

IDOJÁRÁS

QUARTERLY JOURNAL OF THE HUNGARIAN METEOROLOGICAL SERVICE

Special Issue: Symposium on Climate Change and Variability – Agrometeorological Monitoring and Coping Strategies for Agriculture

Guest Editors: **Simone Orlandini, Mannava V. K. Sivakumar, Tor H. Sivertsen, and Arne O. Skjelvåg**



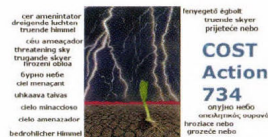
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IDŐJÁRÁS

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Foreword

Agriculture is one of the most important industries in the world. It is estimated that nearly one out of every three people in the world is involved in farming, and agriculture provides all of the cereals, vegetables, meat, fish, and forestry products that we all depend on. Farmers and farming communities throughout the world have, in most instances, survived and developed by mastering the ability to adapt to widely varying weather and climatic conditions. However, the dramatic growth in human population is imposing enormous pressure on existing farming production systems. Human activities—primarily burning of fossil fuels and changes in land cover—are modifying the concentration of atmospheric constituents or properties of the Earth's surface that absorb or scatter radiant energy. Global atmospheric concentrations of carbon dioxide have increased 35% as a result of human activities since 1750 and now far exceed pre-industrial values determined from ice cores spanning many thousands of years. The primary source of the increased atmospheric concentration of carbon dioxide since the pre-industrial period is fossil fuel use, with land use change providing another significant but smaller contribution.

Farmers are expected to manage the more insidious effects of long-term climate change that may now be occurring at an unprecedented rate. Against the very unfavorable economic scenarios of the last decades, farmers have been struggling to maintain their income by continuously trying to increase yields in their production systems. Such increased productivity may be associated with increased economic and environmental risk as the farming systems become more vulnerable to climate variability and climate change. These existing pressures will demand the development and implementation of appropriate methods to address issues of vulnerability to weather and climate. These include agrometeorological monitoring and coping strategies for agriculture.

Awareness of the need to give greater attention to the issues of agrometeorological monitoring and coping strategies for agriculture led the Commission for Agricultural Meteorology (CAgM) of the World Meteorological Organization (WMO) at its fourteenth session held in New Delhi, India in 2006 to establish an Expert Team (ET) on "Climate Risks in Vulnerable Areas: Agrometeorological Monitoring and Coping Strategies" to determine the critical areas where the agricultural production is sensitive and vulnerable to climate change/variability in different regions; and to suggest continuous monitoring strategies for early detection in vulnerable areas. The team was asked to summarize the status of mitigation

and adaptation strategies with respect to impacts of climate change/variability and also the status of coping with climate risks in agriculture, rangelands, forestry, and fisheries in vulnerable areas in the different regions. Another task of the team is to appraise and report on current capabilities in the analysis of climate risks and adaptation strategies in vulnerable areas and assess the status of progress in the project on “Climate Forecasts for User Communities” in agriculture, rangelands, forestry, and fisheries. Finally, the team was asked to develop methodologies for climate risk mapping for use by insurance industry.

WMO and the COST Action of the European Science Foundation have very fruitful ongoing collaboration in several areas and I am indeed very pleased that WMO and COST Action 734 on the “Impact of climate change and variability on European agriculture – CLIVAGRI” jointly organized the “Symposium on Climate Change and Variability-Agrometeorological Monitoring and Coping Strategies for Agriculture” in Oscarsborg, Norway on June 3–6, 2008. The symposium brought together experts from 27 countries from five continents including the members of WMO ET on Climate Risks in Vulnerable Areas: Agrometeorological Monitoring and Coping Strategies and those of COST Action 734 to discuss several important issues concerning agrometeorological monitoring and coping strategies for agriculture to deal with climate change and variability.

Fourteen papers presented at the Symposium are brought together in this special issue of IDŐJÁRÁS, and I hope this issue will serve as a major source of information to all agencies and organizations interested in the subject of climate change and variability, agrometeorological monitoring, and coping strategies for agriculture. I congratulate the editors of this special issue, *Drs Simone Orlandini, Mannava V. K. Sivakumar, Tor H. Sivertsen, and Arne O. Skjelvåg* for their hard work and dedication in putting this issue together and the Hungarian Meteorological Service for bringing out this issue of IDŐJÁRÁS.

A handwritten signature in black ink, appearing to read 'M. Jarraud', is written over a large, stylized, abstract graphic element consisting of several overlapping lines.

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Editorial

This special issue of IDŐJÁRÁS contains the proceedings from the “Symposium on Climate Change and Variability – Agrometeorological Monitoring and Coping Strategies for Agriculture” held at Oscarsborg, Norway on June 3–6, 2008. The symposium was co-sponsored by COST ACTION 734 on the “Impact of climate change and variability on European agriculture – CLIVAGRI” and the World Meteorological Organization (WMO). The local organizers were the Plant Health and Plant Protection Division of the Norwegian Institute for Agricultural and Environmental Research and the Department of Plant and Environmental Sciences at the Norwegian University of Life Sciences.

The sessions of the symposium were structured and named according to the four working groups (WG) of COST 734, WG1: Agroclimatic indices and simulation models, WG2: Evaluation of the current trends of agroclimatic indices and simulation model outputs describing agricultural impacts and hazard levels, WG3: Developing and assessing future regional and local scenarios of agroclimatic indices, and WG4: Risks and foreseen impacts on agriculture.

Participants from WMO include the members of the Expert Team (ET) on Climate Risks in Critical Areas: Agrometeorological Monitoring and Coping Strategies in Vulnerable Areas of the WMO Commission for Agricultural Meteorology. The terms of reference of the ET were adopted and included as the bases of the symposium topics.

The symposium program was divided into four technical sessions, each of which covered specific topics covering agrometeorological monitoring and coping strategies for combating climate change and variability. The following is a brief description of the different technical sessions.

Session 1 covered “*Agroclimatic indices and simulation models*”. The main theme was to review and assess current use of agroclimatic indices and simulation models like the crop growth models in Europe, and their application in analysis of impacts of climate change. Five papers from this session are presented in this special issue. In the first contribution, *J. Eitzinger et al.* presents an overview of the use of agroclimatic indices and process oriented models of crop growth in European agricultural research, specifically connected to the ongoing work of

WG1 of COST 734. The second contribution by *D. T. Mihailovic* and *B. Lalic* shows the connection between regional climatic models and parameterization schemes for describing the physics of dynamics (turbulent fluxes) and radiation balance of tall grass canopies. Several new results are shown. The paper by *Z. Dunkel* deals with a survey of drought definitions (concepts) and drought indices used in agrometeorology. The paper of *V. Vucetic* presents an analysis of the time trend of growing degree days in Croatia, using data from four different weather stations, and shows the results of global warming and growth of crops in Croatia. In the last paper, *Škvarenina et al.* presents a study on the occurrence of dry and wet periods at selected meteorological stations in Slovakia during the period 1951–2005. The parameters considered are the amount of precipitation, potential evapotranspiration, actual evapotranspiration, relative evapotranspiration, and a drought index. In certain lowland regions, the incidence of droughts seems to have increased significantly, and in certain highland regions the climate has become significantly more humid.

Session 2 covered “*Current trends of agroclimatic indices and simulation model outputs*”. Three papers from this session are presented in this issue. In the first contribution, *Tsiros et al.* describe an agroclimatic zonation scheme for sustainable production in Greece using GIS and remote sensing data for the time period 1981–2001. In the second paper, *S. Orlandini et al.* have shown the results of calculating trends of agroclimatic indices applied to grapevine and olive trees in Central Italy. The third contribution by *K. C. Kersebaum et al.* deals with testing results of different CO₂ response algorithms against a FACE (German Free Air Carbon Dioxide Experiment) crop rotation experiment for a number of field crops.

Session 3 dealt with the topic of “*Developing and assessing future regional and local scenarios of agroclimatic indices*”. Four papers from this session are included in this special issue. The first paper by *M. V. K. Sivakumar* and *R. Stefanski* presents a way of dealing with the threats of climate change connected to the conceptual framework of sustainability, impacts on agriculture, adaption, mitigation, and WMO initiatives for climate change adaptation. The conclusion contains elements of strategies for combating climate change. The second contribution by *W. Smith et al.* contains certain perspectives on GHG emission from agricultural production systems in Canada, describing what is happening, and presenting ideas for long term strategies of mitigation and adaption to the emission of GHG. The paper by *R. Motha* discusses how adaptation strategies could be developed for sustainable agriculture by presenting examples from the USA. The conclusions contain ideas for an agricultural weather and climate policy, connecting policy makers and scientists. In the fourth paper, *O. H. Baadshaug* and *L. E. Haugen* describe the effect of climate change on grassland growth potential in the mountainous regions of southeastern Norway.

Session 4 dealt with “*Risks and foreseen impacts on agriculture*”. Two papers from this session are included in this special issue. The paper of *B. Šiška* and *J. Takáč* presents drought analysis of agricultural landscapes as influenced by climatic conditions in the Slovak Republic. Agriculture in the different regions in Slovakia probably will be impacted by different climatic stresses in the future, but most of the country will experience drought conditions. *L. Dióssy* and *A. Anda* describe the consequences of climate change on maize microclimate in Hungary. The model analysis is based on climate change scenarios and different levels of CO₂ in the atmosphere.

Thanks to the strong collaboration between COST 734 and the Commission for Agricultural Meteorology of WMO, and to the excellent cooperation from the local organizers participants from 27 countries from five continents made presentations at the symposium in Oscarsborg. This provided an unique scientific occasion for discussing the important issue of climate change at the global level. Some of the participants are agronomists and biologists, while other participants have their background in physics and meteorology. The theme of the

symposium is quite relevant to the current concerns regarding climate change, and the short overview of the proceedings presented in this special issue shows that many aspects connected to geography as well as methods of research were discussed and a range of climate change consequences for agriculture was covered.

*Simone Orlandini*¹, *Mannava V.K. Sivakumar*², *Tor H. Sivertsen*³, and *Arne O. Skjelvåg*⁴
Guest Editors

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Acknowledgement—We would like to thank IDÓJÁRÁS for giving us the opportunity to present a cross-sectional view of the multidisciplinary themes of the work of COST 734 and the way in which the Oscarsborg symposium tried to address these themes in a systematic manner.

Conclusions and recommendations of the Oscarsborg symposium

Introduction

Participants in the WMO and COST Action 734 “Symposium on Climate Change and Variability – Agrometeorological Monitoring and Coping Strategies for Agriculture” held in Oscarsborg, Norway on June 3–6, 2008, met in four working groups to discuss the topic addressed by the symposium. The working groups developed conclusions and recommendations under the following major headings:

- Determination of critical areas for climate change and variability;
- Current status of strategies for mitigation, adaptation and sustainability;
- Current capabilities in the analysis of climate risks and adaptation;
- Coping with climate risks and foreseen impacts in agriculture.

Conclusions

Determination of critical areas for climate change and variability

- Global warming has been registered since the second half of the 20th century and is causing an increase in the frequency of various extreme weather events and natural hazards (such as droughts, heat waves, intensive precipitation, floods, storms, sea level rise, forest fires, water and wind soil erosion, etc) in many regions. This tendency is expected to continue in the future.
- Climate variability and change affect all sectors with a different level of their impacts. However, agriculture is considered among the most vulnerable sectors in many regions due to the negative impacts of unfavorable variations and changes in weather and climate.
- The most vulnerable agricultural regions are those:
 - adversely affected by current and projected climate variability and change,
 - damaged by occurrence of new pests, diseases, and weeds,
 - faced by insufficient financial resources and methodological experience.

Examples of such vulnerable regions in Europe include the Mediterranean region, the Balkan Peninsula, NW Russia, and likely Fennoscandia (thermal regime combined with change in snow cover).

Current status of strategies for mitigation, adaptation and sustainability

- Most agricultural systems are to some extent capable of mitigating greenhouse gas (GHG) emissions and adapting to changing climate, however, the extent to which this will occur is limited by lack of awareness, policy, economics, and a need for more food and energy.
- Gaps in research regarding climate change in agriculture limit our ability to take sufficient action to implement mitigation and adaptation measures.

- There has been little political and economic incentives to promote mitigation of GHGs from agricultural sources.

Current capabilities in the analysis of climate risks and adaptation

- Currently there is a wide range of indices for characterizing various types of droughts, but there is no standardized index that is universally acceptable.
- In the light of climate change, there is likelihood of floods and landslides in many vulnerable regions, and yet there does not seem to be a critical analysis of these two climate risks.
- Certain crops at certain phenological stages are highly susceptible to heat waves and there does not appear to be an operational warning system.
- Despite the availability of reasonably good frost warning systems, currently frost protection systems can not be universally employed as they are expensive.
- Cyclones/hurricanes do cause structural damages (farm implements, animals, and crops) and there does not seem an adequate assessment of their impacts on agriculture, forestry, and fisheries.
- Although the risk of forest fires in the light of climate change is increasing, there are no seasonal forecasts for controlling forest fires in the areas at risk.

Coping with climate risks and foreseen impacts in agriculture

- While acknowledging that farmers have always dealt with climate variability, the speed and magnitude of recent climate change has to be recognized as an increasing problem.
- Climate change is becoming an additional and more important driver in agricultural systems.
- Climate change impacts not only production services but also the protection and environmental services (multifunctionality).

Recommendations

Determination of critical areas for climate change and variability

- Strengthen climate variability/change monitoring; develop/improve decision support systems and seasonal climate prediction by applying innovative techniques and approaches at local and regional level.
- Foster national/international/regional cooperation in the field of climate variability/change through exchange of know-how, information, etc.
- Develop common methodologies (e.g., determination of vulnerable regions – criteria; new agroclimatic zonation).
- Develop/improve/update and utilize adaptation and mitigation options for agriculture under climate variability/change (e.g., improving plant breeding and protection, assuring resistance to heat stress, dry spells, UV radiation negative effects).

- Promote work on climate variability/change related scientific uncertainties.
- Bring science to society by transmitting the climate variability/change and related impacts research results in appropriate way to the society including policy makers, stakeholders, end users, and broad community by:
 - Closer and direct contacts;
 - Increasing the knowledge of advisers, farmers (end users), etc.;
 - Incorporation of the media.

Current status of strategies for mitigation, adaptation and sustainability

- Develop a portfolio of agricultural strategies that includes adaptation, mitigation, technological development, and research (climate science, impacts, adaptation, and mitigation) to combat climate change.
- Integrate mitigation and adaptation frameworks into sustainable development planning on a priority basis.
- Assess long-term consequences of mitigation and adaptation strategies in agriculture and determine how these actions are affected by climate.
- Select the option of biofuel production as a viable adaptation and mitigation measure when it is not in conflict with essential food production, biodiversity issues, and land conservation.
- Integrate, where possible, agricultural systems with renewable energy systems such as wind, solar, and hydroelectric power.
- Ensure that developing countries play an increasing role in planning national and regional programmes on mitigation and adaptation to climate variability and climate change.
- Reduce the types of agriculture production which require large amounts of energy inputs per unit of food (e.g., meat and milk) to substantially reduce GHG emissions. This could be accomplished by applying a carbon tax on high-energy foods and transportation.

Current capabilities in the analysis of climate risks and adaptation

- Undertake, on an urgent basis, a comprehensive review of the existing drought indices, and recommend a limited set of indices that are universally acceptable and which could serve the needs of different regions and classes of droughts.
- Translate the current knowledge on floods and landslides into operational management systems that government and agencies could adopt.
- Adopt the current heatwave warning systems for humans to crops/cropping systems.
- Develop cost effective frost operational systems and raise awareness among the farmers about the frost damages.
- Undertake the assessment of the impacts of cyclones/hurricanes on agriculture, forestry, and fisheries systematically to develop operational systems in order to limit the losses to property, farms, and farm animals.

- Include in the agenda of the seasonal climate outlook fora, that are organized in different parts of the world, forecasts for the risks of forest fires and encourage the forest fire fighting community to be a part of the user community in these fora.
- Develop the most comprehensive information that could assist the locust-control community to address the increasing incidence of locusts.

Coping with climate risks and foreseen impacts in agriculture

- Ensure closer connection between studies of greenhouse gas emissions and climate change impacts.
- Encourage agrometeorologists to improve impact studies of climate variability and change.
- Make sure that coping strategies address both positive and negative impacts.
- Regionalize, on an urgent basis, climate change impact studies through regional organizations (e.g., Cost Actions) since climate variability is increasing and will be different in different regions.
- Promote the establishment of knowledge circles at different levels (scientists, decision-makers, and farmers at the local, regional, and national levels).
- Reinvalidate agrometeorological and related agricultural research in the light of climate change.

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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.

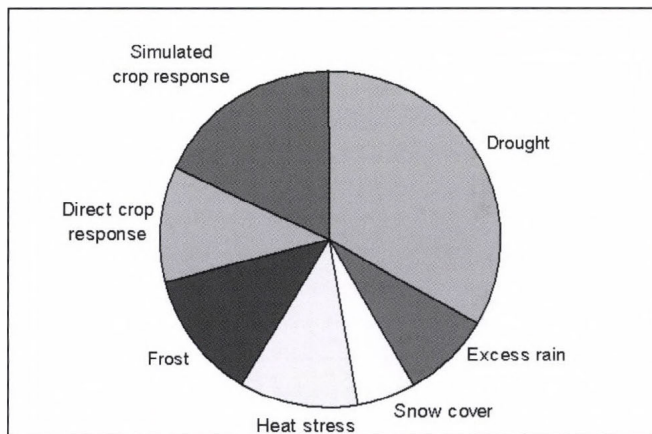


Fig. 1. Distribution of the numbers of agrometeorological indices used in research related to their purpose, according to the COST 734 survey.

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.

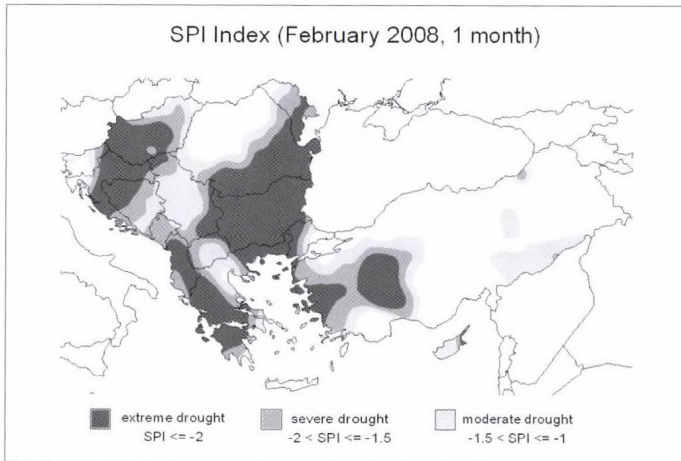


Fig. 2. Standardized precipitation index (SPI) for southeastern Europe issued for February 2008.

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 focus 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 occurrence of fungi. 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 private services. Daily forecasts are, for example, provided at the scale of 10×10 km by the Finnish 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 evapotranspiration 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.

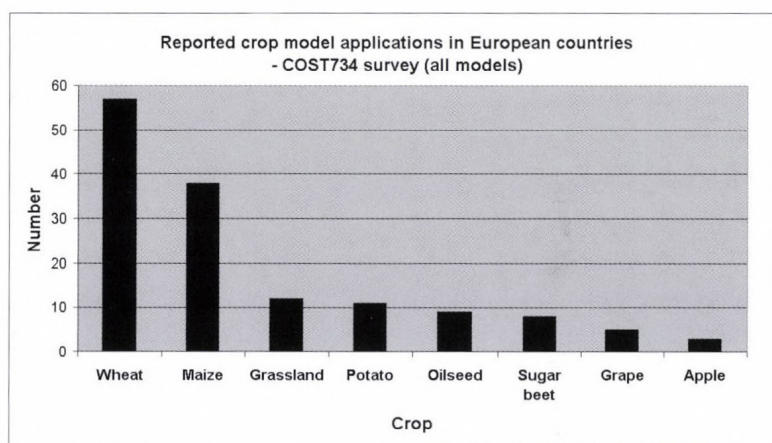


Fig. 3. Reported crop model applications (operational and research, one count per model and country) according to the COST 734 survey.

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 alphanumeric 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.

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Coupled land-air parameterization scheme (LAPS) and non-hydrostatic mesoscale model (NMM) for use in agricultural planning

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Abstract—Characterization of climatic hazards for agriculture can be done using global circulation models (GCMs) and/or regional circulation models (RegGCMs). The GCMs provide credible information of climate, at least for subcontinental scales, while the RegCMs are used to determine specific characteristics of the weather in mesoscale. Regardless of whether these models provide meteorological data through either long-term or short-term runs, the land surface models are strong links between the underlying surface and the atmosphere. Recently they have been remarkably improved in the segment of the parameterization of turbulent fluxes inside and above the tall grass canopies, making them more relevant, in assessing how regional climate may affect agriculture. Except these schemes many other environmental/agricultural models (UV radiation, plant diseases, crop, irrigation models, etc.), linked with the new generation of non-hydrostatic mesoscale models, can provide highly sophisticated information for farmers and agricultural planners. In this paper we shortly describe environmental models, mostly designed in the Centre for Meteorology and Environmental Predictions, University of Novi Sad (Serbia). All of them are linked with the NMM non-hydrostatic mesoscale model for the purpose of an intensive use in agricultural planning. The description and comments are supported by the corresponding numerical simulations.

Key-words: GCMs model, RegCMs models, environmental/agricultural models, agricultural planning

1. Introduction

Agricultural planning – strategic (long-term) and tactical (short-term) – needs to appreciate climate-related and other risks to attain the producer's goals and spell out the sort of information that farmers need to aid their planning – e.g., climate, technical/management information, market. A key aspect needed in linking climate and weather risk to agricultural planners is to appreciate the overall

management system in question from the viewpoint of decision makers. Managers need information for both tactical and strategic decision-making. Climate disasters can be divided into extreme events (e.g., tornadoes, hail, flash floods and severe thunderstorms, effect of prolonged drought and floods) and regional climate anomalies (mesoscale storms, small-scale severe weather phenomena). Global climate change may produce a large number of climatic disaster occurrences. This is based on the fact that a linear increase in the average of a climatic variable implicates a non-linear increase in the occurrence probability of extreme values of the variable. Assessing and forecasting the impacts of short-term climate variability and weather risk, as well as their relationship to extreme events could help mitigate the effects of climate variability and scheduling agricultural activities (Everingham *et al.*, 2002; Meinke and Stone, 2005).

