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Quarterly Journal of the Hungarian Meteorological Service
Vol. 113, No. 1–2, January–June 2009, pp. 1–12

Applications of agroclimatic indices and process oriented crop simulation models in European agriculture

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(Manuscript received in final form February 24, 2009)

Abstract—During the past decades, many new software tools were developed to be used for agricultural research as well as for decision making. For example, crop and whole farm system modeling, pest and disease warning models/algorithms, models for irrigation scheduling or agroclimatic indices can help farmers significantly in decision making for crop management options and related farm technologies. The aim of Working Group 1 of COST 734 was a review and assessment of agroclimatic indices and simulation models relevant for various European agricultural activities. The key results, based on a survey by questionnaires among the COST 734 participating countries (see: www.cost734.eu) and a literature survey, are presented in this study. It includes an overview of most used agrometeorological or agroclimatic indices and process oriented crop models for operational as well as scientific applications, an analysis of the limitations for applications, and an overview of spatial applications in combination with GIS and remote sensing in Europe. The COST 734 survey showed, for example, that research activities regarding the development of agroclimatic indices in Europe are focused on indices on drought, phenology, frost, and heat stress. Process oriented crop models are mainly applied for wheat and maize, which is related to their importance in European crop production. In many cases there are still limitations of crop model applications in Europe, which are often related to the availability of input data. Spatial crop model applications including a combination with remote sensing data are still rare. There are a number of different models and indices in use, varying by regions and countries. From the survey it can be concluded that there is a need of standardization and harmonization of applications of agroclimatic indices as well as crop models in Europe in order to allow inter-comparison of the results and to improve the interpretation of results.

Key-words: agroclimatic indices, crop models, COST 734, European agriculture

1. *Introduction*

A review and assessment of agroclimatic indices (including meteorological, climatological, or agrometeorological indices, which are applied in agrometeorology) as well as crop simulation models relevant for various European agricultural activities was carried in the frame of the COST 734 action (see: www.cost734.eu). The survey was based on questionnaires and a literature survey. The detailed results are described in a COST 734 report (*Orlandini* and *Nejedlik*, 2008). It includes an overview of most used agroclimatic indices and process oriented crop models for operational and scientific applications, an analysis of the limitations for applications as well as an overview of spatial applications in combination with GIS and remote sensing in Europe. During the past decades many new software tools were developed to be used for agricultural research as well as for decision making. For example, crop and whole farm system modeling, pest and disease warning models/algorithms, models for irrigation scheduling or agroclimatic indices can help farmers significantly in decision making for crop management options and related farm technologies. In research, models can be used to simulate and analyze the complex interactions in the soil-plant-atmosphere system, for example in the important field of climate change impacts on crop water balance and crop yields. All these modeled systems and their interactions are simplifications and, therefore, include many different kind of uncertainties and limitations resulting from unknown trends in future technology and human activities, models simplified representation of reality, lack of knowledge on system responses, or lack of calibration data. Much research was done in Europe and worldwide in the field of model development, improvements, or comparisons of models.

2. *Agroclimatic indices and providers*

Indices are explicitly defined by equations, whereas indicators are relationships identified to quantified impacts. Both serve to simplify complex phenomena. Therefore, indices can be indicators once these relationships are quantified and measurable. Indicators can include also output values from mechanistic models, which uncover simplified relationships to impacts.

The following aspects are based on the findings of the COST 734 assessment. Many various indices are used in Europe for operational applications and in research. Indices are mostly used in agrometeorological monitoring and services operated by the national state bodies, such as in national meteorological and hydrometeorological institutes as well as their regional branches. Private agrometeorological services are scattered and usually concentrated on some specific points of service like extreme weather warning service or advisory services in case of plant protection against pests and diseases. In some cases, private companies selling chemicals or other materials and equipments to farmers, such as weather stations, include also some technical support and agrometeorological services and/or forecasting models (mostly pest and disease warning) as a part of their products. General agrometeorological information is mostly produced by national bodies such as meteorological services, which run the meteorological networks, and so they are also the owners of the data. In many cases, they cooperate with other national bodies providing them the data either free of charge or at commercial base.

