting crop growth and development. However, universal models do not exist within the agricultural sector. Models are built for specific purposes and the level of complexity varies according to the application, data availability, and objective of the model. Inevitably, different models are built for different sub-systems, and several models may be built to simulate a particular crop or a particular aspect of the production system.

One of the main aims of constructing operational crop models is to obtain an estimate of the harvestable (economic) yield. The operational applications generally focus on crop yield forecasting, which often includes an assessment of the soil moisture regime and crop growth and development. The assessment of crop development and yield response often includes crop management, such as fertilizing, cultivation, irrigation, and plant protection. However, models are rarely used for early warnings or mitigation of damages from extreme meteorological phenomena and natural disasters.

There are different types of crop models. Empirical models are direct descriptions of observed data. They are generally expressed as regression equations (with one or a few factors) and used to estimate the final yield. Examples of such models include the response of crop yield to severe drought, the response of yield to fertilizer application, and the relationship between leaf area and leaf size in a given plant species. The limitation of this type of model is that it is generally location specific.

An alternative approach involves the use of crop growth simulation models. Crop growth models encapsulate knowledge of eco-physiological processes and allow simulation of crop yield for specific varieties and locations. Simulation models form a group of models designed to imitate the behavior of a system. They are mechanistic and, in the majority of cases, deterministic. Since they are designed to mimic the system at short time intervals (daily weather data, for example), the aspect of variability related to daily change in weather and soil conditions is integrated. The short simulation time-step demands that a large amount of input data (climate parameters, soil characteristics, and crop parameters) be available to generate and run a model.

The parameters used in crop simulation models generally include meteorological, physical, and biological parameters, but a parameter of length of time should also be included. Simulation models require that meteorological data be reliable and complete. Meteorological sites may not fully represent the weather at a chosen location. In some cases, data may be available for only one (usually rainfall) or a few (rainfall and temperature) parameters, but data for solar radiation, which is important in the estimation of photosynthesis and biomass accumulation, may not be available. At times, records may be incomplete and gaps may have to be filled.

A stochastic weather generator produces artificial time series of weather data of unlimited length for a location based on the statistical characteristics of observed weather at that location. These types of statistical models are generally developed in two steps, with the first step focusing on the modeling of daily precipitation and the second concentrating on the remaining variables of interest, such as maximum and minimum temperature, solar radiation, humidity, and wind speed, which are modeled conditional upon precipitation occurrence. For each month, different model parameters are used in order to reflect seasonal variations in both the values of the variables themselves and in their cross-correlations (i.e., in the relationships between the individual variables over time).

There are two basic types of stochastic weather generator: the “Richardson” (Richardson 1981, Richardson and Wright 1984) or “serial” (Racsko et al. 1991, Semenov et al. 1998) types. The types of weather generator available are also described in Wilks and Wilby (1999).
In a “Richardson” type weather generator (e.g., WGEN), precipitation occurrence is modeled using a first-order two-state Markov procedure, which describes two precipitation classes (i.e., wet or dry) and takes into account precipitation occurrence on the previous day only. More complex models may involve more than one precipitation class (e.g., low, medium, and high precipitation amounts) as well as the occurrence of precipitation on a number of days before the current day, rather than on just the previous day.

The Markov process gives information on transition probabilities (e.g., on the probability of a wet day following a dry day or the probability of a wet day following a wet day), calculated from the observed station data. If precipitation occurs, then the amount of precipitation falling on wet days is determined usually by using a predefined frequency distribution, most commonly the gamma distribution, although mixed-exponential distributions may provide a better representation of precipitation amount at some locations. The remaining climate variables are then calculated based on their correlations with each other and on the wet or dry status of each day. One of the main criticisms of Richardson-type weather generators is their inability to adequately describe the length of wet or dry series (i.e., persistent events such as drought or prolonged rainfall), which are extremely important in some applications (e.g., agricultural impacts, where the occurrence of a drought during a particular phase of crop development may result in crop failure).