Characterization of the climatic hazards for agriculture can be done using global circulation models (GCMs) and/or regional circulation models (RegCMs). The GCMs provide credible information of climate, at least for sub-continental scales, while the RCMs are used to determine specific characteristics of the weather in mesoscale. Regardless of whether these models provide meteorological data through either long-term or short-term runs, the land surface scheme is a remarkable link between the underlying surface and atmosphere. This link together with the mesoscale non-hydrostatic model is a base for use a number of environmental models (UV radiation, plant diseases, crop, irrigation, water, and chemical transfer in soil models, etc.) in agricultural science and practice for different purposes, particularly for planning.

The focus of this paper is directed to short description of environmental models, which are available in the Centre for Meteorology and Environmental Predictions (CMEP, in further text), Department of Physics, Faculty of Sciences, University of Novi Sad (Serbia). Most of them are designed in this institution and linked with the NMM non-hydrostatic mesoscale model for the purpose of an intensive use in agricultural tactic and strategic planning (Mihailovic, 2005; Mihailovic and Lalic, 2006). Descriptions are pursued by examples of corresponding numerical simulations.

2. Short overview of the land-air parameterization scheme (LAPS)

We will shortly summarize the main features of the LAPS by setting a focus on the parameterization of processes relevant in agricultural science and practice. The LAPS, developed at the Faculty of Agriculture and CMEP, University of Novi Sad (Serbia), describes mass, energy, and momentum transfer between the land surface and the atmosphere. This scheme is designed as a software package that can be run as part of an environmental model or as a stand-alone one. The LAPS includes modeling the interaction of the land surface and the atmosphere,

under processes divided into three sections: subsurface thermal and hydraulic processes, bare soil transfer processes, and canopy transfer processes. They are: interaction of vegetation with radiation, evaporation from bare soil, evapotranspiration including transpiration and evaporation of intercepted water and dew, conduction of soil water through the vegetation layer, vertical water movement in the soil, surface and subsurface runoff, heat conduction in the soil, and momentum transport within and above the vegetation. A single layer “sandwich” approach for canopy is chosen for the physical and biophysical parameterization. The scheme has seven prognostic variables: three temperature variables (foliage, soil surface, and deep soil), one interception storage variable, and three soil moisture storage variables. For the upper boundary conditions the following forcing variables are used: air temperature, water vapor pressure, wind speed, short wave and long wave radiation, and precipitation at a reference level within the atmospheric boundary layer. The surface fluxes are calculated using resistance representation. The soil module is designed as a three-layer model, which is used to describe the vertical transfer of water in the soil. The LAPS uses the morphological and physiological characteristics of the vegetation community for deriving the coefficients and resistances that govern all the fluxes between the surface and atmosphere. The details about this scheme are available in many papers appeared in the last decade. However, the main features and recent redesign of the LAPS scheme can be found in *Mihailovic et al.* (2004) and *Mihailovic et al.* (2008).

3. The main features of the NMM non-hydrostatic regional model

In agricultural planning the non-hydrostatic mesoscale model (NMM), designed in the National Centre for Environmental Prediction (*Janjic*, 1994; *Janjic et al.*, 2001), with LAPS implemented in it (*Mihailovic*, 2003), is used in providing outputs for other models. The key features of the model are as follows: a fully compressible, non-hydrostatic or hydrostatic model; mass-based sigma-pressure hybrid terrain following system but with constant pressure surface above 400 hPa and Arakawa E-staggering; Adams-Bashforth and Crank-Nicholson time integration schemes; high-order advection scheme; scalar and energy conserving feature; Coriolis, curvature and mapping terms; one-way nesting; lateral boundary conditions suitable for real-data; and one-way nesting and full physics option to represent atmospheric radiation, surface and boundary layer, as well as cloud and precipitation processes. In the running procedure usually for the initial and boundary meteorological conditions, we use the NCEP objective global analysis gridded data with a 1° horizontal increment, for 23 pressure levels (up to 50 hPa). The lateral boundaries of the model domain are available every six hours from the NCEP data. In runs we work with a horizontal increment of $0.222^\circ \times 0.205^\circ$ and a time step of 100 s. In the preparation phase, surface

parameters, either observed or predefined (topography, sea surface temperature, soil and vegetation types, soil temperatures and wetness, slopes and azimuths of the sloping surfaces), were interpolated to the model grid. The topographic data set used is the one provided by the U.S. Navy with 10×10 arc min resolution. The vegetation data set is available from USGS with $30 \text{ arc s} \times 30 \text{ arc s}$ resolution, following the classification by *Dickinson et al.* (1986). For soil textural classes, the UNEP/FAO data set was used, after converting from soil type to soil textural ZOBLER classes (*Zobler*, 1986). Albedo and surface roughness variations were computed in the preprocessing stage according to the vegetation type.

4. BAHUS model for providing the messages of occurrence of plant diseases: A short description

BAHUS is a biometeorological model fully developed in the CMEP. It is designed for providing the messages of occurrence of plant diseases and the proper time for pesticide application (*Mihailovic et al.*, 2001; *Mihailovic et al.*, 2002). Components of this model are: (1) input module – providing meteorological and biological data that are representative for a selected area; (2) modeling module – consisting of empirical relations and conditions related to the diseases occurrence and the intensity of infection, and (3) output module – giving following messages: risk of infection, duration of incubation period, time of the first symptoms, etc. Depending on the method selected in the modeling module, following meteorological data should be provided by input module: maximum air temperature, minimum air temperature, mean daily temperature, actual values of temperature, relative humidity, precipitation, and the duration of leaf wetness.

In the modeling module, BAHUS uses a method defined by *Mills* (1944), later modified by *Jones et al.* (1980), based on air temperature, relative humidity, and duration of leaf wetness in order to describe the intensity of apple scab infection. Requirements for fire blight blossom infection defined by *Steiner* (1990) are incorporated in degree-days (DD) by *Mills* (1955) and MARYBLIGHT methods (*Steiner* and *Lightner*, 1992). These methods are based on accumulation of DD and degree-hours (DH), which are defined as a number of degrees over the base temperature during one day and one hour, respectively (*Zoller* and *Sisevich*, 1979; *Mills*, 1955).

5. NEOPLANTA: A short description of the first Serbian UV index model

The numerical model NEOPLANTA is developed by *Malinovic et al.* (2006) in the CMEP. It computes the solar direct and diffuse UV irradiances under cloud-free conditions for the wavelength range 280–400 nm (with 1 nm resolution) as well as the UV index. Effects of O₃, SO₂, NO₂, aerosols, and nine different

ground surface types on UV radiation are included. The model calculates instantaneous spectral irradiance for a given solar zenith angle, but there is also a possibility for calculation of the UV index for the whole day at half-hour intervals from sunrise to sunset. Also, there is a possibility of taking into account daylight saving time. Atmosphere in the model is divided into several parallel layers (maximum 40). It is assumed that the layers are homogeneous with constant values of meteorological parameters. The vertical resolution of the model is one kilometer for altitudes below 25 km, and 5 km above this height. The upper boundary of the highest layer in the model is 100 km. The model uses standard atmosphere meteorological profiles. However, there is also an option of including the real time meteorological data profiles from the high-level resolution mesoscale models. The required input parameters are the local geographic coordinates and time, or solar zenith angle, altitude, spectral albedo, and the total amount of gases. The model includes its own vertical gas profiles and extinction cross-sections, extraterrestrial solar irradiance shifted to terrestrial wavelength, aerosol optical properties for ten different aerosol types (Hess *et al.*, 1998), and spectral albedo for nine different ground surface types. Output data are spectral direct, diffuse, and global irradiance divided into the UV-A (320–400 nm) and UV-B (280–320 nm) part of the spectrum, biologically active UV irradiance calculated using the erythermal action spectrum by McKinley and Diffey (1987), UV index, spectral optical depth, and spectral transmittance for each atmospheric component. All outputs are computed at the lower boundary of each layer.

6. Numerical simulations with coupled NMM – other environmental models

To demonstrate how coupled NMM and different environmental models can provide sophisticated information for tactical and also strategic planning in this field, we designed three illustrative numerical simulations, which are widely recognizable in agricultural practice.

6.1. Use of NMM model with the LAPS scheme for forecasting of extreme temperatures

The air temperature at 2 m is a reliable indicator of the underlying surface's thermal state (i.e., the quality of the surface parameterization), because the surface temperature strongly affects the air temperature at 2 m. This temperature is determined diagnostically. From the diurnal course of 2-meter temperature are derived extreme temperatures, which are variables on the list of key parameters in the agricultural practice. In this case study, we performed a numerical simulation using the above mentioned NMM model coupled with the LAPS surface scheme (Mihailovic, 2003; Mihailovic *et al.*, 2008). The starting time of

the simulation was 00:00 UTC, June 5, 2002, and the simulation period was 24 hours. The domain (Mihailovic et al., 2008) was centred in 45.0°N, 19.0°E with (101, 99) cells distributed longitudinally and latitudinally. The domain had 651 grid cells. The cover types include water (22.7%), crops (i.e., short grass canopies) (39.9%), tall grass (4.3%), short grass patches (3.2%), evergreen needle leaf (2.6%), deciduous broadleaf (4.3%), and mixed woodland (23.0%), while the soil textural classes were water (22.7%), loamy sand (4.5%), sandy loam (11.5%), silt clay loam (36.6%), clay loam (19.7%), sandy clay (2.5%), and silt clay (2.5%). Fig. 1 shows air temperature values obtained from the NMM plotted against observed values taken from the SYNOP data set of June 5, 2002. It compares the temperature extremes. For the temperature extremes, the simulated maxima are in better agreement with the observations than the simulated minima.

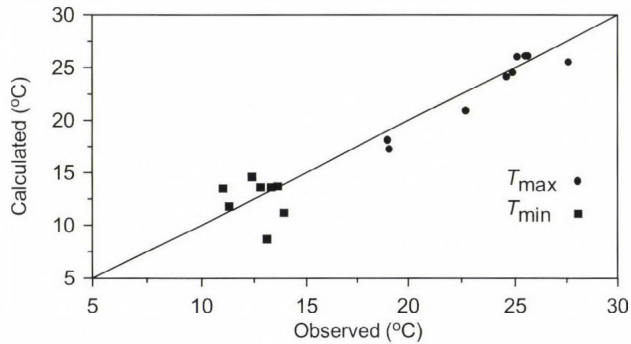


Fig. 1. Air temperatures at 2m obtained by the NMM (including LAPS) plotted against the observed values taken from the SYNOP data of June 5, 2002). Comparison for the temperatures extremes.

6.2. An example of use the BAHUS model linked with the NMM model for plant diseases prediction

In this numerical simulation we demonstrate an example of the assessment of meteorological conditions suitable for appearance of: (i) apple fire blight (infection intensity ranged as none, low, moderate, and high), (ii) grape downy mildew (duration of incubation period), and (iii) potato late blight (duration of incubation period) for Novi Sad area during spring period in year 2008. In the forecasting procedure we supposed, based on our experience, that biological conditions were satisfied: (i) for apple (flowering) after March 15 and (ii) grape and potato (certain stadium of growth) after April 20. Weather data file of the BAHUS input module included the following elements: (i) data from SYNOP data set describing previous weather conditions and (ii) the NMM model outputs including predicted state of weather (Fig. 2). Using these data the BAHUS

model has been continuously run after March 15, in order to assess disease appearance risk on daily bases. Obtained results are presented in *Table 1*.

According to BAHUS model, until May 5, thermal and humidity conditions for fire blight, downy mildew and late blight appearance were not auspicious. Although on April 11 air temperature exceeds lower threshold for fire blight DH accumulation (*Fig. 2*), it was obvious that following temperature decrease will cause termination of the disease development process. On May 12, according to air temperature forecast (*Fig. 2*), at the end of the incubation period, downy mildew has been expected in next two days, while, in case of fire blight, epiphytic infection potential (EIP) should pass 100% on the same time. On May 26 and June 18, suitable conditions were also recorded for downy mildew appearance. However, for incubation period starting on June 12, a little bit longer duration has been expected due to forecasted temperature decrease (*Fig. 2*).

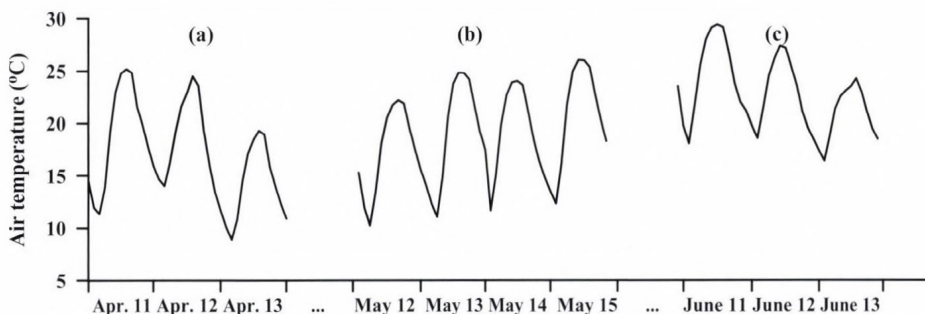


Fig. 2. NMM model forecast of 2m air temperature for periods: (a) April 11–13, (b) May 12–15, and (c) June 11–13 for year 2008.

Table 1. Simulated assessment of disease appearance (i.p. = incubation period) based on meteorological conditions

Date/Disease	Fire blight	Downy mildew	Late blight
Before April 11	no risk	no risk	no risk
April 11	hi risk – no infection	no risk	no risk
April 12	medium risk – no infection	no risk	no risk
April 13	medium risk – no infection	no risk	no risk
April 14	no risk	no risk	no risk
Before May 12	EIP = 15.7 – no infection	less than 2 days till the end of i.p.	no risk
May 13	EIP = 64.1 – no infection	end of i.p.	no risk
May 14	EIP = 123 – infection		no risk
Before May 26		last day of i.p.	no risk
Before June 11		i.p. in progress	end of i.p. in next 7 days
Before June 18		last day of i.p.	

6.3. The NEOPLANTA model for UV radiation prediction and its use in assessment of climate change impact on development of plant diseases

Based on an assessment of important diseases of wheat and other cereals, sugarcane, deciduous fruits, grapevine, vegetables, and forestry species, climate change may reduce, increase, or have no effect on some diseases (Chakraborty *et al.*, 1998). Changes will occur in the type, amount, and relative importance of pathogens and diseases. Host resistance may be overcome more rapidly due to accelerated pathogen evolution from increased fecundity at high CO₂ and/or enhanced UV-B radiation. However, uncertainties about climate change predictions and the paucity of knowledge limit our ability to predict potential impacts on plant diseases. Both experimental and modeling approaches are available for impact assessment research.

For the purpose of this paper we demonstrated the performance of this model by comparing UV index values, obtained by the coupled NMM and NEOPLANTA, with measurements recorded with a Yankee UVB-1 biometer (see Yankee Environmental Systems Inc., 2000). For the test, we have selected data for ten days, measured in the years 2003, 2004, and 2005, with cloudiness less than 0.2. The device used is located at the Novi Sad University campus (45.33°N, 19.85°E, 84 m a.s.l.). All other details about model run can be found in Malinovic *et al.* (2006). Fig. 3 depicts comparisons between the calculated diurnal variations of UV index for cloudless days in 2003, 2004, and 2005. From this figure, it is seen that the NEOPLANTA model gives values that are very close to the observations.

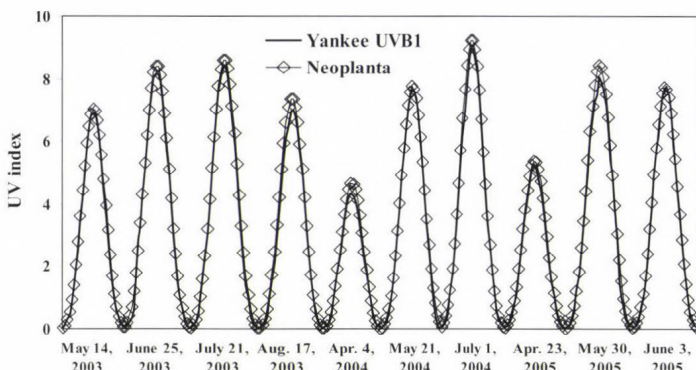


Fig. 3. Variation of UV index obtained by the NEOPLANTA model compared with the observations in Novi Sad for cloudless days.

As the development and implementation of mitigation strategies take long time, more research is urgently needed and we hope this paper will stimulate interest. For example, it is planned to carry out further research on the risk of the

damages and yield losses in orchards and crop fields by plant diseases, increased UV radiation, and heat waves as a consequence of climate change. It will be done on the basis of analysis of outputs obtained by running (i) climate ECHAM model, (ii) regional NMM model with the LAPS scheme, (iii) NEOPLANTA UV radiation model, (iv) BAHUS model for forecasting the occurrence of plant diseases, and (v) a selected crop model. This assessment is particularly important for the central and southern parts of Europe which are potentially the most vulnerable regions in Europe regarding the climate change. It was one of the main reasons why the NEOPLANTA model has been developed, tested and prepared as a user friendly software that can be easily linked with the NMM model.

7. Conclusions

We considered a wide range of possibilities for use of coupled mesoscale non-hydrostatic model and land surface scheme for application in agriculture planning on both tactical and strategic levels. Specifically, in this paper we shortly described the NMM non-hydrostatic model and the LAPS scheme. Additionally, we briefly elaborated two environmental models (BAHUS – for prediction of plant diseases and NEOPLANTA – for prediction of UV radiation) which are fully developed in the Centre for Meteorology and Environmental Predictions, University of Novi Sad (Serbia). Finally, we performed numerical simulations with the coupled NMM-LAPS model and the aforementioned environmental models, giving three examples of forecasting the quantities which are on the list of key parameters that are important in agricultural practice and its planning activities.

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IDŐJÁRÁS

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Brief surveying and discussing of drought indices used in agricultural meteorology

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Abstract—The paper summarizes the indices used for identification of drought phenomenon in the agricultural meteorology practice. Many drought definitions and indices are known. Drought indices seem to be the simplest tools in drought analysis. The indices are classified into six groups, namely *atmospheric, precipitation, water balance, soil moisture, recursive, and remote sensing* indices. For each group typical expressions are given and analyzed for their performance and comparability. Taking into consideration that the drought is a compound concept, a few drought definitions are examined together with the drought indices. As any classification, the presented categories have got their limitation. The discussion on drought definition together with the survey of the indices tries to highlight the wide possible categorization of this very important phenomenon mainly from the meteorological point of view.

Key-words: drought, drought definition, drought index, meteorological drought, Palmer drought severity index, index surveying

1. Introduction

Drought is undoubtedly one of the human being's worst natural enemies (*WMO*, 1975, 1986). Among the extreme meteorological events, drought is possibly the most slowly developing and long existing event, and probably is the least predictable among the atmospheric hazards. Due to these characteristics, particularly their temporal character, drought cannot be compared with other natural hazards such as flood, hurricane, tornado, lightning, hailstorm, frost, or plague of locust, which also significantly can contribute to a nation's annual loss due to disadvantageous natural circumstances. We can record flood and drought in the same vegetation period in some part of the world. Because of its peculiar character, *drought* deserves the greatest scientific and operative/practical

investigation. The goal was to collect the known and used drought indices and to compare their theoretical and practical advantages, limitations, interrelations, and numerical effectiveness. It seems to be necessary to re-evaluate the types of the indices and the definition itself. We can find interesting and important reviews (Heim, 2000; Sivertsen, 2005a, b) and almost impossible to refer all of them. Taking size limitations of present issue into consideration, only a summary of the definition and mathematical formulation will be given without any numerical evaluation. Some numerical evaluation was carried out in other particular reviews (Jankó Szép et al., 2005; <http://drought.unl.edu>, 2008; Mika et al., 2005).

More exact determination of drought could be made by means of plant-specific indicators of moisture deficiency, characterizing the water demand during the consecutive phenological phases of plants if the information was available and could be mathematically formulated. The drought is a compound concept. As a first guess, it seems that everybody determines it similarly. But, if we go into details, we can compare the phenomenon from different parts of the world; from different types of climate zones we cannot find an absolute acceptable definition and absolute categorization. It means, on one side, a prolonged absence or marked deficiency of precipitation, on the other side, a yield decrease caused by the precipitation deficit.

Many drought definitions are known. Several of them use meteorological parameters. Dealing with the drought problem we can take the following types of investigation, not only from the meteorological point of view:

- Drought frequency can be examined in long time series mainly using the long meteorological data series (for 30, 50, or 100 years). This is the *climatic description*.
- Based on territorial distribution of drought-affected areas for a given territory (region, country) generating homogeneous data series, the territorial distribution of drought tendency can be determined. This is the *regionalization*.
- Detection and prediction of drought during a given year (vegetation period) can be performed using weather information, to provide *forecast and warning of drought*.
- Direct detection of the plant water supply, the water stress detection is the key to *irrigation and plant protection advice*.

In all these approaches the same parameters and methods of drought identification can be used (Budyko, 1952; Eitzinger et al., 2008; Ivanov, 1948; Koshelenko and Volevakha, 1971; Ped, 1975; Sun and Ward, 2007; Theophilou, 2006; Tsiros et al., 2006; Wilhite, 2005), which can also be based on the same definition.

Without any ambition to give an absolute definition, that is acceptable for everybody, some kind of survey of the existing drought definitions will be introduced before the evaluation of drought indices. We start with the most

authentic drought definition could be read in the International Meteorological Vocabulary (WMO, 1992). The survey will be not able to incorporate all existing drought indices, it only highlights the most important categories.