The research activities regarding the development of the agrometeorological indices in Europe are focused on drought, crop responses such as phenology, and to a lesser extent, frost and heat stress (*Fig. 1*). The attention paid to research does reflect the practical use of indices in operational use. Relatively little attention is paid for example to the operational monitoring of drought and heat stress, while the majority of responding countries notices the research activities in this field.

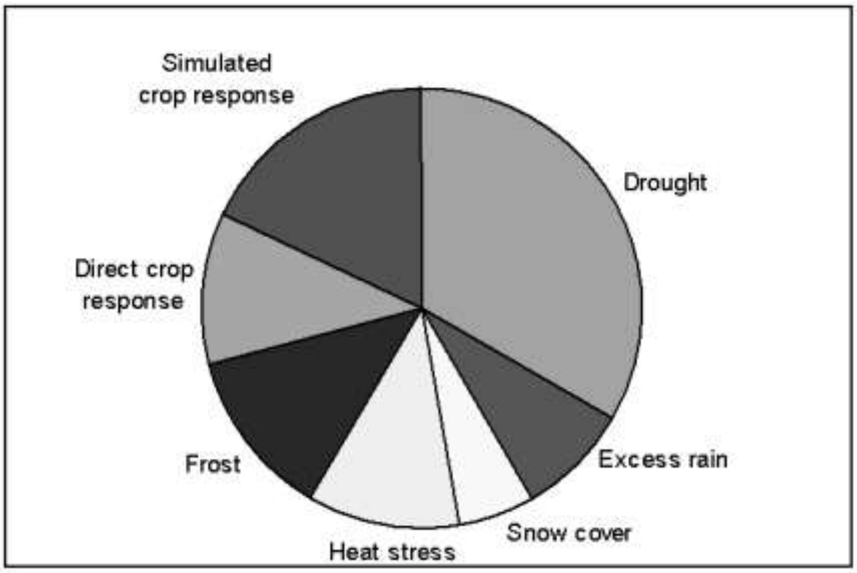

Fig. 1. Distribution of the numbers of agrometeorological indices used in research related to their purpose, according to the COST 734 survey.

In the following the main groups of indices applied in Europe relevant for agriculture are described. An extensive list of the various indices including literature can be found in *Orlandini et al.* (2008).

2.1. Drought

Drought indices are constructed to quantify the lack of water during certain periods, for example the negative deviation of precipitation from the normal in case of meteorological drought indices. Meteorological drought indices, however, do not always describe the real shortage of water for the crops. For agrometeorological drought indices, therefore, the focus is on crop water balance of crop stands during the plant growth and development cycle. The general problem of these indices is to include the physical and biological properties of the particular crop in order to reflect its sensitivity and limitations towards the lack of water supply during the vegetation period. A related problem is the definition of the time step used to calculate the particular indices.

The major part of the drought indices, as reported in the COST survey, is focused on pastcasting and some of them on nowcasting. These indices are often applied locally or regionally as they have to use multiyear measured values of the particular parameters recorded or calculated for a certain locality.

The major part of the indices in use are rather complex and deal with water balance components and precipitation measures. Indices defined in the calculation of water balance components are used in various modifications in almost all countries in the extent from national to a farm level. Both indices, based on water balance components and on precipitation only for a given period, are produced mainly by national weather services, as they run the meteorological networks at regional and national levels. Some institutes use the partial outputs of the models like WOFOST to define the days with the lack of water for the crops. In Slovenia, for example, the irrigation model IRRFIB is used for daily calculation of crop water balance for different regions. It represents an agricultural decision support tool, which is running inside the Slovene Agrometeorological Information System (SAgMIS) package.