The serial approach to weather generation was developed to attempt to overcome this problem. In this type of weather generator, the first step in the process is the modeling of the sequence of dry and wet series of days. The amount of precipitation and the remaining climate variables are then generated dependent on the wet or dry series. The serial-type weather generator, first developed by Racsko et al. (1991), has been substantially updated (LARS-WG; Semenov et al. 1998). Many different versions of weather generators have been developed over the past decade.

Simulation models have been reported as useful in separating yield gain into components due to changing weather trends, genetic improvements, and improved technology. Simulation modeling is increasingly being applied in research, teaching, farm and resource management, policy analysis, and production forecasts. These models can be applied in three areas, namely, research tools, crop system management tools, and policy analysis tools. However, simulation models usually offer the possibility of specifying management options, and they can be used to investigate a wide range of management strategies at low costs. Most crop models that are used to estimate crop yield fall within this category.

When a model is applied in a new situation (e.g., switching to a new variety), the calibration and validation steps are crucial for correct simulations. The need for model verification arises because all processes are not fully understood and even the best mechanistic model still contains some empirism, making parameter adjustments vital in a new situation. 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. Using approximations may lead to erroneous results.

Model users need to understand the structure of the chosen model, its assumptions, its limitations, and its requirements before any application is initiated. At times, model developers may raise the expectations of model users beyond model capabilities. Users, therefore, need to judiciously assess model capabilities and limitations before one is adopted for application and decision-making purposes. Generally, crop models are developed by crop scientists, and if interdisciplinary collaboration is not strong, the coding may not be well-structured and model documentation may be poor. This makes alteration and adaptation to simulate new situations difficult, especially for users with limited expertise. Finally, using a model for an objective for which it had not been designed or using a model in a situation that is drastically different from that for which it had been developed would lead to model failure.

Optimizing models have the specific objective of developing the best option in terms of management inputs for practical operation of the system. These models use decision rules that are consistent with some optimizing algorithm for deriving solutions. This forces some rigidity into their model structure, resulting in restrictions in representing stochastic and dynamic aspects of the modeled agricultural systems. Applications have been developed to assess long-term changes in agriculture, regional competition, transportation studies, and integrated production and distribution systems as well as policy issues in the adoption of technology and natural resource conservation. Optimizing models do not allow the incorporation of many biological details and may be poor representations of reality. However, a useful option has been to use the simulation approach to identify a restricted set of management options that are then evaluated with the optimizing models. CERES is a series of crop simulation models, and DSSAT is also a framework of crop simulation models, including modules of CERES, CROPGRO and CROPSIM, that are incorporated into a system of optimizing models.

Modeling Applications in Agriculture

Crop modeling has been applied at various scales in agriculture, from precision farming, to farm planning, to watershed or regional policy development. CROPGRO Soybean (Hoogenboom et al. 1994) and CERES-Maize (Jones and Kiniry 1986) are process-oriented models that compute growth, development, and yield on homogeneous units from field to regional scales. Although crop modeling is a relatively effective tool for simulating yield and yield-limiting factors, as noted earlier, a large amount of input data is necessary to accurately predict spatial variations. It has also been expensive to measure dense spatial datasets for use in crop models. Reliable and cost-effective techniques must be developed to parameterize crop models across a field with high spatial resolution and to quantify in-field spatial variations.

The crop management system models mentioned above are generally referred to as decision support system (DSS) models for agriculture. A set of crop models that share a common input/output data format has been developed and embedded in a software package called the Decision Support System for Agrotechnology Transfer (DSSAT). DSSAT (IBSNAT 1989, Jones 1993, Tsuji et al. 1994) is a shell that allows the user to organize and manipulate crop, soils, and weather data and to run crop models in various ways and analyze their outputs. CERES-Maize and CROGRO-Soybean models are included in the DSSAT v.3.5 software package (Hoogenboom et al. 1994) to simulate crop growth. These are mechanistic process-based models that, in response to daily weather inputs, predict soil traits, daily photosynthesis, growth, and crop management. Fraisse et al. (2001) and Wang et al. (2003) evaluated the CERES-Maize and CROPGRO-soybean models for simulating site-specific crop development and yield on Missouri claypan soils. Additional models running under DSSAT include the CERES (Crop Environment Resource Synthesis) models for rice, wheat, sorghum, pearl millet, and barley (Ritchie 1985, Ritchie and Otter 1985, Ritchie 1986); the CROPGRO model for peanut and phaseolus bean; and a model for cassava and potato (Tsuji et al. 1994). Phenological development and growth in the CERES models are specified by cultivar-specific genotype coefficients depending on the photoperiod, thermal time, temperature response, and dry matter partitioning.