2. *Drought definitions and categories*

The problem involves a wide variety of definitions, indicators, indices, and methods of evaluation. As a consequence, almost all agrometeorologists, climatologists, and agronomists, engaged in this field, have their own time series, methods, and conclusions about the drought events. Drought may be studied from a number of different points of view. But, what is the drought, at all? If we would like to give any quantitative criteria for the drought, we must identify its quality before its parameterization. Drought has been defined very commonly and frequently as a period of precipitation deficiency (Wilhite, 1983). It seems to be a nice definition, but nobody speaks about drought in case of Sahara or other regions, where the weather is generally dry. In any case when we mention drought, we somehow involve the agricultural product into our consideration, or, more simply, the vegetation production or plant life cycle. It seems to be very easy to produce any combination of meteorological elements and define a threshold value, but if we neglect the behavior of natural or artificial vegetation, we cannot determine good or acceptable categories and threshold values to identify the drought situation. The International Meteorological Vocabulary (WMO, 1992), the most authentic source, gives two definitions of drought:

- (1) *Prolonged absence or marked deficiency of precipitation;*
- (2) *Period of abnormally dry weather sufficiently prolonged for the lack of precipitation to cause a serious hydrological imbalance.*

Both of them are very simple, but if we compare them with the definition given for the dry season: *Period of the year characterized by the (almost) complete absence of rainfall. The term is mainly used for low latitude regions*, we can state that is not very simple task to answer the question. Another category is given in the vocabulary, the *dry spell*. Its definition is more or less close to the drought: *Period of abnormally dry weather. Use of the term should be confined to conditions less severe than those of a drought.*

Drought may be identified from a number of different points of view. It means different things to various people, depending on their specific interest or historical, economical background. It is difficult to find a completely adequate definition of drought, which could be acceptable everywhere in the world. Sometimes the definition is confused with categories. To get a better understanding, some categories or types have been introduced, namely we can speak about the following terms:

- Atmospheric drought occurs if too high saturation deficit has been measured for a durable time. This category more or less refers to the dry spell category.
- Meteorological drought means a longer period of time with considerably less than average precipitation amounts. The definition is more or less the same given for drought in general.
- Agricultural drought has got two approaches. The first one is *the available soil moisture is inadequate*, the second one is: *yield is considerably less than the average because of water shortage*. As it was earlier mentioned, the real drought definition somehow should involve the less than normal vegetation production, so the agricultural drought seems to be close enough to the expected definition.
- Hydrological drought refers to a period of below-normal stream-flow. Another important approach is expressed in this category that the drought is not at all a very local phenomena, it occurs on a larger area, for example it is at least a problem of a water catchment.
- Physiological drought can occur when the plant is unable to take up water in spite of the present sufficient soil moisture. This situation refers to the circumstances when plant shows drought symptom but there is no drought at all in terms of the obvious drought related atmospheric conditions. This phenomenon could be caused by abnormally cold weather or in the case when the plant is infected.
- Socio-economical drought is some kind of integration of several drought categories. It implies any disadvantageous influence of the consecutively repeating dry spells. It is the lack of some economic goods due to meteorological, hydrological, and agricultural drought. In the specific case its definition can be close the definition of famine.

Following the structure of the picture is given in the homepage <http://drought.unl.edu> but making some modification we can summarize the categories and give a hierarchy in the definitions in the Fig. 1.

Anyway, we can determine *drought as a period during which prolonged and abnormal moisture deficiency produces reduced plant growth and productivity can cause significant loss in nation's economy*.

3. Drought indices definitions and categories

Drought index is *an index which is related to some of the cumulative effects of a prolonged and abnormal moisture deficit (WMO, 1986)*. To describe the temporal and spatial distribution of drought or dry spell situation, we can mostly use meteorological parameters (Budyko, 1952). The practice is that any single meteorological element is unable to identify a drought situation, by itself, or, at least there are not uniform categories for drought in this case.

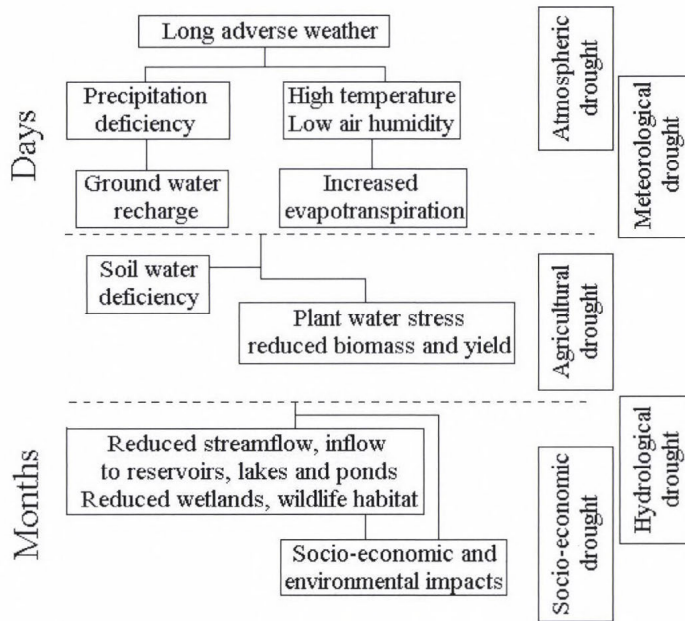


Fig 1. Logical scheme of the drought definition, in combination with the time frame and other water-, plant-, and environment-related phenomena (<http://drought.unl.edu>, 2008).

A more or less acceptable approach is to combine the meteorological variables in order to develop a so-called drought index. Some of these indices can be used only in special circumstances; the other ones can be used for wider area. Anyway, it is very difficult to give universal categories for drought situation that were suitable to determine the drought situation anywhere and anytime, and which could identify the drought for any types of vegetation.

The expectation of the everyday agronomic practice differs from the climatic approach, but the drought index and any kind of irrigation decision signal are not far from each other from meteorological point of view. Until now, many kinds of drought indices were developed, using classical meteorological variables. In this short paper we would like to give a short categorization of drought and dry spell indices, dealing with not only the traditional observations but with some possibilities of using remotely sensed information. The knowledge of temporal and spatial distribution of drought allows us to prevent its damage choosing proper (drought-resistant) species, or to build up a well-working irrigation system in the endangered area. The use of remote sensing technique gives new possibilities to detect the water deficit or drought situation. Vegetation indices derived from satellite's measurements give information about the plant cover of large area and can be the basis of the detection of general condition of vegetation. From this information we can derive a temporal change

of water supply and water-stress status, too. Surface temperature measured from satellite or near the surface informs us about plant water supply, too. The practical use of the near-to-surface gradients and water vapor deficit, combined with other standard meteorological observations, opens new possibilities not only in the everyday coping with water deficit and drought but in the climatic detection, too.

In meteorology, it is a very common way to approach drought situation by generating an index using meteorological data. If an index is properly formulated, and its limitations are well recognized, then the index could be very useful. With very moderate criticism on their different types, we try to classify the reviewed indices. To compare drought or dry spell events either on spatial or temporal scale requires a quantitative expression. Drought indices appear to be more or less the simplest way to carry out this work. Nevertheless, finally we can use either a simple meteorological value with more or less ‘natural’ thresholds or a combination of meteorological elements, sometimes without any physical meanings. Following and partly modifying *Farago et al.* (1989), a compendium of indices are shown where the indices are grouped according to their similarity:

- atmospheric drought,
- indices of precipitation anomaly,
- aridity indices,
- soil moisture indices,
- combined or recursive indices, and
- indices based on remotely sensed information.

Independently of the categorization, the *drought index* is used very widely as a research and operative tool, not only within the agrometeorology, but in many related sciences, as well (*Alexandrov et al.*, 2008).

3.1. Indices of atmospheric drought

The standard signal of dry spell is the low humidity. The water vapor saturation deficit is commonly used for characterization of atmospheric drought, although the temporal scale for similar analysis is usually much shorter than a month, sometimes only a few days, but consequence of these days could be catastrophic in case of few species. These indices are not the commonly accepted indices (*Selyaninov*, 1958), but sometimes it is worth to introduce them mostly in the irrigation practice. The simplest form is a simple meteorological element, called saturation deficit (*WMO*, 1992),

$$E - e = E(1 - f),$$

where E is the pressure of the water vapor at saturation, e is the measured water vapor pressure, both of them given in SI unit, hPa, f is the relative humidity in

percent. For a shorter period threshold values for the identification of atmospheric drought, the so-called *atmospheric dryness*, could be 20–29 hPa, for weak, 30–39 hPa for moderate, 40–49 hPa for intensive, and more than 50 hPa for very intensive dry spell. Dry conditions of longer periods can be described with threshold values of at least weak or moderate dryness.

3.2. Indices of precipitation anomalies

Any forms of drought are related to some antecedent and relative precipitation amounts for the previous period. This period could be last from 3–4 weeks to years. The drought occurs after the anomalous rainy season or period. For example, agricultural drought could be a consequence of dry autumn and winter period. Therefore, the simplest drought index is the deviation from a normal precipitation value. We can generate some combination of deviation, or can somehow normalize the deviation values for a better comparison of generalization. We have to stress that a good drought index is unimaginable without a long-term comparison with yield values before the establishment of threshold values.

Finally, the simplest expression of the difference from the normal could be defined as drought index, the so-called *precipitation index*:

$$P - m(P),$$

where P denotes the longer period's precipitation sum, $m(P)$ is its long term average, standard value, or *climate normal* for the same period. It could be expressed in standard precipitation unit, i.e., in mm. It is desirable to use as long as possible period for the generation of the mean value. The anomalies for non homogeneous regions or larger areas with different climatic conditions are not comparable. To avoid this problem, either relative amounts, or standardized values should be introduced.

Following the same categorization, other indices could be generated as relative values, like the *relative precipitation amount* or *relative precipitation anomaly index*:

$$\frac{P}{m(P)} \quad \text{or} \quad \frac{P - m(P)}{m(P)}.$$

In practice both of them are multiplied by 100, and the index is used in percentage form. The difference could be normalized with the standard deviation of the precipitation data series. In this case we can introduce the *standardized precipitation anomaly index* (SAI):

$$\frac{P - m(P)}{d(P)},$$

where $d(P)$ is the standard deviation. Each relative index could be a drought indicator if its value is less than a previously established threshold value, e.g., 75% on an annual basis, or 50% for a shorter period for example for a month. The use of other, slightly different levels was suggested by *WMO* (1975). For a recent worldwide drought assessment, to outline desertification, smaller than 60% annual value was given for the relative precipitation anomaly index for more than two consecutive years.

3.3. Aridity indices

Aridity is the characteristic of climate relating to insufficiency of inadequacy of precipitation to maintain vegetation. For a single station, where the usual probability levels can be applied to choose particular threshold values in accordance with the hypothetical distribution of standard approximation of potential evapotranspiration, we can find many types of aridity indices. The simplest way to approximate the evaporation is using temperature alone or a kind of temperature sum and degree-days. The theoretical base form of the aridity index is the evapotranspiration/precipitation ration (*Bristov*, 1987; *Budyko*, 1952). The difference in the aridity indices is in the approximation of the evaporation (evapotranspiration). In principle, the aridity index looks like the following formulas:

$$\frac{P}{PE} \quad \text{or} \quad \frac{P}{\frac{R_n}{L}},$$

where PE is the evapotranspiration expressed in precipitation unit, i.e., mm, R_n is the radiation balance, and L is the latent heat of water vaporization. Taking into consideration the difficulty of evaporation calculation, many approaches were used to determine the evaporation substituting its value with other meteorological elements. The well known types from this category are as follows:

Lang's rainfall index

$$\frac{P}{T},$$

where P is the sum of precipitation for the examined period, expressed in precipitation unit, i.e., mm. T is the average temperature of the same period given in °C unit. It is a very simple approximation. A little more adjusted index using the similar variables is the

De Martonne aridity index

$$\frac{12P}{T + 10},$$

written for monthly calculation. Similar construction is followed in the

Thornthwaite index

$$1,65 \left[\frac{P}{T+12,2} \right]^{\frac{10}{9}}.$$

We have to mention that the form of the three last formulas is a typical *agrometeorological index* approach like different types of degree-days. Another type of this category is the degree-days approximation used in Selyaninov index. This index is known as hydro-thermal index. It uses daily values for the calculation of the period.

Selyaninov's hydro-thermal coefficient

$$\frac{P}{\sum_{T \geq 10} T},$$

where T means the consecutive daily mean air temperature above 10 °C. The threshold values for categories of drought or aridity (Selyaninov, 1958) are 0.4–0.7 for very dry, 0.7–1.0 for dry, 1–1.3 for insufficiently wet category, and if the coefficient is higher than 1.3 the category is wet. A specific type of the supply-demand category is the comparison of standardized values of the temperature and precipitation in

Ped's drought index, 1st approximation

$$\frac{\Delta T}{d(T)} - \frac{\Delta P}{d(P)}.$$

Not only in the agricultural meteorology but in any near-to-surface energy transfer studies, a well known parameter is the Bowen ratio (Skvortsov, 1950) expressing the relation between latent and sensible heat transfer. Because of measurement difficulties, before the continuous data logging the Bowen ration was determined only among very restricted trial circumstances. Not only of its theoretical importance but of its growing direct measuring practice, we have to mention as an *aridity index* among the drought indices. Theoretically, the *Bowen ratio* could be expressed in the form

$$\frac{H}{LE},$$

where H denotes the sensible heat flux and LE is the latent heat flux. Both of them are given in standard flux unit, $W m^{-2}s^{-1}$.

3.4. Soil moisture indices

Using measured or calculated soil moisture data (Budagovsky, 1956), we can generate the same type of indices for expressing drought.

Relative soil moisture content

$$\frac{W}{AWC},$$

with W and AWC denoting the actual soil moisture and the available (or dispensible) water capacity for a fixed soil depth (e.g., the upper 1 m layer or the root zone for a given plant). Besides this well-known ratio, an extended form of Ped's (Ped, 1975) drought index incorporates the standardized value of the soil moisture amount.

Ped's drought index, 2nd approximation

$$\frac{\Delta T}{d(T)} - \frac{\Delta P}{d(P)} - \frac{\Delta W}{d(W)},$$

where $d(W)$ is the standard deviation of soil moisture content, as it was calculated for temperature and precipitation in the 1st approximation of PDI .

3.5. Recursive indices

Indices describing the moisture conditions for a relatively long time period through the integrated values of the related meteorological elements provide only a rough picture of the adverse conditions within this period. It is thought that, above all, the cumulative effect of prolonged moisture deficits (month by month) should be properly expressed. These indices proved to be of high utility in the delineation of meteorologically determined droughts or dry spell, which possess a kind of memory of which actual values depend on previous values of the related meteorological variables. Because of their calculation method, they could be called as *recursive indices*. A summarization of consecutive monthly precipitation is *Foley's anomaly index (FAI)*

$$FAI_1 = \Delta P_1,$$
$$FAI_k = FAI_{k-1} + \Delta P_k.$$

The calculation starts with a simple difference for the 1st month. The k th month value is calculated using the *index* of the previous month adding the precipitation difference of the standard and actual precipitation value. Finally the series of the yearly indices could be produced to evaluate the drought tendency from climate change point of view (Fensham and Holman, 1999). Conceptually, the Bhalme-Mooley drought index ($BMDI$) can be considered as a simplified version of the well-known and widely used Palmer drought severity index ($PDSI$) (Alley,

1984). The base of the generation is the monthly precipitation amounts in the *Bhalme-Mooley drought index*

$$i_0 = 0,$$

$$i_k = c_1 i_{k-1} + \frac{SAI_k}{c_2},$$

$$BMDI = \frac{\sum_1^n i_k}{n}.$$

The coefficients c_1 and c_2 are region specific values. The *SAI* is the above mentioned *standardized precipitation anomaly index* (Bhalme and Mooley, 1980). The calculation is carried out for the vegetation period, starting in April, closing in September. Finally one number will be determined for the year as a sign of drought situation.

A very commonly used and accepted index is the *Palmer drought severity index* (PDSI). The PDSI index is based on the thorough analysis of the elements of surface water balance and on the comparison of their actual values to their climatically or physically potential values. The computing procedure of the PDSI consists of several steps. It considers monthly precipitation, evapotranspiration, and soil moisture conditions. In general, several methods can be used to calculate the potential evapotranspiration, a key variable of the water balance and also of the PDSI computation procedure. Palmer (Alley, 1984) applied the Thornthwaite-formula which is rather a climatic character; while later the Blaney-Cridle method provided better estimations (Alley, 1984), especially for vegetation specific alternatives. PDSI is standardized for different regions and time periods, which is useful in common assessment for a wide area with different climate. The steps of computation are:

- *Hydrological accounting.* Computation begins with a climatic water balance using series of monthly precipitation and temperature records. An empirical procedure is used to account for soil moisture storage by dividing the soil into two arbitrary layers. The upper layer is assumed to contain the available moisture at field capacity. The loss from the underlying layer depends on the initial moisture content, as well as on the computed *potential evapotranspiration* (PE) and *the available water capacity* (AWC). Runoff is assumed to occur if both layers reach their combined moisture capacity, AWC. In addition to PE, three more potential terms are used and defined as follows: *potential recharge* is the amount of moisture required to bring the soil to its water holding capacity. *Potential loss* is the amount of moisture that could be lost from the soil by evapotranspiration during a zero precipitation period. *Potential runoff* is defined as the difference between precipitation and potential recharge.
- *Calculation of climatic coefficients.* This is accomplished by simulating the water balance for the period of available weather records. Monthly coefficients are computed as proportions between climatic averages of actual vs. potential values of evaporation, recharge, runoff, and loss, respectively.
- *Calculation of CAFEC* (Climatically Appropriate for Existing Conditions) *values.* The derived coefficients are used to determine the amount of precipitation required for the CAFEC, i.e., *normal* weather during each individual month.

- *Moisture anomaly index.* Difference between the actual and CAFEC precipitation is an indicator of water deficiency or surplus in that month and station, expressed as $D = P - I$. These departures are converted into indices of moisture anomaly as $Z = K(j)D$, where $K(j)$ is a weighting factor, also accounting for spatial variability of the departures (D).
- *Calculation of drought severity.* In the final step the Z-index time series are analyzed to develop criteria for the start and end of drought periods and an empirical formula for determining PDSI

Palmer drought severity index

$$PDSI_k = PDSI_{k-1} + \frac{Z_k}{3} - 0,103 PDSI_{k-1},$$

where Z is the moisture anomaly index. The equation indicates that PDSI of a given month strongly depends on its value in the previous months and on the moisture anomaly of the actual month. It causes strong autocorrelation of PDSI. In general, monthly PDSI time series range between -9 and $+9$, specifically, severe and extreme conditions are characterized by absolute values greater than 4 and 6 , respectively. These thresholds may vary among the geographic regions of the world, whereas the original attribution (monthly PDSI time series range between -4 and $+4$) is considered to be the extremity threshold. Furthermore, drought events occur in the case of negative PDSI values, while positive values imply wet conditions. Compared to other traditional drought indices, PDSI can demonstrate several advantages. It is able to simulate moisture content of the soil month by month, and it is suitable to compare the severity of drought events at regions having rather different climate and seasons.

3.6. Indices based on remotely sensed parameters

The spectral reflectance of vegetation is markedly different from that of most soil materials (*Wagner et al.*, 1996). It is determined by the absorption of chlorophyll at blue and red wavelengths. In the near infrared the radiation is scattered by leaves. This results in generally high reflection which depends mainly on the geometry and size of the leaves. By contrast, vegetation reflectance is low in the visible region with small secondary maximum around $0.55 \mu\text{m}$. When vegetation is stressed by shortage of water, and also at the end of the growing period, the chlorophyll absorption weakens and the ratio of near infrared to red or visible reflectance decreases. This ratio is the so-called *vegetation index*

$$\frac{NIR}{VIS},$$

where NIR denotes the reflected radiation in the near infrared interval and VIS denotes the red or visible intervals according to the satellite channel. It is, therefore, a measure for physiological activity of plants. In practice, the

normalized difference vegetation index (NDVI)

$$\frac{NIR - VIS}{NIR + VIS}$$

is often used to characterize the state of vegetation. Because the state of vegetation highly depends on the water supply condition, we can use the normalized vegetation difference index as drought index. Stress induced by water shortage results in a reduction of the magnitude of the vegetation index. The NDVI is difficult to interpret in case of sparse vegetation, because also the reflectance of most soils increases slightly with wavelength.

The surface temperature can be measured remotely. The difference between the near surface and surface temperatures is the indicator of the latent and heat flux ration. Following the approximation of *Jackson et al.* (1981, 1984), a standardized index the so-called crop water stress index (CWSI) could be generated the *crop water stress index*

$$\frac{PE - ET}{PE},$$

where *PE* denotes the potential, while *ET* the actual evapotranspiration. The CWSI in this theoretical form is neither drought nor remote sensing index. The remotely sensed surface temperature and the combination of other meteorological elements could be the base (*Bristow*, 1987) of the CWSI mainly used in irrigation advisory systems. Its consecutive daily values could be used as drought indices too. The difference of the surface and near surface temperatures (*Idso et al.*, 1981; *Seguin et al.*, 1994) could be alone a drought indicator. Using the well known degree day analogue we can generate the *stress degree day (SDD)*

$$SDD = \sum_k (T_C - T_A),$$

where T_C is the remotely sensed surface (canopy), T_A is the standard air temperature of consecutive days of dry period.

4. Concluding remarks

Drought indices can be calculated at an individual weather station or for a larger area using data of many stations. A simple area-mean can be produced, or a weighted average can be computed. The goal in any cases is to generate a simple and well interpretable *number* or physical variable with its dimension, which can answer the question if there is a drought, or not. Sometimes, when soil moisture measurements or its reasonably good estimations are available, the respective

soil moisture indices are more advantageous. Taking into consideration the data collection and computation capacity, we can use a very simple index (*Budyko, 1952*) and produce a quick, but rough result, or we can prepare a very sophisticated map using GIS technique (*Eitzinger et al., 2008*). The use of remote sensing technique gives new possibilities for the research worker and decision makers mainly in the investigation of larger areas and longer time frames.

In the present survey, the systematic classification of *Farago et al. (1989)* was followed with some modifications, re-evaluations, and extensions. The investigations of indices showed limited agreement among the drought indices. Actually, the imperfect agreement is a direct consequence of the relative nature of drought and the related specific characteristics of all droughts and indices. It has been revealed that the best identification of drought can be achieved by recursive indices like the *Palmer-index*. It could be acceptable for the author to propose new, refined, or extended definitions of drought, by using the existing definitions of the phenomenon. The paper tried to summarize many drought indices with a restricted philosophical approach of how complicated and mixed the definitions and their explanations are. The only thing which should be highlighted is that many drought definitions and numerical categorizations exist, and it is almost impossible to determine any absolute categorization. On the other hand, we can exactly define the drought quantitatively as a numerical category, and qualitatively as a period with prolonged and abnormal moisture deficiency, which produces reduced plant growth and productivity, causing further significant loss in the economy of the affected nation or region.