From the standard indices, the standardized precipitation index (SPI), Palmer drought severity index (PDSI), percent of normal precipitation and rainfall percentiles are in operational use among other national services in Europe, at the Drought Management Center for South eastern Europe (DMCSEE). Relevant maps are published on the web page http://www.dmcsee.org/, and they are updated once per month (*Fig. 2*). Final data maps with two months delay are available after the 20th day of the current month. First-guess maps are available after the 5th day of the next month.

2.2. Excess rain

Excess rain as a water related phenomenon is observed in all European countries by simple measurements of daily sums of precipitation. Further to this parameter, the rainfall intensity is measured either by pluviographs or by weight rain gauges providing online signal. The major part of rainfall parameters are issued in the standard forecast of each meteorological service mainly at the regional scale. Some of the services provide special rainfall maps in their pastcasting, identifying the areas with high precipitation and/or anomalies.

In Greece, for example, apart from high precipitation pastcasting maps, an operational-research application of the non-hydrostatic model LM-COSMO of HNMS (Hellenic National Meteorological Service) has been used for forecasting excess rain events. The model has been used for the simulation of severe thunderstorms (*Avgoustoglou*, 2002). The data are collected from stations of the Hellenic National Meteorological Service and the Ministry of Agriculture. Generally, excess rain represents a damaging weather event and its characteristics are usually issued for general use stressing the regional differences.

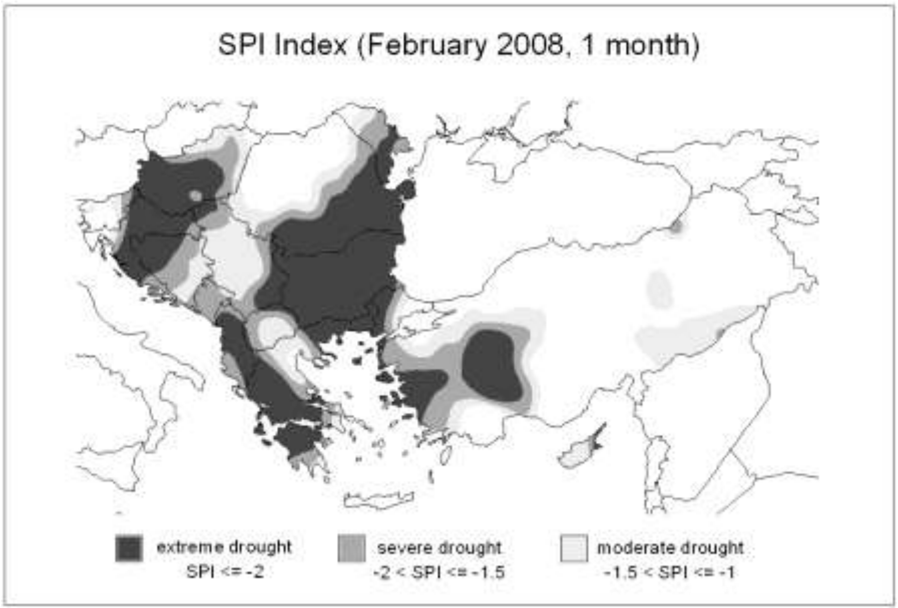

Fig. 2. Standardized precipitation index (SPI) for southeastern Europe issued for February 2008.

2.3. Heat stress

Heat stress is a complex phenomenon, depending on the definition and the sensitivity of the recipient. Factors such the height of temperature, duration, and rate of increase of the temperature as well as air humidity, radiation, and wind can modify the heat stress level of living organisms. The critical thresholds of temperatures for crops, for example, differ pretty much and they vary also according to the plant development stage. A threshold of heat stress usually refers to the daily mean temperature, over which a detectable reduction of growth or damages on plant begins. Heat stress prediction is naturally included in general weather forecasts, though there are very few services listed, which provide special heat stress related indices. A heat index forecast is provided, for example, by Hungarian Meteorological Service, which includes the forecast of daily average temperature above 25 °C. In Greece, forecasts of surface temperature and wind speed over Attica and neighboring areas are provided using the non-hydrostatic model MM5. This model has very high resolution (grid distance of 2 km), and the forecasts of the parameters are calculated every 18 hours (*Kotroni* and *Lagouvardos*, 2002).