Geographic information system (GIS) is a computer-assisted system that acquires, stores, analyzes, and displays geographic data. Because of the increasing pressure on land and water resources and the importance of forecasts at different spatial scales (crop, weather, fire, etc.), geographic information systems have become an essential decision-support tool. GIS has developed into a powerful tool at the disposition of policy and decision makers (Maracchi et al. 2000). Interfacing crop simulation models with a GIS helps to accomplish spatial and temporal analysis at the same time.

Spatial model applications, such as interfacing models with GIS, further increase the possibilities of applying these models for regional planning and policy. GIS is a front-end tool for data preprocessing and a visualization tool for analyzing the final results. The user interface also resides within the GIS and facilitates location-specific and crop-specific data input. On completion of data input, the data access modules acquire the necessary spatial and non-spatial data from GIS layers and a Relational Database Management (RDBM) System, respectively. An RDBM system offers a data management system that comprises a set of operating-system processes and memory structures that interact with the storage. This scenario offers advantages such as better performance, scalability, and redundancy. Large data files can be stored from a number of different sources, processed, archived, and retrieved as necessary.

GIS-based modelling of an agroecosystem offers a powerful tool to agricultural managers to simultaneously assess the effect of soil and water resources on crop production in addition to farm practices. At present, most of the crop models are location specific (point based) in nature, but to have a better understanding of the impact on agricultural systems, it is necessary to have spatially explicit analyses. Therefore, the development of spatially or raster based biophysical crop models helped to clarify many intricacies of modeling large areas.

Hydrologic models are valuable tools for water resources management. For irrigation scheduling and crop water requirement estimation, hydrologic simulation models commonly use the water balance approach (Fangmeier et al. 1990, Fulton et al. 1990, Smajstrla 1990, George et al. 2000). Precision farming research has demonstrated that field-scale variations in crop yield are controlled by soil properties and landscape features that affect patterns in water available to plants, soil drainage, and aeration (Jaynes and Colvin 1997, Mulla and Schepers 1997). Inclusion of spatially distributed climate, soils, and land-use data dramatically increases the model's computational and data requirements. Storage and application of spatial data continues to challenge traditional modeling approaches.

Geographic information systems are capable of providing the necessary spatial database for hydrologic models. By exploiting the modeling power of GIS through integration of GIS with hydrologic models, a GIS can be transformed from a simple spatial query and visualization tool to a powerful analytical and spatially distributed modeling tool. Recent advances in GIS technology facilitate the seamless integration of GIS and computer-based modeling. Multiple approaches exist to integrate GIS and hydrological models (Maidment 1993, Abel et al. 1994, Sui and Maggio 1999). The two general categories of approaches are 1) coupling, providing a common interface or a linkage between the applications, and 2) embedding or merging the features of different applications into a single application. Rao et al. (2000), Tucker et al. (2000), and Xu et al. (2001) have successfully developed integrated GIS and hydrological models.