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Secular trend analysis of growing degree-days in Croatia

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Abstract—The growing degree-days (GDD) for different temperature thresholds above 5 °C at Croatian stations with long-term time series of meteorological data have been analyzed. The range of the mean annual GDD for the 5 °C threshold is from approximately 2000 °C in the highlands to 4200 °C in the mid-Adriatic. The results of the linear trend and the Mann-Kendall test indicate significant positive trends in annual GDD values at the 0.05 significance level for all thresholds in the northern and mid-Adriatic. A progressive test in the mid-Adriatic shows that the GDD for the 25 °C threshold has become significant since the early eighties and in the northern Adriatic since the early nineties. Such increase has a negative effect on plant growth and development on the Adriatic coast and islands.

Key-words: linear trend, climate change, growing degree-days, temperature thresholds, Croatia

1. Introduction

Degree-days, as a measure of accumulated air temperature deviation from the temperature thresholds, have many practical applications in various human-related activities such as home cooling and heating, power generation, and plant growth in agriculture (*Kadioğlu et al.*, 1999).

Knowing how significantly air temperature affects plants, it is of the utmost importance to adequately define their reciprocal relationship. The simplest way of presenting the influence of air temperature on plants is by accumulating the required active air temperatures (degree-days). The beginning of vegetation depends on winter length and intensity, which is particularly important in the highlands, where the vegetation period is considerably shorter than in the rest of Croatia. Therefore, knowing the mean degree-days, it is possible to establish the temperature conditions in an area during a certain season, which helps the planning of plant cultivation.

The temperature thresholds typical for particular plant species in their different development stages are: absolute minimum, vegetation zero-point, optimal air temperature, and absolute maximum (Penzar and Penzar, 2000). With a drop in temperature below the vegetation zero-point, plant growth stops. However, if air temperature drops below the absolute minimum, the cold kills the plants. Plant activity is at its best at optimal air temperature. A growth in temperature above the absolute maximum results in the plants being killed by heat. Thus, one of the goals of this paper is to determine the degree-days above the different temperature thresholds, which is important for plant development. Since most recent climate research indicates an increase in growing-season temperatures, the second goal is to establish the existence of significant trends in degree-days for different temperature thresholds in Croatia using long-term time series of daily meteorological data.

2. Material and methods

Degree-days, also referred to as *heat units* or *temperature sums*, have been divided into cooling degree-days, when the temperature threshold is below 0 °C, and heating degree days, when the temperature threshold is equal to or above 0 °C. With most plant species, vegetation starts when enough temperature has been accumulated, i.e., above the 5 °C temperature threshold. Such specific degree-days are called growing degree-days. Therefore, the growing degree-days (GDD) have been analyzed for the 5 °C, 10 °C, 15 °C, 20 °C, and 25 °C temperature thresholds at five meteorological stations: Zagreb-Grič, Osijek, Gospić, Crikvenica, and Hvar, covering the different climatic regions of Croatia (Fig. 1).

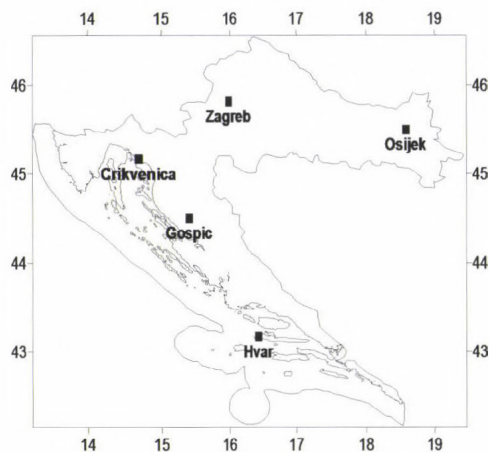


Fig. 1. Geographical position of Croatian stations with long-term time series of meteorological data.

In Croatia there are three types of climate: moderate continental climate in the north-western and eastern part of the country, mountain climate in the highest part of the land, and Mediterranean climate on the Adriatic coast and islands. The northern and eastern parts of the country are the lowest parts of Croatia. It is the Pannonian Plain, which is the main cereal-production region and the most important part of Croatia as regards agriculture. The highest region in Croatia is the Dinaric Alps. This region is characterized by leaf forests and common spruce forests, which are very important for the economy. The Adriatic coast and islands are mostly characterized by viticulture, Mediterranean fruit and olive growing, with little farming and a lot of rocky ground. Pine tree woods and Mediterranean macchia are predominant. In this region, tourism plays the most important role in Croatia.

The Zagreb-Grič and Osijek stations are situated in the region of moderate continental climate: Gospić with mountain, and Crikvenica and Hvar with Mediterranean climate. The data obtained from these stations are the secular series of daily maximum and minimum air temperatures for the period 1901–2000 (except Gospić, which covers 1902–2000). However, only Zagreb-Grič has an uninterrupted series of meteorological data, while Gospić misses 20 years, Hvar 19 years, Osijek six years, and Crikvenica four years.

As the GDD models span from the simple averaging method to complex methods (e.g., Zalon *et al.*, 1983; McMaster and Wilhelm, 1997; Cesaraccio *et al.*, 2001; Schlenker *et al.*, 2007), it is necessary to define the most suitable GDD method according to the different daily air temperature cycles of a specific climate region. Croatian research shows that the best methods are the simple averaging method, when daily minimum temperature is greater than the lower temperature threshold and the simple triangulation method, when the daily air temperature cycle is intercepted by the lower threshold (Salopek, 2007). In this study, the growing degree-days (GDD) have been defined by the simple averaging method as follows:

$$GDD = \sum_{i=1}^n (M_i - T), \quad M = \frac{t_{\max} + t_{\min}}{2}, \quad M_i > T, \quad (1)$$

where T is the temperature threshold, t_{\max} is the maximum daily air temperature, t_{\min} is the minimum daily air temperature, n is the number of days in the certain period, and M is the mean temperature.

The growing degree-days have been studied for the whole year as well as for the sub-periods: warm season from April to September and cold season from October to March, from multiannual data series and for the climatic period 1961–1990.

To determine the secular changes in GDD in Croatia, the linear trends of GDD for different temperature thresholds were analyzed. One of the methods for estimating the existence of a trend is the non-parametric Mann-Kendall rank test, based on the values of individual elements of the series and the position of these elements in the series (Mitchell *et al.*, 1966). Namely, if a linear trend

exists, the values should increase or decrease chronologically. For significant linear trends at the 0.05 significant level a progressive analysis by *Sneyers* (1990) was used to determine the beginning of a linear trend and its significance.

3. Results and discussion

It would be normal to expect the GDD values to decrease as the temperature threshold increases (*Table 1*). For the lowest and highest temperature thresholds the GDD values have also been depicted graphically in *Fig. 2*. For the selected Croatian stations there were three warmer periods: in the late twenties and fifties, and the last one starting in the early nineties of last century. A comparison of the secular series with the 30-year normal shows a positive deviation (higher mean annual values of GDD for the period 1901–2000), except at Hvar, which has a negative deviation up to the 10 °C temperature threshold and a positive deviation above it.

The highest mean values of the GDD for all thresholds are found in Hvar and the lowest in Gospić. A temperature mean above 25 °C is very rare in Gospić. As the Zagreb-Grič and Osijek stations are in the same climatic region, their mean annual and sub-period GDD values are similar. There is a bigger difference between the coastal stations in Crikvenica and Hvar than between the inland stations of Zagreb-Grič and Osijek. The annual and sub-period GDD values vary from year to year, as shown by the relatively high standard deviation values.

So far, research on degree-days in the Croatian highlands and lowlands over a 30-year period (1961–1990) has not indicated a significant trend for any temperature thresholds (*Vučetić and Vučetić, 1994, 1996*). However, the most recent results from the highlands (1951–2004) showed a significant increase in the number of degree-days for the 15 °C and 20 °C thresholds, which is a consequence of a significant increase in the maximum air temperature in spring and summer (*Vučetić and Vučetić, 2006*).

The linear trend results and the application of this test to the data above the defined temperature thresholds are shown in *Table 2*. Linear trends of the mean annual GDD values at the 0.05 significance level exist for the Zagreb-Grič, Crikvenica, and Hvar stations. While for Hvar they are valid for all thresholds in both seasons, for Crikvenica they apply only to the 5 °C threshold. The growth of GDD values at the Zagreb-Grič station, resulting mainly from a significant increase in minimum air temperature (*Vučetić, 2003*), can not be blamed only on global warming but also on the rapid growth of the city of Zagreb in the last hundred years. Linear trend analysis has not confirmed the existence of a significant trend in the annual and sub-period GDD values for Osijek and Gospić, except in Gospić by $T = 10$ °C for the cold season. In Gospić, a growth in the maximum and minimum temperatures has been noticed in winter and spring, but significance has been obtained only for the maximum air temperature in spring (*Vučetić and Vučetić, 2006*). This leads to the conclusion that an extreme temperature increase is still not sufficient for a significant increase in the annual GDD values.

Table 1. Mean (MEAN), standard deviation (STD), maximum (MAX), and minimum values (MIN) of growing degree-days (GDD) for different temperature thresholds (T) for selected Croatian stations during the year (Y), warm season (W, April–September), and cold season (C, October–March) in the periods 1961–1990 and 1901–2000

GDD (°C)	T = 5 °C			T = 10 °C			T = 15 °C			T = 20 °C			T = 25 °C	
	Y	W	C	Y	W	C	Y	W	C	Y	W	C	Y	W
ZAGREB-GRİĆ														
1901–2000														
MEAN	2855.9	2404.9	451.0	1636.5	1512.9	123.6	736.0	720.5	15.5	186.5	186.3	0.1	11.2	11.2
STD	183.7	148.6	89.2	152.2	141.1	43.3	119.3	117.4	12.6	65.8	65.7	0.6	13.8	13.8
MAX	3523.7	2824.4	743.2	2098.1	1915.6	257.4	1044.6	1040.2	66.5	391.9	391.9	4.6	60.1	60.1
MIN	2468.4	2078.9	246.0	1280.8	1217.7	27.1	459.9	459.6	0.0	67.2	67.2	0.0	0.0	0.0
1961–1990														
MEAN	2817.2	2362.0	455.2	1597.5	1468.6	128.9	691.1	675.4	15.7	160.0	159.8	0.1	7.2	7.2
STD	160.7	115.7	89.7	126.5	110.0	44.4	89.9	88.2	13.1	43.0	43.0	0.4	6.6	6.6
MAX	3069.3	2598.0	645.0	1803.5	1688.7	226.5	851.8	837.4	66.5	248.2	248.2	1.5	27.4	27.4
MIN	2468.4	2086.1	332.0	1290.5	1217.7	70.9	459.9	459.6	0.3	67.2	67.2	0.0	0.0	0.0
OSIJEK														
1901–2000														
MEAN	2763.6	2361.7	403.5	1589.7	1476.3	114.7	712.1	695.9	17.2	173.7	173.2	0.3	9.9	9.9
STD	149.9	130.3	80.3	127.2	122.8	42.0	102.0	100.9	15.5	55.0	54.6	1.2	10.0	10.1
MAX	3223.1	2735.0	629.4	1922.7	1829.6	240.8	967.9	967.9	84.2	323.6	323.6	9.0	55.1	55.1
MIN	2415.1	2072.6	224.7	1320.2	1225.7	38.3	488.7	481.7	0.0	74.3	73.8	0.0	0.0	0.0
1961–1990														
MEAN	2739.8	2337.2	402.6	1565.8	1449.3	116.5	684.3	667.4	17.0	154.7	154.5	0.2	6.2	6.2
STD	148.5	117.6	82.9	118.7	111.2	39.6	89.7	88.8	15.7	41.9	42.0	0.6	6.7	6.7
MAX	2974.2	2540.7	562.5	1774.7	1649.9	240.8	845.2	827.8	84.2	239.5	239.5	2.9	26.9	26.9
MIN	2415.1	2072.6	271.4	1320.2	1225.7	61.0	488.7	481.7	1.0	77.4	77.4	0.0	0.0	0.0
GOSPIĆ														
1902–2000														
MEAN	2039.3	1766.2	272.2	985.3	932.6	54.8	298.7	296.8	4.0	25.1	25.1	0.0	0.3	0.3
STD	158.3	137.6	67.0	130.8	124.1	29.8	86.0	85.0	5.2	23.6	23.3	0.2	0.9	0.9
MAX	2511.5	2168.0	469.9	1328.8	1285.0	153.6	522.3	519.8	27.9	112.8	112.8	1.5	6.1	6.1
MIN	1689.9	1479.1	108.8	706.1	685.0	4.2	139.5	139.5	0.0	0.0	0.0	0.0	0.0	0.0
1961–1990														
MEAN	1968.8	1704.8	264.0	925.1	872.5	52.6	255.4	252.5	2.9	16.2	16.2	0.0	0.0	0.0
STD	125.9	107.1	60.7	97.5	92.2	26.0	56.7	56.1	3.4	11.9	11.9	0.0	0.1	0.1
MAX	2160.9	1878.1	409.4	1123.6	1071.0	122.0	373.4	368.9	11.5	45.6	45.6	0.0	0.4	0.4
MIN	1689.9	1479.1	154.3	706.1	685.0	4.2	139.5	139.5	0.0	0.7	0.7	0.0	0.0	0.0
CRIKVENICA														
1901–2000														
MEAN	3446.1	2632.2	814.6	1972.5	1724.5	248.0	940.1	898.0	42.1	282.8	281.6	1.3	25.3	25.3
STD	230.0	174.7	100.0	203.0	172.0	59.1	164.9	154.3	24.2	106.3	105.4	2.5	27.4	27.4
MAX	4057.4	3134.3	1061.5	2558.3	2219.3	397.6	1418.0	1344.4	118.7	617.8	617.8	13.9	130.3	130.3
MIN	3006.3	2275.3	554.9	1516.5	1377.0	107.3	615.0	607.3	0.0	71.6	71.3	0.0	0.0	0.0
1961–1990														
MEAN	3416.9	2599.9	819.5	1941.7	1691.5	250.5	910.8	867.3	43.8	265.4	264.7	1.0	20.4	20.4
STD	134.8	108.4	71.6	126.5	108.3	48.1	104.5	99.0	19.2	63.3	63.4	1.8	12.7	12.7
MAX	3650.2	2786.6	975.0	2199.0	1884.0	318.6	1128.0	1076.4	88.9	401.6	401.6	6.9	53.4	53.4
MIN	3117.9	2405.5	678.5	1684.2	1500.1	121.5	737.2	708.6	0.0	167.3	167.3	0.0	1.2	1.2
HVAR														
1901–2000														
MEAN	4209.1	2942.3	1268.4	2531.4	2030.2	499.7	1277.4	1161.2	117.6	460.2	452.9	9.1	56.3	56.3
STD	170.0	123.1	93.8	151.1	121.4	67.6	127.9	112.4	38.2	96.2	94.6	8.5	32.4	32.4
MAX	4644.2	3264.3	1470.9	2948.2	2349.2	649.6	1602.6	1453.8	199.9	709.6	697.2	47.6	166.1	166.1
MIN	3779.7	2692.6	1055.5	2158.3	1782.8	314.8	999.3	928.0	29.9	152.4	151.8	0.0	4.0	4.0
1961–1990														
MEAN	4225.8	2943.4	1282.4	2536.6	2029.4	507.2	1277.1	1155.1	121.9	459.1	449.8	9.3	53.6	53.6
STD	122.3	103.7	63.7	118.2	103.5	48.2	106.7	94.7	37.5	76.8	74.4	7.2	24.2	24.2
MAX	4406.8	3102.6	1433.8	2719.5	2187.6	602.0	1444.6	1309.2	189.6	600.6	593.0	22.6	106.5	106.5
MIN	3939.8	2709.3	1165.8	2248.8	1794.6	440.9	1016.1	937.7	37.1	300.8	300.4	0.0	11.4	11.4

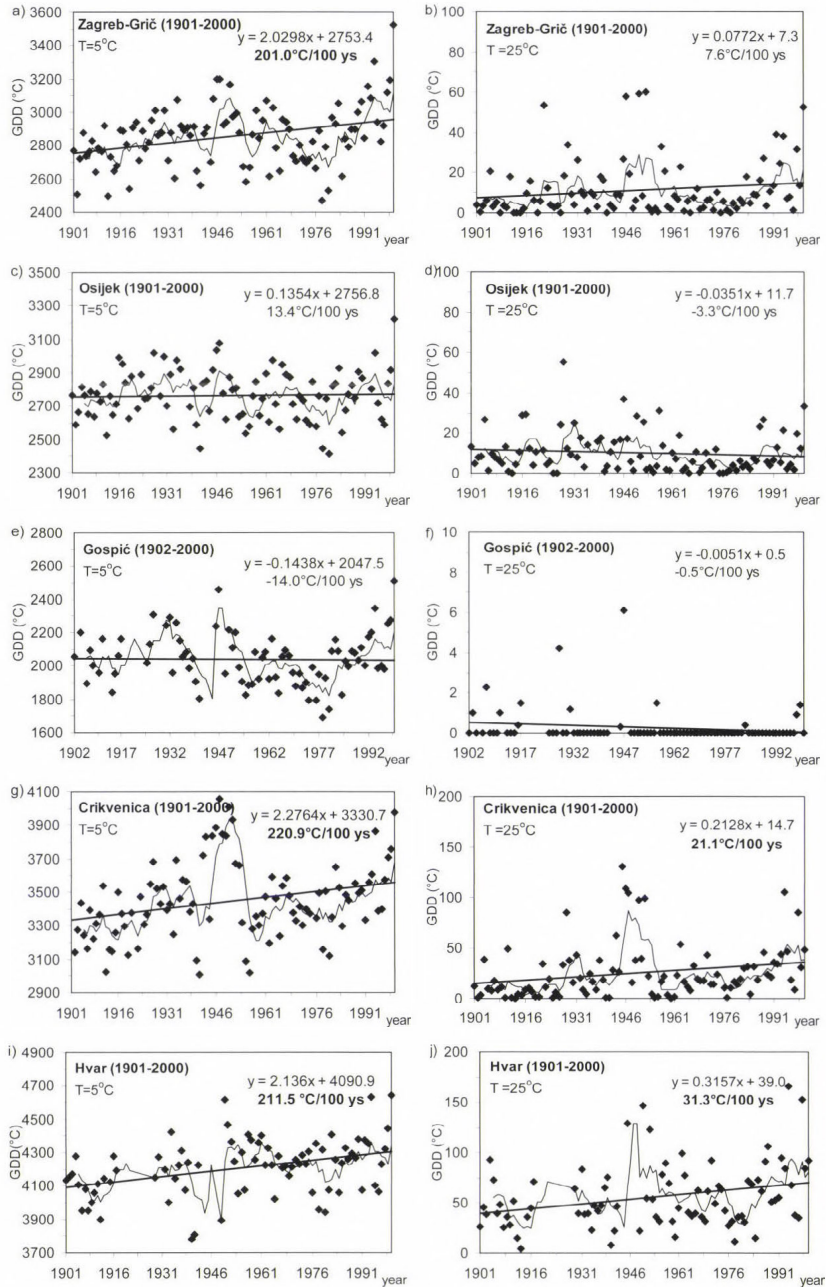


Fig. 2. Time series of the growing degree-days (GDD, diamonds) for the temperature thresholds of 5°C and 25°C, curves of the 5-year running average (thin line) and linear trends (thick line) for selected Croatian stations during the period 1901–2000. x is the number of years (1, 2, 3...) and the α significant level of 0.05 is bold according to the Mann-Kendal test.

Table 2. Linear trend of growing degree-days ($^{\circ}\text{C}/100$ years) for different temperature threshold (T) for selected Croatian stations during the year (Y), warm season (W, April–September), and cold season (C, October–March) for the period 1901–2000. Linear trends at the 0.05 significant level are bolded according to the Mann-Kendal test

Trend	T = 5 $^{\circ}\text{C}$			T = 10 $^{\circ}\text{C}$			T = 15 $^{\circ}\text{C}$			T = 20 $^{\circ}\text{C}$			T = 25 $^{\circ}\text{C}$	
	Y	W	C	Y	W	C	Y	W	C	Y	W	C	Y	W
Zagreb-Grič	201.0	115.6	85.4	144.0	105.4	38.6	76.7	71.3	5.5	35.0	35.0	–	7.6	7.6
Osijek	13.4	3.3	5.3	12.9	-2.4	12.0	-1.4	-9.6	-0.1	-12.7	-12.6	–	-3.3	-3.3
Gospić	-14.0	-25.1	33.4	-28.2	-35.5	15.2	-28.3	-33.5	0.7	-2.4	-2.4	–	-0.5	-0.5
Crikvenica	220.9	143.9	73.6	177.7	140.1	34.2	142.2	127.9	11.6	94.0	93.8	–	21.1	21.1
Hvar	211.5	107.5	99.8	168.9	103.0	67.1	126.9	93.4	32.1	100.8	94.7	–	31.3	31.3

A progressive test (Sneyers, 1990) of the annual GDD trend in Hvar shows that GDD growth started at the end of the 1940s (Fig. 3). It became significant in the early 1960s for the thresholds below 10 $^{\circ}\text{C}$ and in the early 1980s for the higher thresholds, while the significant period in Crikvenica started in the early 1990s. As most plants suffer from heat stress, the positive trend in GDD above 25 $^{\circ}\text{C}$ reveals an increasing negative effect of high temperatures on plants, especially on the Adriatic coast and islands.

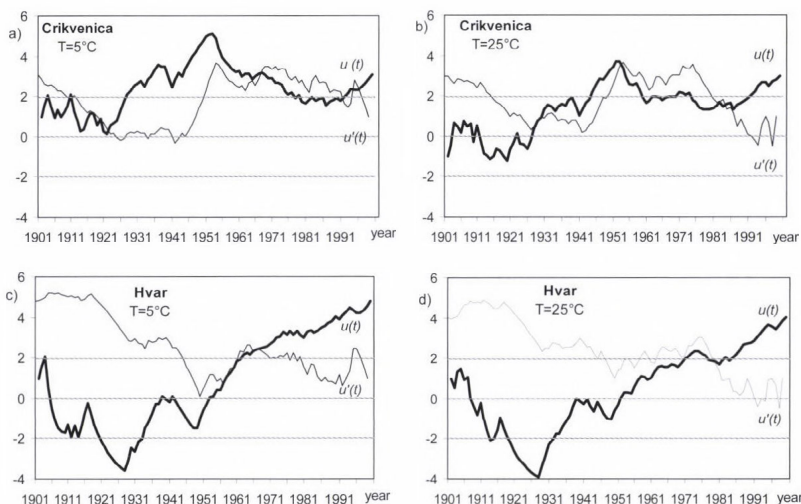


Fig. 3. The progressive trend test in growing degree-days for the temperature thresholds of 5 $^{\circ}\text{C}$ and 25 $^{\circ}\text{C}$ for the forward series $u(t)$ (thick line) and backward series $u'(t)$ (thin line) for Crikvenica and Hvar during the period 1901–2000. The positive $u(t)$ points show an increasing trend, while the negative $u'(t)$ points are at a decreasing trend. In order to identify the beginning of the possible trend, $u(t)$ has been calculated from the first to the last date, forming a progressive onward test series. The backward test series $u'(t)$ has been formed in the same manner, calculated from the last to the first term. If there is no trend, the $u(t)$ and $u'(t)$ curves overlap several times, whereas in the case of a trend, the intersection point designates the beginning of the trend, becoming significant at the 0.05 level in the case when the absolute $u(t)$ exceeds the 1.96 value.