2.4. Frost

Critical temperatures needed for frost damage to occur may vary depending on the temperature and the duration, while the temperature remains below freezing point, as well as on the sensitivity of the recipient. However, the common detection and prediction on frost conditions considers the duration of temperatures below 0 °C and daily minimum values. Frosts are frequently classified as either advective or radiative, and this also defines their impact on the different type of crops and possibilities for frost protection. During radiative frosts, local orographic conditions can modify near surface temperatures considerably, for example, the frost line does not reach more than 1–2 m above ground, so that only the crops close to the ground are affected by frost. These aspects make local frost prediction very difficult, and only generalized, large scale based assessments can be given by operational services.

Frost events are both forecasted and monitored by the national meteorological services in all countries. A standard weather forecast includes the forecast of the frost or the possibility of ground frost occurrence. However, only a few special indices in operational use focuse on nowcasting and pastcasting in Europe. Frost forecast is usually issued at the national level for general purposes, while specific indices for local assessments are mainly used by farmers (e.g., for frost irrigation scheduling), consultants, and insurance companies.

2.5. Snow cover

The presence of snow cover brings a valuable protection of plants against hard frosts during the winter. On the other hand, a long snow cover duration under unfavorable conditions can damage the crops, for example, by a forced occurence of fungs. Further, a frequent change of snow cover and bare soil, combined with freezing/thawing events can physically damage the roots of crops (e.g., winter cereals). The indices or algorithms dealing with snow cover are, beyond research applications, mostly focused on operational pastcasting, which, for example, is done daily at different spatial scales of 10 × 10 km grids in Finland to the regional and national scales in other European countries. In some cases the water content of the snow cover is announced which brings the possibility to estimate the amount of the water being stored in the snow as a water source in spring. Specific snow conditions are frequently observed in the Alpine region for detecting risk of avalanches.

2.6. Specific events

Further to the above described indices, several specific agrometeorological indices are in operational use, often focused on suitable conditions for crop management.

Relevant special weather forecasts for farmers and complex growing season information are provided by many European services, including institutional and privat services. Daily forecasts are, for example, provided at the scale of 10 × 10 km by the Finish Meteorological Service and a private company in Finland. This information includes probability of rain and frost, rain amount, temperature, relative humidity, wind speed and direction, index describing weather conditions for plant protection. The German Weather Service provides actualized 7-day forecasts up to 4 times a day, concerning the drying of hay and grain moisture of cereals and maize. Other parameters include potential and crop evpotranspiration soil temperatures as well as soil wetness and workability trends. Additionally, recommendations are given for the sowing day of winter cereals, oats, potato, sugar beets, and maize for the upcoming 6 days. Some services provide information about the workability of the soil with regard to the depth of the frozen soil considering also the impact of frost on lumps of clay during the winter.

Regarding the hail events, an operational project has been carried out in Greece, the Greek National Hail Suppression Project (NHSP) weather modification program. The objectives were to reduce hail damage and at the same time to examine and study the thermodynamic, dynamic, and microphysical characteristics of the potential hail producing clouds. Also, instability indices are calculated for Operational Hail Forecasting in Greece. In some countries specific radar services are installed for hail warning systems, such as in Serbia.

Forest/grass fire indices in various forms are in use in Mediterranean countries mainly. Considering increasing occurrence of forest fire events under the climate change, more frequent use of these indices is expected. The German Weather Service (DWD) provides a daily risk index for forest fire which combines several indices: a Swedish index (Angström), two German indices (Baumgartner, M-68), and the Canadian forest fire warning system (FWI: fire weather index, FFMC: fine fuel moisture code) (http://www.agrowetter.de/Agrarwetter/Waldbrand_en.html).