Agro-climatic models consisting of coupled GIS and crop models, including AEGIS/WIN by Engel et al. (1997) and CropSyst by Stockle and Nelson (1994), have been used to enhance farm management practices. Both models simulate the soil water budget, soil-plant nutrient budgets, crop canopy and root growth, dry matter production, yield, residue production and decomposition, and erosion. These biological simulation models excel at quantifying the effect of different management systems on crop production and environmental impacts. AEGIS/WIN links DSSAT v3 with ArcView to model spatially distributed crop growth (Engel et al. 1997). Crop-Syst, a multi-year and multi-crop model, spatially and temporally simulates the soil water budget components and crop growth potential by coupling the model with databases of soil type, long-term weather conditions, and crop management (Stockle et al. 1997). Both AEGIS/WIN and CropSyst characterize the soil variability on a regional scale, but assume a single soil layer within a field. The above models are capable of dealing with a limited variety of crops, homogeneous soil (on a farm scale), and climate information from a single location.

The GIS-based Water Resources and Agricultural Permitting and Planning System (GWRAPPS) (Satti 2002) is a more comprehensive distributed model with several unique features: 1) estimates of crop water requirements are simultaneously simulated for multiple crops and allow for climate and soil variation as well as differing irrigation management practices, 2) spatial scales range from a single field to a regional scale, 3) annual and monthly drought water requirements are determined using a statistically robust frequency analysis of the simulated historical daily water demand, and 4) the system provides an easy-to-use Graphical User Interface (GUI) to access GIS data and an RDBMS. Though GIS is capable of storing and supporting large spatial data, it cannot readily maintain large temporal data. The data storage approach implemented in the GWRAPPS overcomes this shortcoming and efficiently handles large temporal and spatial databases by storing the temporally explicit data in a RDBMS and maintaining appropriate links from a GIS layer to the RDBMS tables.

GWRAPPS is a decision support system for permitting and planning irrigation water demand. GWRAPPS operates in a Windows environment that tightly couples ArcGIS (ESRI) with the Agricultural Field Scale Irrigation Requirements Simulation (AFSIRS) model (Smajstrla and Zazueta 1988) using object-oriented technology. The AFSIRS numerical simulation model determines the statistical characteristics of the irrigation requirements for a crop based on soil type, irrigation system, growing season, long-term climate, and irrigation management practice (Smajstrla 1990). The model calculates the daily soil water budget using the water balance approach that effectively models crop water requirements in the southeastern United States (Smajstrla and Zazueta 1988, Villalobos and Fereres 1989). AFSIRS simulates the dynamic processes of soil water infiltration, redistribution, and extraction by evapotranspiration as steady state processes and schedules irrigation based on an allowable level of soil water depletion from a two-layer crop root zone.

The analysis components determine water demand at two different scales, the single farm scale and the regional scale. The permitting tool operates at a single farm scale and allows the user to simulate water requirements for a crop using either a single soil or an area-weighted average of all the soils within the farm. The model results include monthly and annual crop water requirements for median conditions and different drought probabilities. Typical drought scenarios include 1-in-5 year and 1-in-10 year drought conditions. The planning tool analyzes the irrigation requirements at a regional scale. The planning tool is similar to the permitting tool in that the same AFSIRS model and GIS soils and climate data are used to generate the water requirements. However, the planning tool analyzes all water permits in the region simultaneously. The simultaneous analysis greatly reduces the time required to analyze a region’s water demand and facilitates the planning for multiple time horizons and land-use change scenarios. The generated GIS irrigation requirements layer provides monthly and annual crop water requirements for the median, 1-in-5 year drought, and 1-in-10 year drought irrigation scenarios.

GWRAPPS provides a consistent tool for water use planning and permitting by extending the AFSIRS model from a farm-scale model to a regional-scale irrigation requirements simulation model. The integrated GIS system facilitates effective usage of spatial distributed data to estimate farm and regional-scale irrigation requirements. GWRAPPS, with multiple soils, provides a comprehensive picture of the total water demand that is not readily apparent because of the complex interaction of soil characteristics and their relative contribution to the area of interest. GWRAPPS provides water demand maps that facilitate the study of regional irrigation requirements using farm level inputs. A simple user-friendly interface provides easy access to the components of the system by maintaining the complex data and control transfer operations in the background. The system's most important feature is its ability to quickly and easily provide regional crop water requirements for different drought scenarios. The present research demonstrates that the integrated system is capable of providing critical information to planners and farmers about different crops' plant–soil–water relationship under a range of drought conditions. In conclusion, GWRAPPS, with its ability to consider spatial variability of soils and climate at both farm and regional scales under normal and drought conditions, is a practical tool that is applicable to a wide range of water resources management and development problems.