4. Conclusion

The significant positive trend in the growing degree-days for the 25 °C temperature threshold indicates that the mid-Adriatic coast and islands are subject to the highest vulnerability to climate change in Croatia. In this region, the growth in high temperatures and the risk of summer droughts account for high current vulnerability in agriculture and forestry. This vulnerable region has spread from the middle Adriatic to the northern Adriatic in the warm season, but there is no higher risk towards the inland mountains. If all available potential adaptation measures (particularly irrigation systems) were implemented in this region, the vulnerabilities could be brought to a lower level.

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Progress in dryness and wetness parameters in altitudinal vegetation stages of West Carpathians: Time-series analysis 1951–2007

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Abstract—This article analyzes trends in the occurrence of dry and wet periods in altitudinal vegetation stages in the West Carpathian region of Slovakia for the period 1951–2007. The relative evapotranspiration, drought index, and radiation drought index were applied on meteorological data from eight meteorological stations representing the predominant vegetation stages in the investigated region. These indices were used to characterize humidity conditions. The radiation drought index ranges from 1.31 for the area heavily prone to drought (southern part), to 0.41 for the mountainous areas (northern part), where the sum of precipitation exceeds potential evapotranspiration. The relative evapotranspiration shows values as high as 97% in northern mountainous regions to the low value of 58% in the Danubian Lowland. A significant increase in the severity of drought was identified by means of the radiation drought index for the period 1951–2007 only in the Danubian Lowland (stage 1, oak vegetation). A significant trend in the case of humidity was determined in the mountains and in the northern part of East Slovakia.

Key-words: drought, drought index, radiation drought index, actual evapotranspiration, potential evapotranspiration, precipitation, relative evapotranspiration, vegetation stage

1. Introduction

In principle, drought is defined as the state of water deficit concerning soil, plants, and atmosphere (Krečmer, 1980). In agriculture and forestry, it is understood as an important meteorological factor, distressing all ecosystems. Drought features strongly vary from region to region. The primary cause of drought under the conditions prevalent in the investigated territory is a deficit at precipitation over a certain period of the growing season. Other climatic factors, such as high temperature, strong wind, and low relative humidity, can significantly aggravate its severity (Hayes *et al.*, 1999; Heim, 2002).

Altitude and topography are strong climate-differentiating factors. Consequently, under conditions of considerably broken topography in the West Carpathians, drought plays an extra-important role. The primary importance of climate from the point of view of the natural vegetation has already been pointed out by Zlatník (1976). The author defines the vegetation stages as basic units characterizing altitudinal climate conditions (vertical differentiation) through vegetation (biocenoses). The bio-geocenoses resulted from variability in altitude, exposure, and topography can be classified as belonging to 9 vegetation stages. The Slovak territory has been divided by Zlatník (1976) into altitudinal vegetation stages named after the significant tree or bush indicator species dominating the area. These stages are characterized by their dominant climax tree species as follows: stage 1, oak (*Quercus*) vegetation, stage 2, beech-oak (*Fagus-Quercus*) vegetation, stage 3, oak-beech (*Quercus-Fagus*) vegetation, stage 4, beech (*Fagus*) vegetation, stage 5, fir-beech (*Abies-Fagus*) vegetation, stage 6, spruce-fir-beech (*Picea-Abies-Fagus*) vegetation, stage 7, spruce (*Picea*) vegetation, stage 8, mountain pine (*Mughetum*) vegetation, stage 9, alpine vegetation (non-forest high mountain pastures).

The vegetation stages of lower elevations, i.e., oak vegetation (stage 1), oak vegetation with admixture of beech (stage 2), and beech vegetation with admixture of oak (stage 3) are rather arid during the vegetation period (from March to September). The precipitation deficit reaches 100–300 mm during the vegetation season. The beech vegetation (stage 4) is characterized by an equitable climatic water balance. The climate humidity increases in higher vegetation stages (beech vegetation with fir (stage 5) and fir with beech and spruce (stage 6)). Humidity belongs to the fundamental properties of mountain forests. The water balance reaches the highest values in the 8th vegetation stage of mountain dwarf pine and the 9th alpine stage, where the amount of precipitation considerably exceeds the evaporation requirements of the atmosphere. Within the annual balance, the surplus of precipitation water is approximately 1000 mm (Škvarenina *et al.*, 2004). Experiments confirmed that under optimum conditions of plant growth, the actual evapotranspiration (E) is proximate to the potential one (to the maximum possible evapotranspiration under the given climatic conditions from sufficient soil moisture – E_0). That is

why the ratio E/E_o (relative evapotranspiration) and the drought index (E_o/P , where P is the total precipitation) enable the quantification of the deficit of water in the soil root zone for optimum plant growth (*Budyko and Zubenok, 1961*). The radiation drought index (B/LP), where B is net radiation and L is the latent heat of vaporization, expresses the energy of net radiation in amounts of heat needed to evaporate the annual precipitation total. The indices were proposed to characterize general environmental conditions and processes on the Earth's surface. It approximates the ability of precipitation to provide the water required by native vegetation for an undisturbed evapotranspiration process and is often used in ecological studies (*Tomlain, 1996; Tomlain, 2004*).

In this paper, for the first time, we present the relative evapotranspiration, radiation drought index, and drought index results for the altitudinal vegetation stages in Slovakia, covering the period 1951–2007.

2. Method

Relative evapotranspiration and drought indices express functional dependencies among all energy and water balance equation components of the locality (net radiation, air temperature and humidity, turbulent state of atmosphere, difference of saturation water vapor pressure at the temperature of evaporating surface and water vapor pressure in the air, precipitation, change of critical soil moisture during the year, and heat flux in the soil). The model resulted from common solution of the energy and water balance equations was performed at eight selected climatic stations in the investigated territory. The following data were taken as inputs into the model: air temperature and humidity, cloudiness, precipitation, and number of days with snow cover. The potential evapotranspiration was computed by the equation of water vapor diffusion in the atmosphere according to *Budyko and Zubenok (Budyko, 1980)*, and the actual evapotranspiration was supposed to be proportional to the potential evapotranspiration:

$$E = E_o W / W_o, \quad (1)$$

where the water storage W is specified as a moisture content stored in the upper soil layer of 1 m depth and W_o as a critical value above which E equals to E_o . W_o usually amounts to a layer of 100–200 mm of water with seasonal and regional variations. The average soil moisture, $W = (W_1 + W_2)/2$, is determined from the water balance equation by the method of step-by-step approximation (W_1 is the moisture stored in the soil layer at the beginning of the month, and W_2 is the same at its end). As the number of meteorological stations for which the potential evapotranspiration has been calculated was limited, we decided to use the method of representative climatic stations, where the station represents the climate-hydric conditions of a particular vegetation stage. The climatic stations

were classified into the appropriate vegetation stages (stages 1–8). For stage 9 there were no data based on the map of vegetation stages (Raušer and Zlatník, 1966) and typological maps of the forest type groups (scale 1:200,000).

3. Results and discussion

Table 1 presents the average annual values of seven parameters affecting the humidity conditions at selected stations in 1951–2007 as well as their classification into vegetation stages. The distribution of stations in the territory is shown in Fig. 1. The territory of the West Carpathians is divided into the area of Pannonia (Pannonian Lowland) and the foothills to the north, influenced by Mediterranean climate, and the area of the inner Carpathians, influenced by sub-ocean mountainous climate and by the climate of both Northern and Baltic Seas. The line dividing these areas has been determined by Zlatník (1959) by the so-called main climatic line, where the Carpathian bow separates two European climatic areas. The area to the north of this line is quite wetter and colder than the southern one, which is drier and warmer. The northern part is favorable for the growth of spruce, unlike the southern part, where spruce grows only in the highest vegetation zone.

The E/E_0 is a suitable measure of the water sufficiency for vegetation. It approaches its lowest values of about 60% in the lowest areas. Towards the higher vegetation stages, the E/E_0 increases reaching more than 90% in stage 4 beech vegetation. However, in the mountain sites this measure partly loses its accuracy. By the 5th vegetation stage its resolution approaches only about 1–5%. Finally, the B/LP has appeared as the most suitable complex index for describing the humidity and drought phenomenon in the region. It keeps higher stability than E_0/P , while accounting both for energy and precipitation elements.

Table 1. Average annual values of net radiation (B) in kWh m^{-2} , precipitation (P) in mm, radiation drought index (B/LP), drought index (E_0/P), potential (E_0) and actual evapotranspiration (E) in mm, and relative evapotranspiration (E/E_0) in percentages at selected locations of Slovakia for the period 1951–2007 (L is the latent heat of vaporization)

Station	H(m)	B	P	B/LP	E_0/P	E_0	E	E/E_0	Vegetation stage
Hurbanovo	115	488	537	1.31	1.40	751	433	58	1, oak
Myjava	375	461	672	0.99	0.94	630	449	71	2, beech-oak
Kamenica and Cirochou	178	467	722	0.93	0.89	645	500	78	3, oak-beech
Plaveč	488	410	694	0.85	0.75	523	450	86	4, beech
Červený Kláštor	474	410	763	0.77	0.67	509	458	90	5, fir-beech
Oravská Lesná	780	392	1116	0.51	0.41	458	433	95	6, spruce-fir-beech
Ždiar-Javorina	1020	356	1258	0.41	0.34	426	414	97	7, spruce
Štrbské Pleso	1360	357	997	0.52	0.44	437	408	93	7, spruce, 8, mountain pine

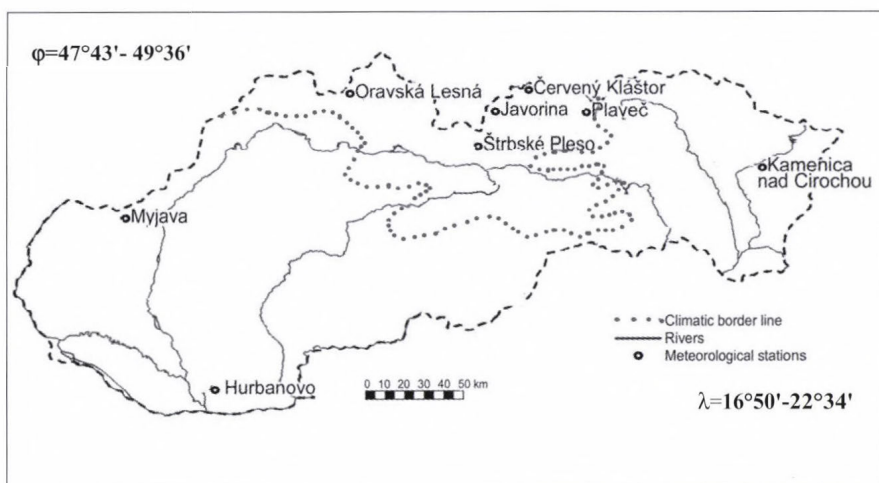


Fig. 1. The borders of Slovakia (dashed line) representing the West Carpathians with particular meteorological stations that represent conditions in the vegetations stages. The map displays the climatic border line (dotted line) and rivers (solid lines).

The E_o/P describes the relationship between the energy and precipitation inputs within particular vegetation stages. Beyond any expectations, the E_o/P index proved to be very sensitive to altitudinal changes and it was able to detect differences in bioclimatological conditions also in the comparatively small territory of the investigated region. As presented by Budyko (1980), the values of $E_o/P > 1$ indicate the territory of dry (arid) climate (steppe, forest-steppe). Values of $0.3 < E_o/P < 1$ specify forest bioms and values of $E_o/P < 0.3$ reveal the climate ecosystems of tundra or mountain forest of a temperate zone as well. The presented distribution of E_o/P values also corresponds to climate conditions in Slovakia. Warm forest-steppe formations dominated by oak, provides E_o/P values about 1. This represents the 1st vegetation stage (in the sense of Zlatnik classification) or a part of the 2nd vegetation stage dominated by beech-oak formations. Vegetation stages up to the E_o/P value of 0.3 represent the predominant area of Slovak forest; the values of index E_o/P decrease relatively proportionally when related to both increasing altitude and precipitation amounts. The vegetation stages with $E_o/P < 0.3$ are of mountainous (boreal) climate, characterized by low temperatures and high precipitation amounts, with norway spruce and dwarf pine being the predominant tree species growing here.

The radiation drought index reaches the value about 1.3 in our driest region Hurbanovo. In mountainous areas which are rich in precipitation (Štrbské Pleso, Ždiar-Javorina) it moves about a mean value of 0.5. Fig. 2 presents the regression dependence between the average annual values of the radiation drought index and the terrain altitude. Annual values of this index in the period 1951–2007 varied from 0.90 (1965, $P = 827$ mm) to 2.08 (2003, $P = 333$ mm) at

Hurbanovo, from 0.64 (1974, P = 1010 mm) to 1.68 (1961, P = 400 mm) at Kamenica nad Cirochou, from 0.76 (1987, P = 825 mm) to 1.55 (2003, P = 445 mm) at Myjava, from 0.53 (1980, P = 908 mm) to 1.15 (1971, P = 548 mm) at Červený Kláštor, from 0.62 (1985, P = 930 mm) to 1.31 (1961, P = 477 mm) at Plaveč, from 0.36 (1974, P = 1463 mm) to 0.72 (1959, P = 860 mm) at Oravská Lesná, from 0.25 (1980, P = 1630 mm) to 0.61 (1971, P = 908 mm) at Ždiar-Javorina, and from 0.35 (2004, P = 1299 mm) to 0.79 (1986, P = 690 mm) at Štrbské Pleso.

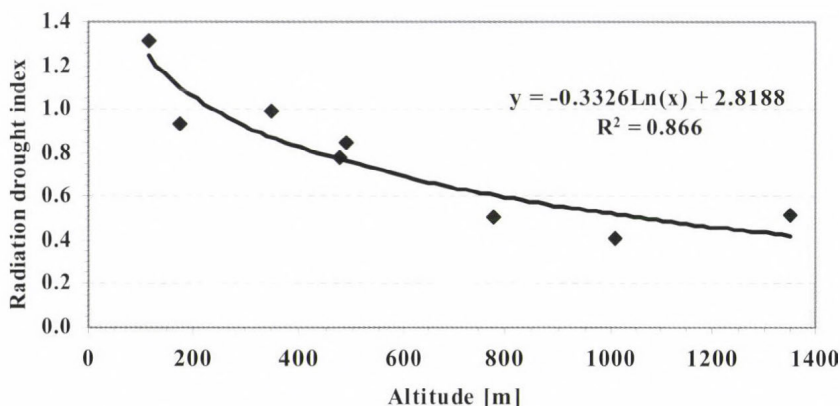


Fig 2. Logarithmic regression dependence of the radiation drought index annual values on the altitude (m a.s.l.) on the territory of Slovakia for the period 1951–2007.

The results presented in Fig. 3 point out the overwhelming trend to aridity at the station in Hurbanovo, situated in the southern part of Slovakia. In Hurbanovo, as well as at other stations, linear and polynomial trends practically mingled one with another, so that only the linear trend is shown. This station represents the regions of most intensive agricultural production in Slovakia. Frequent occurrence of drought as well as its rising frequency negatively influences the production of the main crops in this region as well as in other regions of Central Europe (Hlavinka et al., 2008; Dubrovský et al., 2008). Further more, a statistically significant tendency to more intensive dry episodes in the region were stated by recent studies (Brazdil et al., 2008). The next two stations with elevations below 500 m a.s.l. show practically no time trend in B/LP with relatively good water supplies as E_0/P drops below 1. B/LP starts to show the trend to lower values from the elevation around 500 m a.s.l. The stations situated to the north of the climatic line (Štrbské Pleso, Ždiar-Javorina, and Červený Kláštor) show an overwhelming trend to humidity during 1951–2007. Similar results are also presented by Škvarenina et al. (2008).

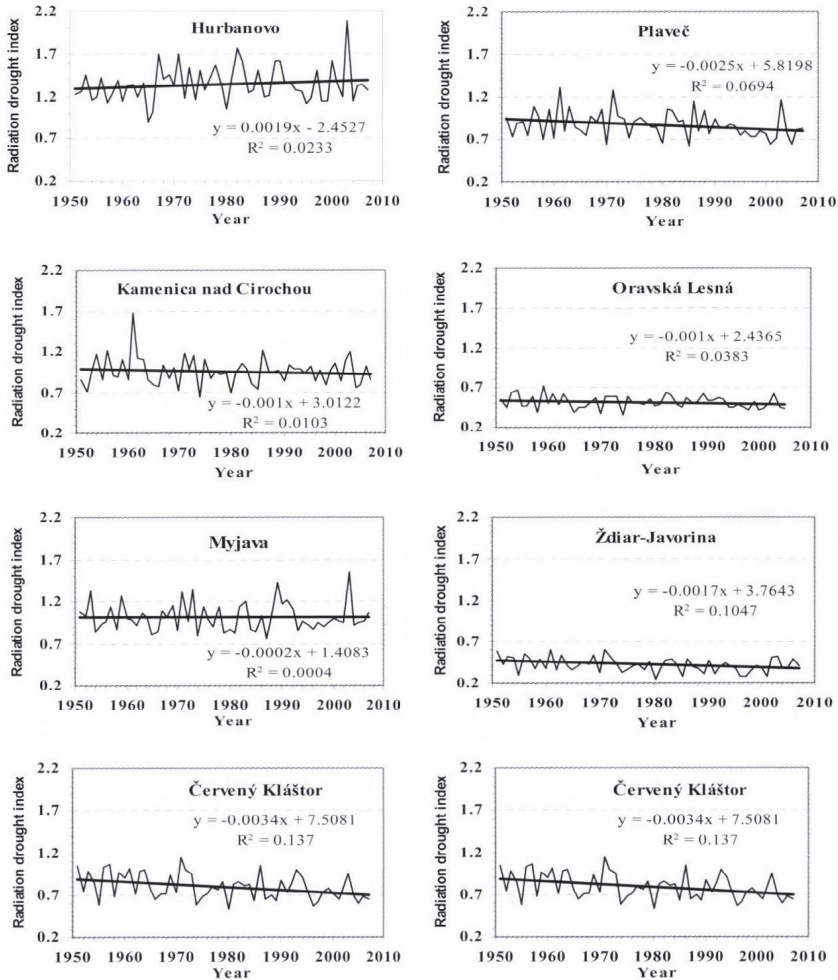


Fig. 3. Long-term course of the radiation drought index annual values at stations Hurbanovo, Kamenica nad Cirochou, Myjava, Červený Kláštor, Plaveč, Oravská Lesná, Ždiar-Javorina, and Štrbské Pleso for the period 1951–2007 with the linear trend.

4. Conclusions

- The calculations show that the radiation drought index is a suitable bioclimatic parameter. Its averages vary in a wide range from 1.31 in our driest region to 0.41 in mountain locations, but it is sensitive enough to indicate and reflect the diverse ecological conditions of the West

Carpathians from xerotherm oak plant communities to mountainous plant communities of spruce and dwarf pine.

- Maximum values of the radiation drought index for the processed period did not occur in the east and west parts of Slovakia in the same year.
- A significant increase in the severity of drought was identified from 1951 to 2007 only in the Danubian Lowland (stage 1, oak vegetation).
- In the mountains and in the northern part of East Slovakia, a significant trend of humidity increase was determined.

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Sustainable production zoning for agroclimatic classification using GIS and remote sensing

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Abstract—Agriculture is a primary productivity sector which is highly dependent on environmental conditions. The agroclimatic potential of agricultural areas has to be assessed in order to achieve sustainable and efficient use of natural resources in combination with production maximization. Temperature and rainfall, in terms of quantity and spatiotemporal variability, are variables which determine the type of crops suitable to a given location. Rainfall variable can also be interpreted as availability of sufficient water required for production of given crops. These variables, in combination with soil type and geomorphology, also determine areas where high levels of production are appropriate, avoiding the threat of degrading the natural resources. In the current work, zones indicating water availability are combined with topographic features and soil types in order to identify areas for sustainable production. Firstly, aridity index (AI) and vegetation health index (VHI) are used in order to define zones adequate for sustainable farming according to water limitations. As crop growth is affected by water supply, these zones are named water limited growth environment (WLGE) zones. AI and VHI are computed on monthly time step for twenty hydrological years, from October 1981 to September 2001. VHI is derived from NOAA/AVHRR data, while in AI computations both satellite and conventional field data are used. Then, WLGE zones are combined with soil maps and a digital elevation model (DEM) of the area under investigation in order to define zones appropriate for sustainable production. The study area is the aquatic district of Thessaly, located in Central Greece. The current application has resulted in the definition of sustainable production zones by means of parallelepiped supervised classification using the two indices, soil maps and DEM. These zones can be further used for agroclimatic classification.

Key-words: sustainable production, WLGE, VHI, AI, remote sensing, GIS

1. Introduction

The climate is among the most important factors that determine the agricultural potentialities of a region and the suitability of a region for a specific crop, whereas the yield is determined by weather conditions (*Pereira, 1982*). Since

agriculture is highly dependent on environmental conditions, a quantitative understanding of the climate of a region is essential for developing improved farming systems (Reddy, 1983).

Temperature and rainfall, in terms of quantity and spatiotemporal variability, are variables which determine the type of crops suitable to a given location (Mavi and Tupper, 2004). Even though crop production depends on every environmental condition, almost all agroclimatic classifications take into account these variables. These climatic parameters in combination with soil type and geomorphology can determine areas where high levels of production are appropriate, avoiding the threat of degrading the natural resources (Mavi and Tupper, 2004).