3. Crop response, pests and diseases monitoring

There are not many services monitoring the response of the crops to weather conditions regarding crop growth and phenological development. Operational phenological networks, which comprise a sufficient number of stations work, are mainly in the region of Central Europe (especially Germany). These networks are run by the meteorological services and systematically monitor phenological development stages of selected plants, and in several cases, crop development including some pheno-metric parameters, pests and diseases, as well as yields. The use of the data is mainly in pastcasting. In some cases some special parameters are monitored by remote sensing (e.g., greenness index). Remote sensing of phenological parameters is intensively used at the European scale by

JRC Ispra within the MARS project. A special set of parameters regarding the plant conditions close to the harvest is provided by the German Meteorological Service. Further to that, either standard (WOFOST) or specific (IPHEN) models are used to simulate the development of different plants.

On the other hand, crop parameters including yields and the level of pest and diseases occurrence are widely simulated by using either specific algorithms or partial outputs of crop growth models. Several agrometeorological services, often regionally based extension services, provide operational pest and disease warnings for specific crops in many European countries. A significant part of pest and disease warning is, however, carried out by farm based systems by using agrometeorological weather stations.

4. Process oriented crop simulation models

Mechanistic models have been studied for more than 50 years. The three most important “schools of development” from Australia, the Netherlands, and the United States include APSIM models (*Asseng et al*., 2000), SUCROS based models (such as WOFOST) from the “School of De Wit” (*Van Ittersum et al*., 2003), and the DSSAT family (such as CERES) of crop models (*Jones et al*., 2003), although there are links between these models. As a result of the survey, in Europe, the most frequently used process oriented crop models for research or operational applications are CERES, WOFOST, and STICS, however, with distinct differences between countries. WOFOST is the only model, which is operationally integrated at the European level for the European crop yield prediction system, covering all countries.

It can be seen, that research applications dominate and that only few models are already applied operationally at the beginning of the 21st century. Often the number of national or European applications of the relevant models are related to established research institutions working on model developments. The main application of the crop models is in climate change impact research on agriculture, whereas the operational applications have the focus on crop yield forecasting. The applications often include an assessment of the dependence of growth, development, and yields of crops on limitations of soil-water regime. The assessment of crop development and yield response to related timing of crop management such as fertilizing, cultivation, irrigation, plant protection, etc., is another application. Rarely they are used for early warnings or mitigation of damages from extreme meteorological phenomena and processes.

Most crop simulation models in Europe are applied for annual crops, especially cereals and maize, reflecting the economically most important crops in Europe (*Fig. 3*). Regionally, however, also permanent grassland, potatoes, sugar beet, oilseeds, and others play an important role, which results in specific model applications.

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 reported most frequent 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 on 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.