The Agricultural Production Systems Simulator (APSIM) has been designed as a multi-purpose simulation platform (McCown et al. 1996). The APSIM model concept is able to accommodate various levels of complexity, depending on the intended application. It is composed of a modular framework. Systems models such as APSIM take this concept further by providing a means for effective communication across all the disciplines involved to address issues affecting farming and agriculture.

Originally, the crop models were developed to deal with risky crop management decisions in the face of climatic variability. The models simulated plant growth and crop development in response to environmental inputs (water, temperature, solar radiation, nutrients) with the ultimate aim of estimating the yield of harvestable material from a commercial crop as precisely as possible. At the heart of these models is the relationship between crop yield and various inputs (climatic conditions such as rain, temperature, and solar radiation; nutrients; and management interventions such as irrigation or fertilization) that may or may not be affected by crop residues left on the soil surface from a previous crop. These residues can affect surface runoff, soil temperature, surface evaporation, and soil moisture, and thus can affect many processes that contribute to crop growth and yield as well as the state of the environment in which the crop is being grown. This is where the need for good science arises so that the model simulates the processes appropriately and precisely, in ways that are easily computable, and the results are believable. In addition to crop yield, models such as APSIM generate a large range of complementary output variables that can be very helpful in analyzing resource management problems. Community concern about off-farm impacts of farm inputs such as nitrogen fertilizer has increased in recent years. Therefore, farm management practices that might cause long-term resource degradation have come under close scrutiny.

Models such as APSIM are complex, and as such require specialist support and a range of skills to support simulation building. A soil scientist will need crop physiology or agronomy expertise to ensure that water use, dry matter production, and maybe yield (assuming a holistic soil scientist) are drivers for soil processes. Modelers often work in an environment where this broad expertise is available and essential for the development of useful and reliable systems tools.

Although APSIM is primarily aimed at researchers, an increasing number of derived products have been developed. Adoption by commercial partners is also increasing, and it is through these arrangements that consultants and growers who have no prior modeling experience can evaluate a large range of alternative crop and fallow management options. Given the rapid changes that are currently taking place in rural industries (driven by economic as well as environmental factors such as climate change), the importance of APSIM as a quantitative, predictive tool for scenario development and evaluation is likely to increase.

Heinemann et al. (2008) used a crop simulation model to determine the patterns of drought stress for short- and medium-duration upland rice around flowering and early grain-filling across 12 locations in Brazil. Simulation models can also provide a tool to assist in understanding, and incorporating, genotype-by-environment interaction, by combining mechanistic understanding of a drought (Chapman 2008). Given a historical record of weather for a location, the probability of a yield increase (and maybe a decrease) resulting from the incorporation of any trait into the crop can be simulated. Combining the probabilities for yield change with the farmers' adversity to risk gives a strong indication to a breeder of the desirability of incorporating a particular drought trait for cultivars to be grown in a specific location. System analysis can hence allow breeding for specific drought-adaptive traits to be targeted to those geographical regions where their benefit will be largest (Sinclair and Muchow 2001). However, in the case of rice, most simulation efforts have focused on irrigated environments, and an improved rice model needs to be developed or adapted specifically for the drought-prone rainfed systems, based on better physiological understanding of rice interaction with the environment under water deficits.

In Europe, only a few models are applied operationally (Eitzinger et al. 2008). Most research institutions are working on research applications of crop modeling for climate change impact research on agriculture, whereas the operational applications have the focus on crop yield forecasting. The applications often include an assessment of soil moisture, crop growth and development, and crop yields. The assessment of crop development and yield response to related crop management, such as fertilizing, cultivation, irrigation, and plant protection, is another application. Crop models are rarely used for early warnings or mitigation of crop damages from extreme meteorological phenomena and processes.