Crop production requires the availability of sufficient water. In irrigated and rainfed agriculture, production is often constrained by water limitations during the growing season. Amount and distribution of rain during the growing season and supplemental irrigation along with soil characteristics and evapotranspiration losses determine the temporal pattern of water availability for plant use and the ensuing crop biomass and economic yield (Arora and Gajri, 1998).

The amount of rain needed for the production of a crop differs from region to region, mainly due to the decreasing “effectiveness” of rainfall in order to maintain plant growth due to the increasing evaporation (Tow, 1991). Effective rainfall is related to the moisture available in the plant’s root zone, allowing the plant to germinate, emerge, and maintain its growth (Mavi and Tupper, 2004). There are many climatic and agroclimatic classifications seeking to describe the moisture conditions of crops (e.g., Thornwaite, 1948; Reddy, 1983). These classifications vary in complexity, ranging from the use of one parameter to methods incorporating a number of parameters. Most of these agroclimatic classifications used rainfall and potential evapotranspiration in order to delimit the growth environment of crops (Badini *et al.*, 1997).

Badini *et al.* (1997) investigated the water limited growth environment (WLGE) for millet cultivation in Burkina Faso, where rainfed production is a major source of food and income. They used aridity index (AI) and crop water stress index (CWSI) for defining such environments. AI incorporates rainfall and potential evapotranspiration. CWSI integrates all factors affecting water availability for crop growth but has the limitation of being crop specific.

One major application of remote sensing to agriculture is crop monitoring and assessment of vegetative stress. Satellite derived indices have been extensively used for identifying stress periods in crops or generally vegetation (Steven and Jaggard, 1995). In most cases the identification of vegetative stress is being held by the use of vegetation indices (Domenikiotis *et al.*, 2002; Kogan, 1995, 2001, 2002; Tsiros *et al.*, 2004).

Kogan (2001) proposed the vegetation health index (VHI) for monitoring the impact of weather to vegetation, and to use it for agricultural drought monitoring and mapping. Agricultural droughts reflect vegetation stress caused

by the adverse climatic and hydrologic factors (*Bhuiyan et al.*, 2006; *Kogan*, 2002). VHI is a combination of vegetation condition index (VCI) and temperature condition index (TCI) derived by NOAA/AVHRR satellite data. In Greece, VCI and TCI have proven to be useful tools for the detection of agricultural drought (*Domenikiotis et al.*, 2002; *Tsiros et al.*, 2004).

In Greece, *Tsiros et al.* (2008) classified the WLGE using satellite derived VHI and AI. VHI represents overall vegetation health (moisture and thermal conditions) (*Kogan*, 2001) and is suitable for identification of vegetative stress, especially in cases where no specific crop is examined. AI represents climatic aridity and is used to determine the adequacy of rainfall in satisfying the water needs of crops.

The first objective of this study is to define a general methodology (not crop specific) for identifying WLGE using GIS and remote sensing. Therefore, the two indices are used to define zones adequate for agricultural use according to water limitations (WLGE zones). The second objective is to identify sustainable production zones in terms of water sufficiency, fertility (appropriate or not for agricultural use), desertification vulnerability, and altitude restrictions. Thus, WLGE zones are combined with soil maps and a digital elevation model (DEM). In order to apply new management techniques, transfer new technologies and plan alternative crops according to the bio-physical characteristics of each region, a quantitative understanding of the relationships among crop, climate, and soil are needed (*Badini et al.*, 1997). Defining areas of sustainable crop production is a major step for identifying agroclimatic zones, considering environmental limitations and the sustainable use of natural resources.

2. Study area and preprocessing

The study area is the geographical region of Thessaly (*Fig. 1*) and specifically the water district of Thessaly, located in Central Greece. Thessaly is a region of plains surrounded by mountains. The ridges of these mountains are the borders of the water district of Thessaly. Having higher percent of flatlands than any other district in Greece, 38.7% of the population is occupied in the primary productivity sector and thus, Thessaly is a major supplier of agricultural products.

The increase in agricultural activities and the intensive type of agricultural practices applied in Thessaly, resulted in an insufficient use of natural resources. Low and irregular amount of rain during the summer period lead to regional drought events which in combination with the oversized pumping and the bad management of irrigation water (old irrigation practices and network, increased water losses, more amount of irrigation water than needed) led to degradation of water resources and lowering of the ground water table. Thus, there is a

necessity for identifying areas which are capable to fulfill crop water needs without aggravating the current conditions.

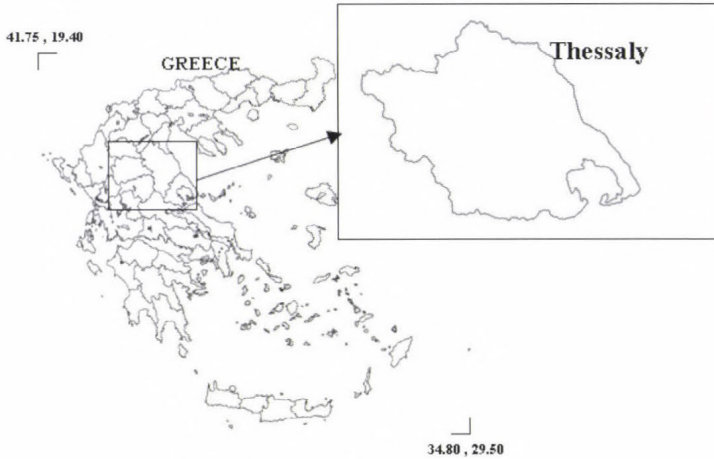


Fig. 1. Location of the study area.

The data base consists of NOAA/AVHRR satellite data and conventional data for 20 hydrological years, from October 1981 to September 2001. In specific:

- Normalized difference vegetation index (NDVI), channel 4 (CH4) and channel 5 (CH5) brightness temperature (BT) ten-day composite satellite images (8×8 km spatial resolution).
- Monthly rainfall maps with grid cell size 50×50 km (ISPRA, 2006).
- Mean monthly air temperature measurements from Larissa meteorological station (National Meteorological Service, NMS).
- Soil map of the study area (Yassoglou, 2004).
- Digital elevation model derived from 100m contours.

All satellite data are obtained on-line by NASA archives. NDVI maps are ten-day maximum value composite (MVC) images. CH4 and CH5 images are converted to BT using the equation provided by the info file of the data set. Using the ten-day images, NDVI and BT images are composed over a monthly period using the MVC and mean pixel value, respectively. Missing data due to cloud cover or sensor's technical problems are completed using monthly climatic values derived from the images of the time series which presented no blunders. Rainfall maps were produced using the data of ISPRA European database (ISPRA, 2006). The subset satellite images and rainfall maps cover the

entire area of Greece. After all computations have been carried out, the area under investigation is isolated.

Before using NDVI and BT images, fluctuations induced by noise must be removed. The combination of the filtering and the MVC can significantly reduce the noise from residual clouds, fluctuating transparency of the atmosphere, target/sensor geometry, and satellite orbital drift (Goward *et al.*, 1991). Other noise can be related to processing, data errors, or simple random noise (Kogan, 1995).

In the current study, a “4253 compound twice” median filter (Van Dijk *et al.*, 1987) is applied to the NDVI images, whereas a “conditional” statistical mean spatial filter (window size ranging from 3×3 to 7×7 , according to image needs) has been used for smoothing the BT series (Tsiros *et al.*, 2008). The BT series presented continuous spatial fluctuations, and thus, a spatial filter (statistical mean) has been preferred for smoothing channel 4 and channel 5 BTs. “Conditional” means that the filter is applied only to the pixels that presented errors.

3. Methodology

Remote sensing is a useful tool to analyze the vegetation dynamic. Several studies have shown that inter-annual differences in vegetation parameters are mainly driven by water availability (Al-Bakri and Taylor, 2003; Weiss *et al.*, 2004). Thus, AI and VHI are used in order to define zones adequate for sustainable farming according to water limitations (Tsiros *et al.*, 2008). As crop growth is affected by water supply, these zones are named water limited growth environment zones (Badini *et al.*, 1997). Furthermore, these zones are combined with soil maps and a DEM of the area under investigation in order to define zones appropriate for sustainable crop production due to water, soil, and altitude restrictions.

3.1. Water limited growth environment

The first index used to identify WLGE is VHI. VHI is a combination of VCI and TCI derived by a long term NDVI and channel 4 images from NOAA/AVHRR satellite. NDVI, is obtained by combining the channels 1 and 2, the visible and near infrared, respectively, of NOAA/AVHRR. NDVI is a quick and efficient way for the estimation of vivid vegetation. NDVI is indicative of the level of photosynthetic activity in the vegetation monitored, reflecting whether the vegetation is stressed or not. After stressed conditions, significant reduction in NDVI of the field is expected.

VCI and TCI characterize the moisture and thermal conditions of vegetation, respectively (Bhuiyan *et al.*, 2006; Kogan, 1995, 2001, 2002) and are given by the equations:

$$VCI = 100 \cdot \frac{NDVI - NDVI_{\min}}{NDVI_{\max} - NDVI_{\min}}, \quad (1)$$

$$TCI = 100 \cdot \frac{BT_{\max} - BT}{BT_{\max} - BT_{\min}}, \quad (2)$$

where $NDVI$, $NDVI_{\max}$, and $NDVI_{\min}$ are the smoothed ten-day normalized difference vegetation index, its multi-year maximum and minimum, respectively; BT , BT_{\max} , and BT_{\min} are the smoothed ten-day radiant temperature, its multi-year maximum and minimum, respectively, for each pixel, in a given area. Thermal conditions are especially important when moisture shortage is accompanied by high temperature, increasing agricultural's drought severity, having direct impact to vegetation's health. VCI and TCI vary from zero, for extremely unfavorable conditions, to 100, for optimal conditions. Thus, higher VCI and TCI values represent healthy and unstressed vegetation.

Both indices are based on the same concept. Maximum amount of vegetation is developed in years with optimal weather conditions, whereas minimum vegetation amount develops in years with extremely unfavorable weather (mostly dry and hot). Therefore, the absolute maximum and minimum values of $NDVI$ and BT , calculated from several years, contain the extreme weather events (drought and no drought conditions). The resulted maximum and minimum values can be used as criteria for quantifying the environmental potential of a region (Kogan, 1995).

VHI represents overall vegetation health (Kogan, 2001). The five classes of VHI that represent agricultural drought are illustrated in Table 1 (Bhuiyan et al., 2006; Kogan, 2001). VHI is expressed by the following equation:

$$VHI = 0.5 \cdot (VCI) + 0.5 \cdot (TCI). \quad (3)$$

In VHI computation, an equal weight has been assumed for both VCI and TCI , since moisture and temperature contribution during the vegetation cycle is currently not known (Kogan, 2001).

Table 1. VHI drought classification schemes (Kogan, 2001)

VHI values	Agricultural drought classes
<10	Extreme drought
<20	Severe drought
<30	Moderate drought
<40	Mild drought
>40	No drought

The other index used to identify WLGE zones is AI. AI is a function of the ratio of precipitation to potential evapotranspiration. The categories as they are defined by the values of AI are illustrated in *Table 2* (UNESCO, 1979). In this study, AI represents climatic aridity and is used to determine the adequacy of rainfall in satisfying the water needs of crops. The index is calculated on multi-year basis, using monthly values. The potential evapotranspiration is calculated with the use of Blaney-Criddle method (Tsiros *et al.*, 2008). The method estimates potential evapotranspiration (ET_p) using monthly air temperature data, the ratio of daytime hours (month/year), and a weighted crop coefficient (C). Regarding the weighted crop coefficient, 12 maps with grid cell size of 100×100 m (one for each month) have been utilized. C values are defined according to land use provided by CORINE 2001 database.

Table 2. Characterization of an area according to aridity index, AI (UNESCO, 1979)

Category	AI
Extremely dry	<0.03
Dry	0.03 – 0.20
Semi-dry	0.20 – 0.50
Semi-wet	0.50 – 0.75
Wet	>0.75

In ET_p calculations, land surface temperature (LST) is used instead of air temperature. The generation of LST maps is based on the “split-window” algorithm from Becker and Li (1990), which uses the differential absorption effects in channels 4 and 5 for correcting atmospheric attenuation mainly caused by water vapour absorption. For estimating surface emissivity, the relationship given by Van de Griend and Owe (1993) is applied.

In order to avoid over-estimating ET_p , LST is converted to air temperature using a linear empirical relationship. The relationship has been derived by applying a regression analysis to the LST and air temperature data of the time series ($R^2 = 0.84$). Results are depicted in *Fig. 2*.

Since both indices have been computed, two maps are created. From the VHI images a final map is obtained using the frequency of occurrence of agricultural drought events. The derived map is combined with the climatic aridity map and led to the definition of WLGE zones. The generalized thematic classification scheme is illustrated in *Table 3*.

3.2. Soil map and DEM

Overlapping WLGE zones, a soil map, and a DEM of the study area has led to the definition of regions where crop production is sustainable and agriculture is the best suited agronomic use. Soil types are digitized according to fertility

(appropriate or not for sustainable agricultural use) and desertification vulnerability. The sustainable agronomic use and the desertification risk according to soil category are adopted by *Yassoglou (2004)*. Soil types are grouped into three classes during the digitization. Soils appropriate for agricultural use, controlled agricultural use, and no agricultural use. The classification pattern is illustrated in *Table 4*. Finally, the digitized vector map is converted to raster (grid) with cell size of 100×100 m.

As mentioned earlier, the DEM is constructed using 100 m interval contours. Three major crop growth zones are selected according to altitude limitations (*Danalatos, 2007*). The first, ranging from zero to 600 m, is appropriate for almost all crops. The second, ranging from 600 m to 900 m is appropriate for non-tropic crops and fruit trees (maize, winter wheat, apple trees, chestnuts, etc.). The last one, having altitude values higher than 900 m is not appropriate for crops. Again, the derived zones are converted to raster (grid) with cell size of 100×100 m.

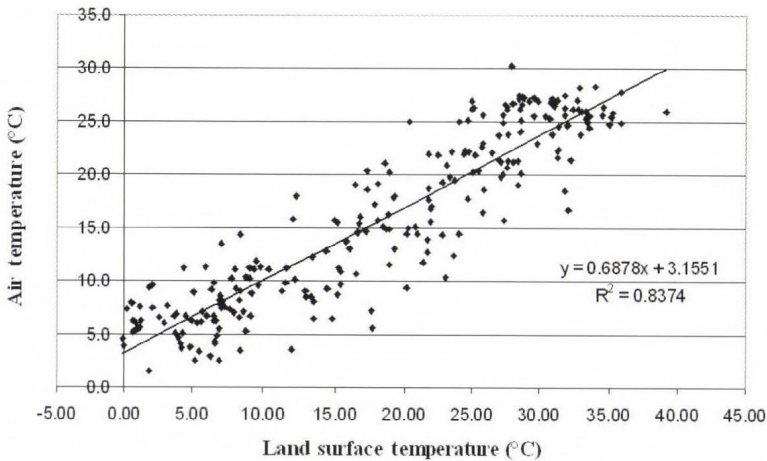


Fig. 2. Application of linear regression analysis to land surface temperature and air temperature.

Table 3. WLGE generalized classification scheme (*Tsiros et al., 2008*)

Agricultural drought classes	Aridity classes	WLGE classes
Extreme drought	Extremely dry	Limited
Severe drought	Dry	Environment
Moderate drought	Semi-dry	Partially limited
Mild drought	Semi-wet	Environment
No drought	Wet	No limitations

Table 4. Classification scheme of soil types according to sustainable use and desertification vulnerability

Class name	Sustainable agronomic uses	Desertification vulnerability	Soil types category
No agricultural use	Wild nature, Forest	Very high	Rock outcrops Leptosols, Regosols (low quality)
	Controlled pasture	High	Cambisols (medium-low quality)
Controlled agricultural use	Controlled agriculture and pasture	Medium	Regosols (medium quality) Cambisols (medium-high, high quality)
	Forest		Luvisols (medium quality)
Agricultural use	Agriculture	Low	Fluvisols, Vertisols, Luvisols (high quality)

3.3. Supervised classification

During the supervised classification, the parallelepiped technique is used in order to combine the WLGE zones, the soil map and the DEM and define the sustainable production zones. During the classification, the following rule pattern is used. Crop production is:

- “Unsustainable” in areas characterized by any of the “limiting” classes.
- “Sustainable under restrictions” when “partial limitations” regarding to WLGE or soil map or DEM (intermediate classes) exist.
- “Sustainable for non-tropic crops” in regions with “no limitations” and 600–900 m altitude range.
- “Sustainable” in areas with “no limitations” and altitude lower than 600 m.

4. Results and discussion

In this study, two satellite derived indices, VHI and AI are used to define areas where plant growth is limited by water availability. The calculation of the two indices resulted in the creation of two maps. One is characterizing areas according to the frequency of agricultural drought incidents (*Fig. 3a*) and the other is representing climatic aridity (*Fig. 3b*) for the period under consideration. *Figs. 3a* and *3b* show that there is no area in Thessaly water district where the climate regarding to AI is “dry” or “extremely dry”, and “severe” and “extreme” drought events are frequent.

The definition of WLGE zones is the result of the combination of these two maps. The thematic classification scheme used is described as follows. A number has been assigned to every class of the two indices (five classes each). Number one corresponds to “wet” and “no drought” classes, grading the sequence up to five, which corresponds to “extremely dry” and “extreme

drought” classes. By adding those numbers, three categories are utilized to delimit WLGE zones: (i) “limited” (values from 7 to 10) and (ii) “partially limited” (values from 3 to 6) growth environment, and (iii) the class where “no limitations” (values equal to two) exist according to water availability. The map of WLGE zones is presented in Fig. 4.

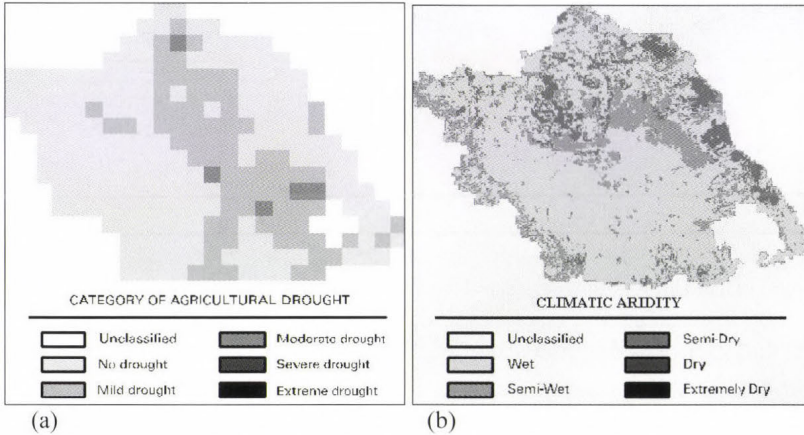


Fig. 3. (a) Agricultural drought map of Thessaly water district derived using incidents frequency, (b) climatic aridity map of Thessaly water district.

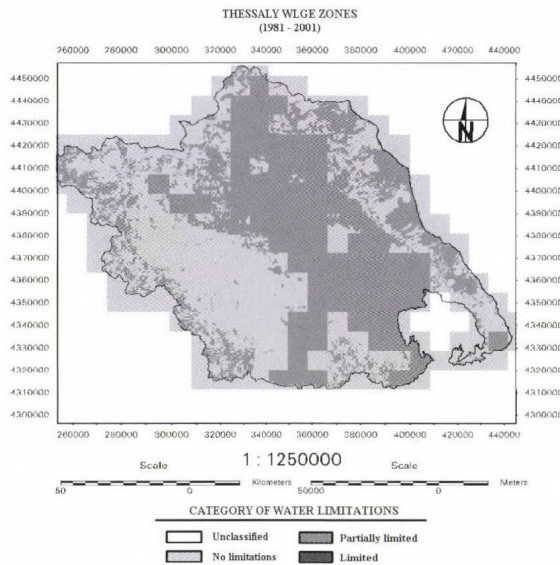


Fig. 4. Water limited growth environment zones of the water district of Thessaly.

Fig. 4 indicates that there is no area in Thessaly water district where plant growth is prohibited by water availability. The definition of “limited” growth environment indicates areas where moisture and rainfall cannot satisfy the water needs of crops or even a part of them. In order to satisfy crop requirements in those areas, large quantities of water supply from irrigation are required, leading to unsustainable use of water resources and increase of the cost of the final product. Areas of “partially limited” growth environment due to water availability need smaller amount of irrigation, whereas areas with “no limitations” even smaller. In such areas, a more effective use of water resources is being held, since a major part of crop water needs is supplied by rainfall and existing moisture conditions.

The combination of the WLGE zones, soil maps, and DEM resulted in the definition of sustainable production zones by means of parallelepiped supervised classification. The zones of sustainable use according to soil characteristics and the altitude based crop growth zones in Thessaly are depicted in Figs. 5a and 5b, respectively, whereas the derived map of the sustainable production zones is presented in Fig. 6.

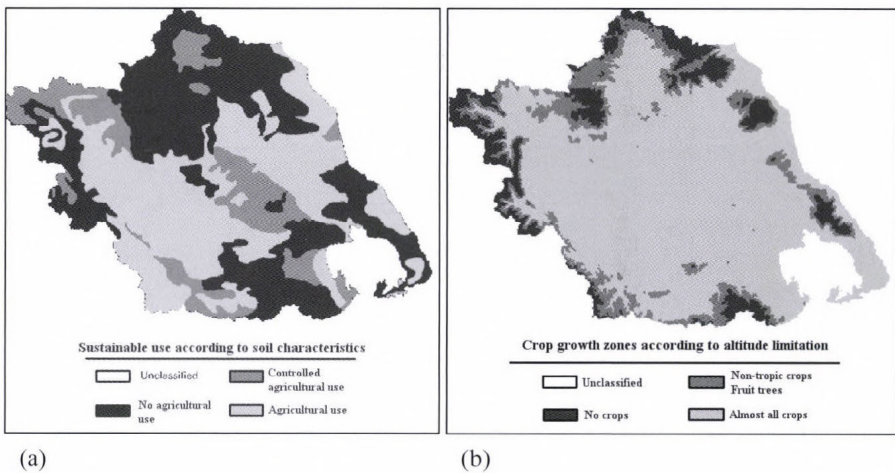


Fig. 5. (a) Zones of sustainable use according to soil characteristics in Thessaly, (b) altitude based crop growth zones of Thessaly water district.