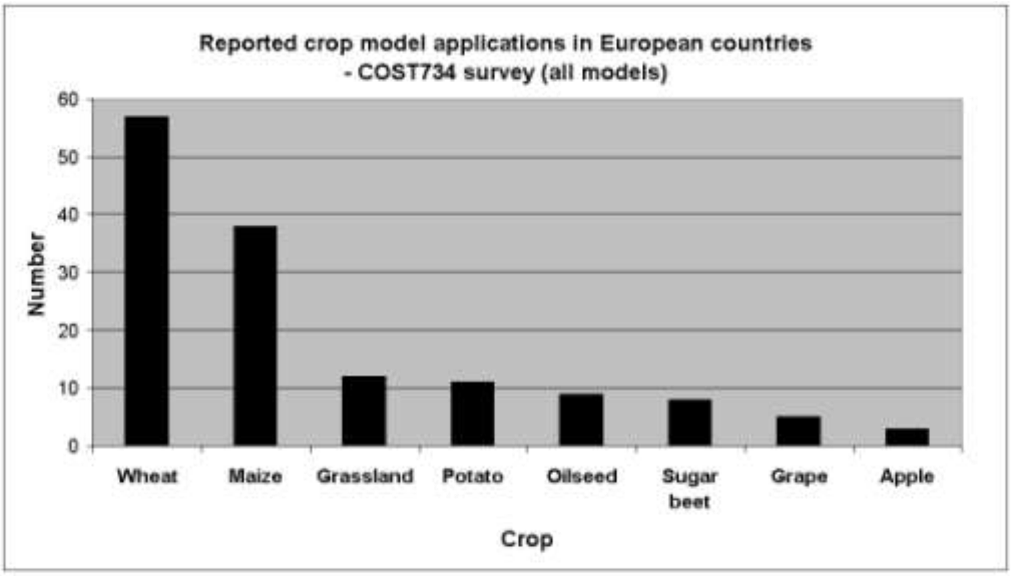

Fig. 3. Reported crop model applications (operational and research, one count per model and country) according to the COST 734 survey.

5. *Spatial applications of models and indices*

Spatial model applications, such as interfacing models with geographic information system (GIS), increase the possibilities of applying these models for 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. The most common examples of these are drought indices. Also several crop models are applied on spatial scales beyond the field level.

The most promising method to estimate crop yield over larger areas is combining crop growth models and remote sensing data. The main benefit of using remote sensed information is that it provides a quantification of the actual state of crop for large area, while crop models give a continuous estimate of growth over time. Only few applications of spatial crop growth monitoring systems are already operational in Europe. However, the general item of remote sensing data assimilation in crop models has been the subject of mainly methodological research in the last years. They have allowed to elaborate practical solutions, but the operational application is still limited by the large amount of data to be processed. The best known example of an operational application is the MARS Crop Yield Forecasting System (MCYFS) for food security for Europe and other parts of the world (http://agrifish.jrc.it/marsstat/), which is providing quantitative crop statistics at EU (for a 50 × 50 km² grid for NUTS units) and national levels, in near real time.

MCYFS was adapted also for national CGMS at a finer grid scale of 1 × 1 km² to 10 × 10 km² (for defined zones below NUTS level) for Belgium (B - CGMS; http://b-cgms.cra.wallonie.be/en/). B-CGMS is based on the existing European harvest forecasting system, but the data bases are supplemented and refined by Belgian physical (soil data) and technical (temperature sums, crop management) parameters. Satellite data are used as an aid to arrive at a quantitative estimate of production in B-CGMS, where at the European CGMS it is used for qualitative interpretation.

A national example of spatial agroclimatic monitoring is SIGA (Servicio de Información Geográfico Agrario-Service of Agrarian Geographics Information), an application running at the Ministry of Agriculture (Deputy Direction of annual crops) in Spain (*Sanchez et al*., 2005). The application (SIGCH-GIS related to the management of annual crops) offers cartographic and alfanumerical information, thematic maps on agroclimatic variables, as well as information about the plan of productive regionalization of Spain for the application of the EC rules (EC-1251/1999) of the European Commission. There are also regional projects with similar characteristics like SITNA, such as a territorial information system developed by the regional government of Navarra region. SAgMIS is an internet based GIS information system managed by the Environmental Agency of the Republic of Slovenia, which includes in situ information on crop water balance and irrigation forecast. Maps of water balance for different areas in Slovenia can be obtained for different time scales upon request (*Sušnik* and *Kurnik*, 2004).