Crop model applications are influenced by several uncertainties determining limitations of their use in research and practice (e.g., Eitzinger et al. 2008). The main reported limitation for application of crop models in Europe is related to the input data. The most frequently reported problems are the availability or the low quality of the soil physical model input data (especially for spatial model applications), the lack of long-term biophysical crop data for model validation and calibration, and, in some cases, the availability or costs of meteorological data. This is related to the socio-economic conditions in countries and different local administration of data in the different regions of Europe. The reliability of data for climate scenarios or seasonal forecasts is another crucial point for the use of such models for operational purposes or for making long-term strategic decisions.

Spatial model applications, such as interfacing models with GIS, increase the possibilities of applying these models in regional planning and policy. Because of their relatively simple calculation methods, agroclimatic indices are often implemented in GIS in order to show spatial distribution and developments of the relevant calculated index. These drought indices are used in the crop models for decision-making tools.

The most promising method of estimating crop yield over larger areas is to combine crop growth models and remote sensing data. The main benefit of using remotely sensed information is that it provides a quantification of the actual state of the crop for a large area, while crop models give a continuous estimate of growth over time. Only a few applications of spatial crop growth monitoring systems are fully operational in Europe. However, the general theme of remote sensing data assimilation in crop models has been the subject of numerous research papers in the last few years. These papers have discussed practical solutions, but the operational application is still limited by the large amount of data to be processed.

AquaCrop (Raes et al. 2008) is a water-driven stimulation model that requires a relatively small number of parameters and is a functional balance between simplicity, accuracy, and robustness. FAO evolved the AquaCrop model from an earlier crop simulation modeling approach that has been well recognized for operational applications. In AquaCrop, the crop system has five major components and associated dynamic responses: phenology, aerial canopy, rooting depth, biomass production, and harvestable yield. Five weather input variables are required to run AquaCrop: early maximum and minimum air temperatures, daily rainfall, daily evaporative demand of the atmosphere expressed as reference evapotranspiration (ET), and the mean annual carbon dioxide concentration in the bulk atmosphere (Mauna Lou Observatory records in Hawaii).

The features that distinguish AquaCrop from other crop models are its focus on water, the use of ground canopy cover instead of leaf area index, the use of water productivity values normalized for atmospheric evaporative demand, and the carbon dioxide concentration that extends the capacity of the model to extrapolate to diverse locations and seasons, including future climate scenarios.

With respect to the more complex approaches, namely simulation or process-oriented models, operational applications are still very limited, except for the simple models. Some simple crop models focus on irrigation scheduling, or the widely applied models for pest and disease management. In research, however, process-oriented crop models play a very important role in the assessment of global and climate change impacts on agriculture. Most of these studies are carried out on a larger scale, neglecting the necessarily finer spatial resolution to be of relevance for local practical recommendations for farmers. One of the main difficulties for the spatial application of process-oriented crop models in a high spatial resolution at the research level is often the lack of model input data (not available, high costs, expensive data management, etc.). On the other hand, new methods are being developed to overcome these problems by using GIS and integrating remote sensing data. Operational crop yield forecasting that integrates all these available tools is only used at the expert level, and very few examples of it exist.

Summary

Although models are developed by agricultural scientists, the user group includes agronomists, extension workers, policy makers, farmers, and plant breeders. Because different users possess varying degrees of expertise in modeling, the misuse of models may occur. Since crop models are not universal, the user has to choose the most appropriate model according to his objectives. 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. Crop/soil simulation models are basically applied in three areas: 1) tools for research, 2) tools for decision making, and 3) tools for education, training, and technology transfer. The greatest use of crop/soil models so far has been by the research community, as models are primarily tools for building a knowledge base. However, effective crop models can be used for a vast array of operational applications, especially when integrated with GIS and remote sensing technologies. As research tools, model development and application can help identify gaps in our knowledge, thus enabling more efficient and targeted research planning. Models that are based on sound data are capable of providing significant agricultural drought analyses to assist management strategies.

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