Fig. 6 shows that in the 35% of Thessaly water district agriculture is not a sustainable due to water, altitude, or soil limitations. The term “sustainable under restrictions” refers to the cultivation of crops that do not need large quantities as “input” regarding irrigation and fertilizers. Also, “sustainable under restrictions” indicates that the type of cultivation preferred to those areas is extensive and not intensive. Further work has to be done in order to define the type of crops and cultivation techniques applied to those areas. The sustainable

production areas for non-tropic crops have small spatial coverage, because they are delimited by the relatively high altitudes. Lastly, sustainable production zones cover about 25% of Thessaly indicating that those areas of the water district are suitable for any agricultural use. But, in order to obtain sustainability, farming management practices such as crop rotation, use of crop cover, and combination with livestock grazing out of the growing season are essential. Most of the times, monocultures are not sustainable systems.

The main advantage of the methodology is that it uses satellite and raster data, providing continuous spatial and temporal information. In this way there are no fuzzy borders regarding the derived zones. Instead, methods that use conventional data are lacking the above advantages. But, despite the advantages, it is essential that the satellite data are calibrated and preprocessed properly before they are used as input data in any methodology. Lastly, another advantage of using these indices is that they are not crop specific.

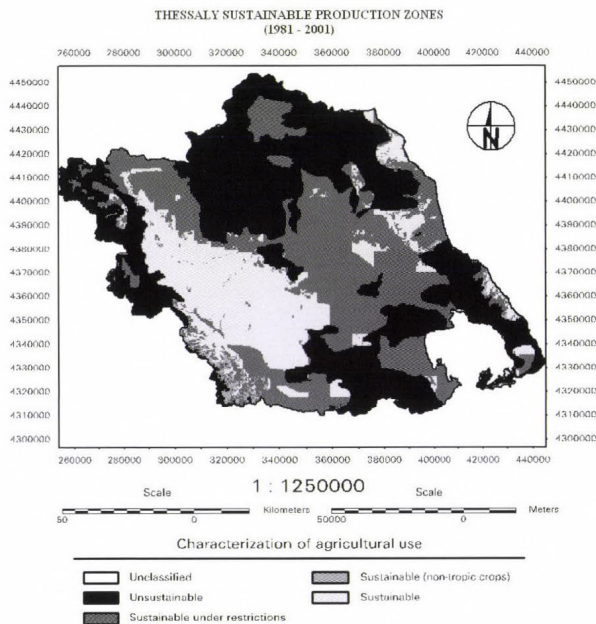


Fig. 6. Sustainable production zones of Thessaly water district.

5. Conclusions

The results of the current application justify the use of AI and VHI. Using VHI, areas frequently affected by agricultural drought are identified and excluded. The combination of the frequency of occurrence of such extreme events along

with climatic aridity is useful for identifying areas unsuitable for crop production due to water availability. Such areas must be excluded from any sustainable management plan.

Thus, WLGE zones are important since they delineate areas where plant growth is limited by water availability. Moreover, the use of soil maps and DEMs excludes areas unsuitable for agricultural activities. Thus, the combination of WLGE zones along with soil maps and DEMs can be used to identify sustainable production zones. Such zones are essential in developing any sustainable development/farming plan, since they can be combined with crop specific agroclimatic indices in order to obtain agroclimatic zones.

The innovation of the proposed methodology consists of the joint use of the above described steps, as well as the classification of areas escalating the suitability of agricultural activities. Lastly, the methodology is not crop specific and has the advantage of providing total spatial coverage of the area under investigation.

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Current trends of agroclimatic indices applied to grapevine in Tuscany (Central Italy)

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Abstract—Global warming is causing wide changes in atmospheric events with critical impacts on vegetations. Indeed, an increase of temperature variability has been observed, primarily due to increase in warm extremes. Temperature rising will lead to several consequences. For example, growing season lengthening is observed, but at the same time, plants grow faster, thus giving productions low in quality and quantity. Finally, concerning the Mediterranean region, it is evaluated that a greater water request is needed for irrigation. Besides, high maximum temperatures during summer months may cause drop in quality. On the opposite, concerning winter risks, earlier bud break will increase late frost risks. The aim of this study is to cover some aspects of warming temperature and phenological responses on grapevine in central Italy. The research is focused on climatic and agroclimatic indices calculated in 1955–2007 period. Regression trend, linear or non-parametric, depending on the distribution of data, was fitted to provide pictures of changes that have occurred.

Key-words: global warming, climate variability, rising temperature, phenology, quality, frost, *Vitis vinifera*

1. Introduction

A long history of grapevine (*Vitis vinifera*) is associated with the fitoclimatic Mediterranean area. Indeed, famous wine regions were established in this area during the Roman Empire, because it was recognized the fundamental link between the geographic location and the climatologic condition.

Nowadays this idea is the basis of the wine zoning. The wine style produced by regions is the result of the baseline climate, while climate variability determines vintage-to-vintage quality differences (Jones, 2003; Jones and Hellman, 2003). In particular, climate strongly affects the given wine style, because it has a deep influence on the optimum levels of sugar, acid, and flavor

on grape. As for global warming, some studies highlight both positive and negative impacts in Europe. Among positive ones, the total surface suitable for cultivation foreseen by climatological models is going to increase and extend to European north latitudes and higher altitudes (*IPCC, 2007; Bindi et al., 2002*). On the contrary, in southern areas of Europe, the benefits of the forecasted climate change will be limited, while the disadvantages will be predominant (*Maracchi et al., 2005*). The Mediterranean area, in particular, shows high susceptibility to the most recent increase and variability of temperature: these strongly affect viticultural activities, modifying grapevine responses and determining the quality and quantity of vine production (*Jones and Hellman, 2003*). Among the other consequences, rising temperature is going to cause both geographical and varietal changes in grape cultivation (*Orlandini, 2004*).

As regard crops quality risks, high temperature and dry condition, especially in September, can be critical for grape quality, because they cause excessive fruit ripening, affecting fruit quality (*Schultz, 2000*).

Moreover, as for the impacts on the physiology, a few case studies point out that rising temperature in this area determines increase of water request and needs of monitoring. Indeed, even if grapevine is quite resistant to high summer temperature and drought, the increase of extreme conditions can be responsible of physiological stresses, such as the reduction of photosynthetic efficiency.

Concerning the phenology, higher minimum temperatures activate cellular split (*Nemani et al., 2001*), thus causing advanced harvest. Moreover, a study conducted in the north-east part of Italy during the 1956–2002 period, shows an increase of thermal sum that determines earlier phenological phases (*Puglisi et al., 2005*).

One of the most important indices used to investigate plant phenology is the growing season starting date, that is strongly related with air temperatures (*Fregoni, 2002*). For example, it is recently largely observed that a positive anomaly on the temperature trend during the growing season determines grape phases shift, with negative effect on vine quality. Indeed, it leads to the premature change of color, sugars accumulation, and partial or total failure of flavor ripening (*Mullins et al., 1992*), in some cases enzyme inactivation (*Jones et al., 2005*).

Moreover, the increase of interannual variability in temperature and precipitations makes adaptation to such continuous changes very expensive, thus winemakers have to be flexible in viticulture techniques planning and management beyond rescheduling crop operations (*Bindi et al., 2002*). A study on Sangiovese and Cabernet Sauvignon in Italy revealed that warmer conditions will lead to shorter growth range and higher yield variability (*Bindi et al., 1996*).

Finally, the more delicate grapevine growth phases, such as the very early ones, will be more and more vulnerable. In particular, bud-break will be affected by the late frost risk increase (*Nemani et al., 2001*).

Assessment of the potential impacts of climate change on viticulture is demanded by scientists, policy makers, producers, and others to make decisions on policies and management practices that may minimize negative impacts and take advantage of positive impacts or opportunities.

On these bases, this study analyzes some climatic and agroclimatic indices trend to assess temperature changing and the consequent potential impacts on grapevine cultivation in Tuscany (central Italy).

2. Material and method

From a meteorological network, 22 stations were selected in Tuscany, Italy, for the 1955–2007 period (*Table 1; Fig. 1*). The following criteria were adopted to select stations: first, low percentage of missing data, because even if the techniques to reconstruct the series are known, it is preferable to start the analysis with original data; second, a long period covered by dataset, thirty years at least. Finally, stations must be distributed all over the territory to have a complete overview of the climate in Tuscany.

Table 1. Geographical information of the meteorological stations

Meteorological station	UTM_X (m)	UTM_Y (m)	Altitude (m a.s.l.)
Arezzo	730805	4815384	249
Boscolungo	633977	4888891	1340
Camaldoli	727025	4853030	1110
Castel del Piano	706920	4752060	596
Castelnuovo Garf.	613275	4885305	280
Elba Calamita	614306	4731893	380
Firenzuola	689640	4888022	454
Grosseto	669415	4735216	5
Livorno	606140	4822595	9
Lucca	620990	4855580	25
Massa	591800	4875450	38
Massa Marittima	653850	4768500	362
Montepulciano	726520	4774950	575
Orbetello	681025	4699970	1
Peretola	676985	4852101	38
Pisa	613017	4838671	3
Pistoia	653080	4867535	88
Pontremoli	570117	4913436	247
San Miniato	647740	4838630	132
Siena	687630	4799185	346
Vallombrosa	706000	4845450	972
Volterra	649965	4808235	465



Fig. 1. Meteorological station distribution in Tuscany.

In the first place, the dataset (period of 1955–2007) was verified as the GCOS (Global Climate Observing System) recommends: in order to avoid inhomogeneities or discontinuities in the climate record (caused by changes to the station, such as site location and instrumentation), time series were homogenized through the method described in *Brunetti et al.* (2006). After that, basic data exploration was carried out, considering absolute values and then differences between contiguous day values. Suspect values were coded as NA (not available). If neighboring stations with well correlated data were available, original suspect ones were reconstructed by statistical process. Afterwards, climatological mean and extreme temperature indices were selected in order to analyze climate and climatic variability. Climatic temperature indices were mean minimum (TN) and mean maximum temperature (TX). These indices were calculated both on seasonal and annual time scale. Extreme temperature indices were split in summer and winter and calculated only on the season when they showed effects. The summer period included June–August while winter period consisted in December–February. Selected summer extreme temperature indices were warm days and warm nights (*Manton et al.*, 2001; *Peterson et al.*, 2001; *Klein Tank and Können*, 2003; *Bartolini et al.*, 2008). For the winter period number of cold nights and number of days with minimum temperature lower than 0 °C (FD) were selected.

Concerning the potential impacts of climate change on grapevine, they were detected by applying agroclimatic indices such as growing degree days (GDD) related to the starting date of the most important phenological phases (bud-break, flowering, ripening) and expressed in doy (day of the year); length

of growing season with 0 °C threshold (VGS0), thermal summation with 10 °C threshold in the period March–September (STA10), thermal summation with 10 °C threshold in the period April–October (STA10 Winkler), and Huglin index. These are good indicators of the interactions between climate trend and the physiological needs. In fact, to detect bud break trigger it must be considered that each species need a specific heat quantity to activate the phenological stages. Huglin index, as GDD index, is used in viticulture to explain temperature availability in a specific area. In particular, high values of this index reveal suitable areas for grapevine with late maturation, while low values fit for early maturation varieties. Huglin index is estimated by making use of maximum and mean daily temperatures. *Table 2* shows all the selected indices with the acronyms.

Table 2. Climatic and agroclimatic indices

Acronym	Unit	Description
TN (a)	°C	Mean of minimum temperature (annual)
TN (sp)	°C	Mean of daily minimum temperature (spring: March–May)
TN (s)	°C	Mean of daily minimum temperature (summer: June–August)
TN (au)	°C	Mean of daily minimum temperature (autumn: September–November)
TN (w)	°C	Mean of daily minimum temperature (winter: December–February)
TX (a)	°C	Mean of daily maximum temperature (annual)
TX (sp)	°C	Mean of daily maximum temperature (spring: March–May)
TX (s)	°C	Mean of maximum temperature (summer: June–August)
TX (au)	°C	Mean of maximum temperature (autumn: September–November)
TX (w)	°C	Mean of maximum temperature (winter: December–February)
TN90p*	°C	Number of days with daily minimum temperature higher than 90 percentile (1961–1990) calculated in summer period (July–August)
TX90p*	°C	Number of days with daily maximum temperature higher than 90 percentile (1961–1990) calculated in summer period (July–August)
FD (a)	Days	Annual number of days with minimum temperature lower than 0 °C
GDD Bud break	Day	Date of bud break: It is the doy (day of the year) when the summation of the differences between the mean daily temperature and the threshold temperature (10 °C) reaches a specific value
GDD Flowering	Day	Date of grape flowering: It is the doy (day of the year) when the summation of the differences between the mean daily temperature and the threshold temperature (10 °C) reaches a specific value
GDD Ripening	Day	Date of grape ripening: It is the doy (day of the year) when the summation of the differences between the mean daily temperature and the threshold temperature (10 °C) reaches a specific value
HI	Degrees	Huglin index: Daily summation of the mean between maximum and mean temperature calculated during the growing season (March–September) multiplied by a latitude coefficient
STA10	°C	Thermal summation (10 °C threshold): Daily mean temperature summation in the growing period (March–September)
STA10 Winkler	°C	Thermal summation (10 °C threshold): Daily mean temperature summation in the growing period (April–October)
VGS0	Days	Vegetative growing season (0 °C threshold): Number of days between the last and first frost events of the year

Data were analyzed to test the normality of the distribution with the Shapiro-Wilk normality test. If normal, the linear trend was fitted, otherwise the Theil-Sen (*Theil*, 1950; *Sen*, 1968) non-parametric test was applied.

Parametric and non-parametric regression was fitted to each index and meteorological station. Regression slope was evaluated in order to detect trends and changes occurred over the considered period.

3. Results

Table 3 shows all the results for each analyzed index. Climatic temperature indices (TN and TX) show a tendency to increase. In particular, the increase of annual maximum temperature (+0.9 °C/50 years) was similar to that of minimum temperature. Seasonal analysis shows a much greater increase of minimum and maximum temperatures in summer (+1.5 °C/50 years; +1.7 °C/50 years, respectively) and spring season (+0.9 °C/50 years and +1.1 °C/50 years, respectively).

Table 3. Trends of the climatological indices of the 22 meteorological stations (1955–2007)

S	Index	n°	n	N°	NN°	m	m1	m*	m1*
22	TN (a)	22 ; 0	0	20 ; 0	19 ; 0	+0.8		+0.9	
22	TN (sp)	21 ; 1	0	12 ; 0	10 ; 0	+0.9		+1.1	
22	TN (s)	22 ; 0	0	20 ; 0	20 ; 0	+1.5		+1.6	
22	TN (au)	18 ; 4	0	6 ; 0	5 ; 0	+0.6		+1.3	
22	TN (w)	20 ; 2	0	4 ; 0	2 ; 0	+0.5		+1.8	
22	TX (a)	22 ; 0	0	21 ; 0	21 ; 0	+0.9		+0.9	
22	TX (sp)	22 ; 0	0	16 ; 0	15 ; 0	+1.1		+1.3	
22	TX (s)	22 ; 0	0	22 ; 0	21 ; 0	+1.7		+1.7	
22	TX (au)	16 ; 6	0	1 ; 1	0 ; 1	+0.1		-1.3	
22	TX (w)	22 ; 0	0	6 ; 0	5 ; 0	+0.9		+1.2	
22	TN90p*	22 ; 0	0	20 ; 0	20 ; 0		+1		+18
22	TX90p*	22 ; 0	0	20 ; 0	19 ; 0		+1		+13
22	FD (a)	3 ; 19	0	0 ; 5	0 ; 3		-5		-15
22	GDD Bud break*	7 ; 12	3	0 ; 4	0 ; 2		-3		-16
22	GDD Flowering*	2 ; 18	2	1 ; 15	0 ; 13		-7		-9
17	GDD Ripening*	0 ; 17	0	0 ; 14	0 ; 14		-19		-23
22	HI	22 ; 0	0	18 ; 0	17 ; 0	+273		+318	
22	STA10	20 ; 2	0	19 ; 0	17 ; 0	+203		+236	
22	STA10 Winkler	20 ; 2	0	19 ; 0	18 ; 0	+219		+252	
22	VGS0*	11 ; 6	5	4 ; 1	4 ; 1		+5		+15

Legend:

S – number of stations for which it was possible to calculate the trend,

(a) annual, (sp) spring, (s) summer, (au) autumn, (w) winter,

The asterisk means that Theil-Sen method was applied to calculate the slope (non-normal distribution),

n° – number of stations with positive and negative trend, respectively,

n – number of stations with slope = 0,

N° – number of stations with statistically significant coefficient ($p < 0.1$) with positive and negative trend, respectively,

NN° – number of stations with statistically significant coefficient ($p < 0.05$) with positive and negative trend, respectively,

m, m* – mean value of the regression coefficient for all the stations and mean value of the regression coefficient of the statistically significant stations ($p < 0.10$) ($^{\circ}\text{C}/50$ year), respectively,

m1, m1* – mean value of the regression coefficient for all the stations and mean value of the regression coefficient of the statistically significant stations ($p < 0.10$) (days/50 year), respectively.

For the indices acronyms see Table 2.

Extreme summer temperature (TN90p and TX90p) indices show a positive trend too. In particular, the occurrences of warm nights show a greater increase than warm days (+17 days/50 years vs. +12 days/50 years). The number of days with minimum temperature lower than 0°C (FD) highlights a slight decreasing trend.

Agroclimatological indices, in particular phenological phase indices, such as those referred to GDD, show an advanced tendency (Fig. 2). In particular, ripening phase shows a great advance tendency (-19 days/50 years).

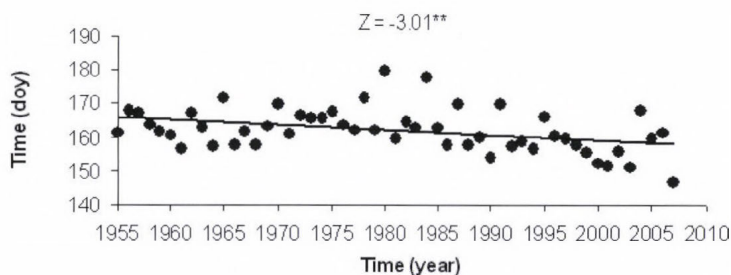


Fig. 2. Trend of the mean date of grapevine flowering for the 22 meteorological stations (1955–2007). ** = significance is greater than 99%; Z = standard normal distribution value; day = day of the year.

The Huglin index (Fig. 3), according to the great rise of spring and summer temperatures, shows a generalized increasing trend in all over the region with a mean regional increase of $273^{\circ}\text{C}/50$ years.

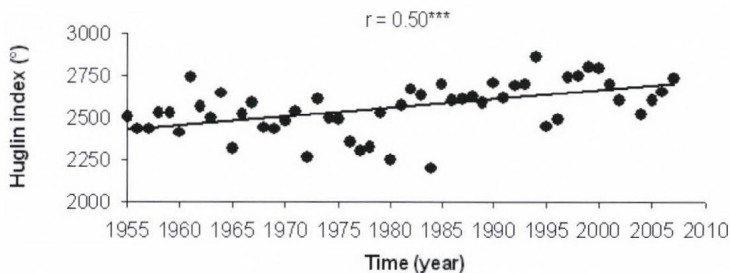


Fig. 3. Trend of the mean Huglin index for the 22 meteorological stations (1955–2007). *** = significance is greater than 99.9%; r = correlation coefficient.

Also STA10 (Fig. 4) and STA10 Winkler (Fig. 5) show positive trend (+203 °C/50 years and +219 °C/50 years, respectively). Vegetative growing season length with 0 °C threshold (VGS0) shows a slight positive trend (+5 days/50 year).

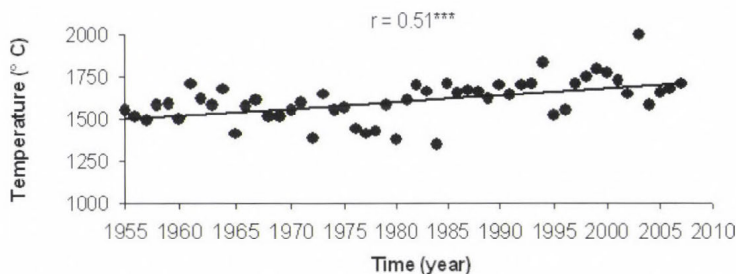


Fig. 4. Trend of the mean STA10 index for the 22 meteorological stations (1955–2007). *** = significance is greater than 99.9%; r = correlation coefficient.

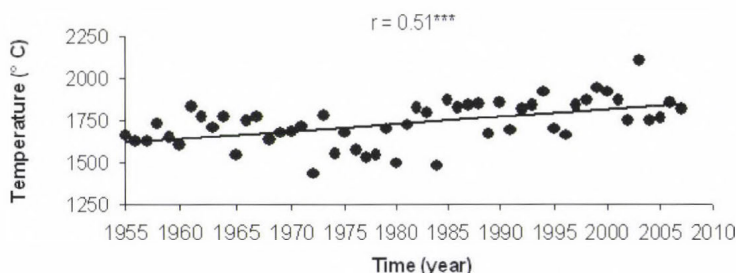


Fig. 5. Trend of the mean STA10 Winkler index for the 22 meteorological stations (1955–2007). *** = significance is greater than 99.9%; r = correlation coefficient.

4. Discussion and conclusions

The primary goal of this study was to assess Tuscany’s annual and seasonal climatic and agroclimatic trend patterns, in order to more accurately represent local climate complexities and its potential impacts on grapevine. Moreover, the results of this study show a significant warming trend and a general advance in phenological phases confirming the global trend.

As grape quality is influenced by the temperatures in spring and summer, the observed temperature increase can produce physiological water stress and photosynthesis inefficiency (Orlandini *et al.*, 2005). Higher temperature summation lead to higher sugar accumulation in berry (Gladstone, 1992), less acidity and greater mean berry weight (Fregoni, 2002). Higher minimum temperatures speed up grape phenological phases and the advanced ripening affects the quality.

Huglin index shows general suitable conditions for grape varieties coming from southern region. Although frost day's trend is negative, late frosts damage risks are not decreased due to phenological general anticipations.

A more detailed research concerning the interannual variability by using standard deviation and moving average is need to understand the potential impacts on grapevine quality. Moreover, rainfall analysis and correlations with rising temperature may be useful to completely show the climate change effects on regional scale.