6. Concluding remarks

The COST 734 report contains probably the most complete overview on the big number of models and indices currently used in Europe for different operational and scientific applications in agriculture. Due to their simplicity, agroclimatological indices can be considered as valuable tools for research and operational applications. Particularly, the possibility of using wide temporal time steps (daily, weekly, monthly) makes these indices suitable for application with historical climatic series. There are few cases (e.g., drought indices, grapevine quality index), where indices also include thresholds describing the consequences of obtained values and recommended interventions needed to manage and to protect the agricultural systems from climate related impacts. The results of the questionnaires elaboration pointed out their large use at European level for many purposes, spatial (regional, national) and temporal (nowcasting, past-casting, etc.) scales. Especially for indices, it seems also to be clear, that there is a need of standardization and harmonization of applications in Europe in order to allow inter-comparison and to improve the interpretation of results. The more complex approaches, namely process oriented models, are still very limited in operational applications (especially crop yield models), except for the simple models, which 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. A majority of these studies were 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. Only very few examples exist for operational crop yield forecasting which integrate all these available tools, and they are only used at the expert level.

Beside the effects of climate change on crop productivity, which are the dominating studies till now, it is recommended that the modeling community should also have a closer look on other aspects such as soil fertility, and environmental issues like groundwater recharge and water quality, soil carbon stocks, erosion, trace gas emissions, etc., in the future. Therefore, integrated modeling approaches are required, which include the most relevant interactions in the soil-crop-atmosphere system. We, therefore, should also try to combine our modeling of climate change impacts with ideas and experiences of sustainable production.

Acknowledgment—This study was carried out within the COST 734 action, where many experts from various countries contributed in the survey. More details of the survey can be found in the COST 734 report.

References

Asseng, S., van Keulen, H., and *Stol, W.,* 2000: Performance and application of the APSIM Nwheat model in the Netherlands. *Eur. J. Agron. 12,* 37-54.

Avgoustoglou, E., 2002: Operational-research investigation of the model (LM-COSMO) at the

Hellenic National Meteorological Service. *Proceedings of 6th Hellenic Conference in Meteorology Climatology and Atmospheric Physics, Vol. 1.* Ioannina, 25-28 September 2002, 35-42.

Eitzinger, J., Formayer, H., Thaler, S., Trnka, M., Zalud, Z., and *Alexandrov, V.,* 2008: Results and uncertainties of climate change impact research in agricultural crop production in Central Europe. *Bodenkultur 59,* 1-4.

Jones, J.W., Hoogenboom, G., Porter, C.H., Boote, K.J., Batchelor, W.D., Hunt, L.A., Wilkens, P.W., Singh, U., Gijsman, A.J., and *Ritchie, J.T.,* 2003: The DSSAT cropping system model. *Eur. J. Agron. 18*, 235-265.

Kotroni, V. and *Lagouvardos, K.*, 2002: Fune grid weather forecasts over Attica, Greece: Results of one year operational use. *Proceedings of 6th Hellenic Conference in Meteorology Climatology and Atmospheric Physics, Vol. 1.* Ioannina, 25-28 September 2002, 132-137.

Orlandini, S. and *Nejedlik, P.* (eds.), 2008: Survey of agrometeorological practices and application in Europe regarding climate change impacts. *COST Report: COST ACTION 734 – Impact of Climate Change and Variability on European Agriculture* (available at : www.cost734.eu).

Sánchez, J.A., Cánovas, F., and *Lacasa, A.*, 2005: Un sistema de información geográfica (SIG) para el manejo de enemigos naturales, plagas y enfermedades en los cultivo de pimiento del Campo de Cartagena (Murcia) (in Spanish). *Agroinformación.com*

Sušnik, A., and *Kurnik, B.,* 2004: On-line irrigation support system in Slovenia. On-line agrometeorological application with decision support at the farm level. COST 718: Meteorological application to agriculture. *DINA Research Report*, no. 109, 113-128.

Van Ittersum, M.K., Leffelaar, P.A., van Keulen, H., Kropff, M.J., Bastiaans, L., Goudriaan, J., 2003: On approaches and applications of the Wageningen crop models. *Eur. J. Agron. 18,* 201-234.