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Testing different CO₂ response algorithms against a face crop rotation experiment and application for climate change impact assessment at different sites in Germany

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Abstract—In regional studies the effect of elevated CO₂ level on crop biomass and yield had not been considered in most cases, although several approaches were described in literature. Different algorithms describing CO₂ response on crop growth and crop water use efficiency have been integrated in the soil-crop model HERMES. The approaches are different in complexity and parameter requirement. Their suitability to explain crop growth responses and soil water dynamics observed in a six-year agricultural crop rotation (winter barley, sugar beet, winter wheat) under elevated atmospheric CO₂ level in a FACE experiment was tested. All algorithms were able to describe an observed increase in above-ground dry matter for all crops in the rotation. Increasing water use efficiency with rising CO₂ was also reflected. A combination of a semi-empirical Michaelis-Menten approach describing a direct impact of CO₂ on photosynthesis and a Penman-Monteith approach with a simple stomata conduction model for evapotranspiration yielded the best simulation result expressed by model performance indicators. Scenario simulations with and without CO₂ effect were performed for different sites in Germany for the present situation and the SRES-A1B scenario using statistically downscaled climate change scenarios from the WETTREG model. Results show that without consideration of the CO₂ effect mostly negative impacts on crop yields were simulated. Considering the CO₂ effect compensated the negative trend in most cases and turned yield effects to a positive impact.

Key-words: climate change, CO₂ effect, FACE experiment, crop yield, water use

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1. Introduction

Climate change impact on food production is one of the key concerns of policy and research. Impact assessment usually requires spatial and temporal resolutions smaller than provided by the global climate models (GCM), since crop growth is temporarily very sensitive, e.g., to radiation, temperature, soil moisture. Regional climate models (Jacob *et al.*, 2007) downscale the GCM results to a meso-climate level that can be used to assess climate effects on regional agriculture.

Climate change is expected to affect crop growth mainly by increasing temperatures, shifting distribution of precipitation, changing amount of precipitation, and rising atmospheric carbon dioxide concentration.

Describing the interactions of crop growth, soil processes, and weather variables in a simulation model is current state-of-art methodology to interpret downscaled GCM outputs for yield predictions. The effect of CO₂ on crop growth was recently implemented in agro-ecosystem models. Mainly two processes are affected: (i) in C3 plants, an increasing CO₂ would directly increase the photosynthesis rate (Gaastra, 1959) and (ii) a higher CO₂ would also lead to a decrease in stomatal conductance and thus to a higher water use efficiency (Manderscheid and Weigel, 2007).

The impact of CO₂ on photosynthesis has been included in simulation models in different ways (Tubiello and Ewert, 2002). More simple approaches use an empirical relation between CO₂ and a crop specific radiation use efficiency (RUE) factor (e.g., Bindi *et al.*, 1996), others employ a CO₂ dependency of the photosynthesis-light response curve (e.g., Porter, 1993; Goudriaan and van Laar, 1994). Only few leaf-level biochemical algorithms are used, which require an extensive parameterization restricting their application to biochemical process research.

In this study, we integrated a number of selected algorithms into the soil-crop model HERMES to test their suitability to describe CO₂ impact on crop growth against data of a Free Air Carbon Enrichment (FACE) experiment (Weigel and Dämmgen, 2000). The best algorithm was then used in combination with downscaled climate change scenarios for simulations at different sites in Germany under the SRES-A1B scenario. Site selection considered locations with different climatic situations to demonstrate the combined climate change and CO₂ effect on crop yields of winter wheat.

2. Material and methods

2.1. The FACE experiment

At the experimental station of the von Thünen-Institute (vTI) at Braunschweig, Germany (52°18'N; 10°26'E), a three-year crop rotation (winter barley, sugar

beet, winter wheat) was grown over two cycles at normal (~374 ppm) and elevated (~550 ppm) CO₂ levels. The crops were grown under optimum nutritional and moisture conditions. A FACE system, consisting of six rings with 20 m diameter was set up. Treatments included two rings equipped with blowers and enriched with CO₂, two rings operated with blowers and ambient air only and two rings without blowers. Subplots within the rings with 50% (N50) of the adequate nitrogen supply (N100) were established to study interactions between C and N. A detailed description is given by *Weigel and Dämmgen* (2000).

The soil is a loamy sand with 1.4% organic carbon (SOC) in the top soil. Soil texture allows a volumetric plant available water content (PAWC) of about 18% in the plough layer, which decreases slightly with increasing profile depth. Rooting depth is about 60 cm. During the experiment, soil moisture contents were determined gravimetrically. Fresh and dry weights of individual plant organs (culm, leaves, and ears, or tubers, respectively) were measured at intermediate harvests. At the final harvest, cereal grain yield was additionally quantified. Daily weather data were recorded at a nearby weather station.

2.2. *The model framework*

We tested the different CO₂ response algorithms within the HERMES model, which was designed to simulate crop growth, water and nitrogen uptake, and the nitrogen dynamics in the soil for applied purposes. This implies simple and robust model approaches, which are able to operate under restricted data availability. A more detailed description of the model is provided by *Kersebaum* (2007). Therefore, the characteristics of the model are described only briefly.

A capacity approach was used to describe soil water dynamics. The reference evapotranspiration was calculated using the Penman-Monteith method according to *Allen et al.* (1998). Crop specific potential evapotranspiration is calculated using crop specific factors (*kc*) during the growing season, which were linked to the developmental stages of the crops, and bare soil factors between harvest and crop emergence. Nitrogen mineralization and denitrification are simulated depending on temperature and soil moisture and nitrate content respectively.

Crop growth follows a generic approach, which is based on the SUCROS model. Daily net dry matter production by photosynthesis and respiration is driven by global radiation and temperature. Assimilates are partitioned depending on crop development stage, which is calculated from a thermal sum (degree-days) and modified, if applicable, by day length and vernalization. Root dry matter is distributed exponentially over depth with the rooting depth increasing with the thermal sum. Water and nitrogen uptake is calculated from potential evaporation and crop N status, depending on the simulated root distribution, and water and N availability in different soil layers. Crop growth is limited by water and N stress. Water and nitrogen stress accelerates crop

ontogenesis for specific development stages. Crop yield was estimated at harvest from the weight of the storage organ.

The HERMES model was calibrated to the data of the control treatment of the FACE experiment, using the output variables soil moisture (sum of 0–60 cm soil depth), above-ground crop dry matter, and yield. Willmott's index of agreement (IoA) was used as a goodness-of-fit criterion (Willmott, 1981).

2.3. The CO₂ response algorithms

In order to equip the model with a suitable approach to describe CO₂ impact on crop growth, three algorithms were selected. The mechanistic and partly empirical character of the HERMES model determines the range of complexity the response algorithms have to match. The following approaches were selected:

(I) The Mitchell approach (Mitchell *et al.*, 1995) used a set of algorithms based on the ideas of Farquhar and von Caemmerer (1982) and Long (1991), calculating the maximum photosynthesis rate

$$A_{\max} = \frac{(C_i - \Gamma^*) \cdot V_{c\max}}{C_i + K_c \cdot \left(1 + \frac{O_i}{K_o}\right)}, \quad (1)$$

where C_i and O_i are the intercellular CO₂ and O₂ concentrations, respectively, Γ^* is the CO₂ compensation point of photosynthesis in absence of dark respiration, $V_{c\max}$ is the maximum Rubisco saturated rate of carboxylation, and K_c and K_o are Michaelis-Menten constants for CO₂ and O₂. The calculation of the latter four parameters is carried out according to Long (1991). Some modifications were applied to simplify the algorithms for suboptimal light conditions and light use efficiency.

(II) The Nonhebel approach is a much simpler approach extracted from the SUCROS87 model (Nonhebel, 1996). Here, RUE is directly affected by CO₂ as

$$RUE_{CO_2} = \left(\frac{C_a - \Gamma}{C_a + 2\Gamma} \right) \cdot E_0, \quad (2)$$

where C_a denotes CO₂ and E_0 the quantum use efficiency. Additionally, the maximum photosynthesis rate is influenced by CO₂ using

$$A_{\max(CO_2)} = \frac{C_a - \Gamma}{350 - \Gamma} \cdot A_{\max(350)}. \quad (3)$$

(III) The Hoffmann approach (Hoffmann, 1995) was similar to Nonhebel (1996) based on his own work with sugar beet and tree species, and on data previously obtained by Gaastra (1959). He adjusted A_{\max} by the factor

$$K_{CO_2} = \frac{\frac{C_a - \Gamma^*}{k_1 + C_a - \Gamma^*}}{\frac{C_{a0} - \Gamma^*}{k_1 + C_{a0} - \Gamma^*}}, \quad (4)$$

where C_{a0} denotes the ambient CO_2 and C_a the elevated CO_2 . Furthermore, $k_1 = 220 + 0.158 \cdot I_g$ and $\Gamma^* = 80 - 0.0036 \cdot I_g$, with I_g being the global radiation.

These three approaches were combined with a mixed Allen/Yu approach describing the CO_2 impact on crop transpiration. Evapotranspiration was calculated using the Penman and Monteith formula according to Allen *et al.* (1998) using the stomata resistance calculated as suggested by Yu *et al.* (2001) as

$$r_s = \frac{C_s \left(1 + \frac{D}{D_0} \right)}{a \cdot A_g}, \quad (5)$$

where a is a constant, A_g denotes the gross photosynthesis rate, D/D_0 describes the air water vapor deficit, and C_s is the ambient CO_2 concentration at leaf level, which was set equal to C_a in this case. D_0 and a were used for parameter calibration.

2.4. Model behavior under climate change scenarios

To demonstrate the combined effect of climate change and elevated CO_2 on wheat production, we selected 4 weather stations across Germany to cover the different climatic and soil conditions. The climate change scenarios were based on the SRES-A1B scenario and the output of the global climate model (GCM) ECHAM5/MPI-OMT63L31. The GCM output was downscaled using a statistical generation of classified weather situation sequences based on a data analysis of long term historical data of single meteorological stations by the WETTREG model (Enke *et al.* 2005). We selected 3 realizations (normal, wet, dry) for wetness for the period from 1961 to 2050. We used the time slice 1970–1989 as reference period and the time slice 2031–2050 for the projected future.

For each site, a typical soil profile was used. The characterization of the sites including the soil class, elevation, and the climatic conditions of the reference, as well as projected period are given in Table 1.

Table 1. Site characteristics and climatic changes estimated for the A1B scenario using the WETTREG model (Enke *et al.*, 2005) for selected locations across Germany. Numbers in parenthesis are changes in %

Station	Period	Hannover	Müncheberg	Hof	Weihenstephan
Latitude		52°28'N	52°52'N	50°19'N	48°24'N
Longitude		9°42'E	14°07'E	11°53'E	11°42'E
Altitude (a.s.l.)		55 m	62 m	567 m	470 m
Annual mean temperature (°C)	1970–1989	9.3	8.8	6.8	7.8
	2031–2050	10.1 (+8.8)	9.4 (+7.3)	7.5 (+10.8)	8.6 (+10.9)
Annual precipitation (mm)	1970–1989	628	533	739	726
	2031–2050	596 (-5.1)	506 (-5.1)	713 (-3.5)	679 (-6.5)
Precipitation winter (DJF) (mm)	1970–1989	156	131	182	118
	2031–2050	158 (+1.4)	121 (-7.6)	195 (+7.3)	133 (+12.9)
Precipitation spring (MAM) (mm)	1970–1989	195	166	221	202
	2031–2050	188 (-3.4)	165 (-0.9)	229 (+3.6)	213 (+5.6)
Precipitation summer (JJA) (mm)	1970–1989	181	165	230	272
	2031–2050	167 (-7.9)	160 (-3.0)	220 (-4.4)	229 (-5.8)
Precipitation autumn (SON) (mm)	1970–1989	146	113	166	174
	2031–2050	133 (-9.1)	98 (-13.5)	135 (-8.8)	146 (-6.2)
Soil		sandy loam	sand	sandy loam	silty loam

DJF = December, January, February; MAM = March, April, May; JJA = June, July, August; SON = September, October, November

3. Results and discussion

The Braunschweig FACE experiment showed two important results: increased CO₂ (i) enhanced crop growth for all investigated species and (ii) decreased evapotranspiration rate of the canopies resulting in higher soil moisture content (Weigel *et al.*, 2006). All algorithms tested within the HERMES model framework were able to describe the observed crop growth and soil moisture dynamics sufficiently under ambient and elevated CO₂ levels (Table 2). Since the Nonhebel and Mitchell approaches also affected the way of calculating photosynthesis under ambient CO₂ conditions, the simulation of the control treatment process yielded different results for all selected approaches. IoA yielded values of between 0.93 and 0.99 for the calibrated simulation of above ground dry matter (including tubers for sugar beet) and yield at sufficient N supply. Fig. 1 shows the results using the combined Hoffmann/Yu/Allen approach. However, under limited N supply and under elevated CO₂ level the simulation performance was similar. For these variables, the Nonhebel approach performed slightly less satisfyingly than the others (Table 2). Such a

performance is often found for single season crop growth simulations. However, for a six years rotation with three different crops this result is satisfying.

Table 2. Index of agreement IoA (Willmott, 1981) as a goodness-of-fit criterion for the simulation of the crop rotation experiment, using different approaches for the description of CO₂ impact on crop growth

CO ₂ level	ppm	Ambient		550		Ambient		550	
		100	50	100	50	100	50	100	50
		Hoffmann				Hoffmann + Allen/Yu			
Above ground dry matter		0.99	0.98	0.99	0.99	0.99	0.99	0.99	0.99
Yield		0.98	0.96	0.97	0.94	0.98	0.98	0.97	0.97
Leaf area index		0.61	0.55	0.57	0.54	0.57	0.55	0.61	0.56
Soil moisture (0-60 cm)		0.77		0.76		0.79		0.82	
Mean IoA		0.83				0.84			
		Nonhebel				Nonhebel + Allen/Yu			
Above ground dry matter		0.95	0.94	0.98	0.96	0.95	0.99	0.98	0.98
Yield		0.93	0.94	0.95	0.93	0.93	0.94	0.95	0.92
Leaf area index		0.66	0.58	0.55	0.52	0.66	0.59	0.55	0.54
Soil moisture (0-60 cm)		0.77		0.77		0.85		0.85	
Mean IoA		0.82				0.83			
		Mitchell				Mitchell + Allen/Yu			
Above ground dry matter		0.99	0.95	0.99	0.99	0.99	0.95	0.99	0.99
Yield		0.98	0.98	0.97	0.96	0.97	0.97	0.97	0.96
Leaf area index		0.52	0.49	0.51	0.49	0.52	0.50	0.52	0.50
Soil moisture (0-60 cm)		0.78		0.78		0.80		0.83	
Mean IoA		0.81				0.82			

The simulation of soil moisture was compared to aggregated data (0–60 cm soil depth) and showed an IoA of 0.82 for calibrated conditions and 0.79–0.80 under elevated CO₂. When the CO₂ effect on transpiration was taken into account additionally, the overall performance improved slightly (Table 2) due to the better performance of the soil moisture simulation for all approaches (Fig. 1c). On the basis on above ground dry matter, yield, and soil moisture simulation, the Hoffmann approach in combination with the Allen/Yu approach performed best. However, the differences were marginal. Fig. 1c shows the measured and simulated soil water content under winter wheat in 2005 for ambient and elevated CO₂ level. The difference between the two CO₂ treatments expressed as the sum over six years corresponded well with the observed mean difference of approximately 20 mm water per year.

Application of the model with and without the combined Hoffmann/Yu/Allen approach for 4 selected sites in Germany shows different responses of crop yield to the projected climate change (Fig. 2). Without consideration of the CO₂ effect, only the site at Hof shows a beneficial trend for the wheat yield, because this elevated site is presently temperature limited. Therefore, crops would benefit from warming since precipitation is still

sufficient. At the other sites, climate change without CO₂ would have a negative impact on crop yield mainly due to decreasing summer precipitation. Introducing the CO₂ effect in the model simulations in most cases leveled out the negative trend. Only at Müncheberg, the combination of poor sandy soil and very low precipitation could not be compensated completely by the CO₂ effect. Similar results for sites in Austria were published by *Alexandrov et al. (2002)*. Separating the indirect from the direct CO₂ effect by switching off only the indirect effect shows, e.g., for the site at Hannover, that the indirect effect through the modified transpiration accounts for 2/3 of the total CO₂ effect simulated by the combined approach. The sites were selected exemplarily and neither represent wheat production areas in Germany nor give a representation of the whole specific regions, since they are only examples of one selected typical soil of the region.

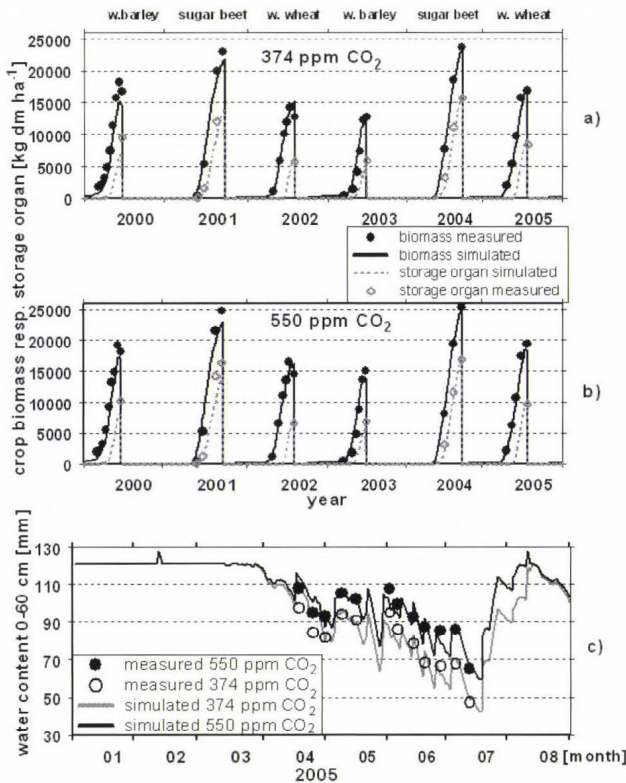


Fig. 1. Measured and simulated crop biomass (excluding root biomass) and storage organ mass of the Braunschweig FACE experiment for (a) 374 ppm CO₂ concentration, (b) 550 ppm CO₂ concentration, and (c) soil water contents (0–60 cm) under winter wheat in 2005 in the 374 and 550 ppm plots (100% N treatment, simulation using the combined Hoffmann/Yu/Allen approach).

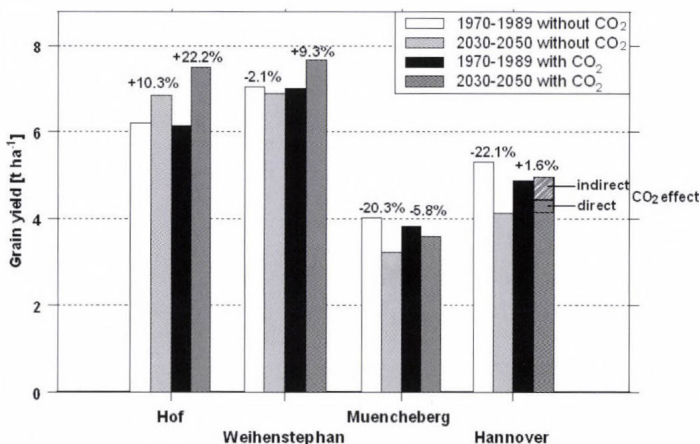


Fig. 2. Simulated impact of climate change scenario SRES-A1B on grain yield of winter wheat on selected sites across Germany with and without consideration of the CO₂ effect (combined Hoffmann/Yu/Allen approach).

4. Conclusions

For the simulation of expected climate change effects on regional agriculture an algorithm was found to successfully describe combined effects CO₂ levels, temperature, and moisture regime in a typical agricultural crop rotation in Germany. Application for 4 selected sites across Germany revealed that the simulated negative effect due to decreasing summer precipitation can be compensated in most cases if the combined CO₂ effect is considered. While sites at high elevation will benefit from global warming, the combination of poor sites and summer drought conditions resulted in yield reduction, which cannot be leveled out by the CO₂ effect.

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Climate change mitigation, adaptation, and sustainability in agriculture

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Abstract—Sustainability conveys the idea of a balance between human needs and environmental concerns. A common theme amongst definitions of sustainability is that sustainable agricultural systems remain productive over time. They should provide for the needs of current, as well as future generations, while conserving natural resources. The enhancement of environmental quality and careful use of resource base on which agriculture depends is viewed as a requisite for sustained agricultural productivity. The notion that sustainable agricultural systems maintain output in spite of major disturbances, e.g., such as those caused by projected climate change, is relevant to vulnerable areas, especially in the semi-arid and sub-humid regions of developing countries.

According to the Fourth Assessment Report of the WMO/UNEP Intergovernmental Panel on Climate Change (IPCC) released in 2007, semi-arid regions of Asia, Africa, and Latin America are likely to warm during this century, and freshwater availability is projected to decrease. Agricultural productivity in tropical Asia is sensitive not only to temperature increases, but also to changes in the nature and characteristics of monsoon. In the semi-arid tropics of Africa, which are already having difficulty coping with environmental stress, climate change resulting in increased frequencies of drought poses the greatest risk to agriculture. In Latin America, agriculture and water resources are most affected through the impact of extreme temperatures and changes in rainfall.

Climate change mitigation strategies which include interventions to reduce the sources or enhance the sinks of greenhouse gases have a marked management component aiming at conservation of natural resources such as improved fertilizer use, improved ruminant digestion, use of water harvesting, and conservation techniques. These strategies are equally consistent with the concept of sustainability. Adaptation strategies include initiatives and measures to reduce the vulnerability of agroecosystems to projected climate change, such as changing varieties, altering the timing or location of cropping activities, improving the effectiveness of pest, disease and weed management practices, making better use of seasonal climate forecasts, etc. It is essential to develop and integrate agriculture mitigation and adaptation frameworks for climate change into sustainable development planning at the national and regional levels to cope with the projected impacts of climate change.

Key-words: mitigation strategies, adaptation strategies, IPCC, mitigation and adaptation frameworks

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1. Introduction

Climate change, a key global biophysical indicator, is widely accepted as the single most pressing issue facing society on a global basis, and the growing awareness of the impacts of climate change on agriculture is forcing decision makers to refocus on the sustainability of agricultural production. Broad concepts in sustainable agriculture encompass ecological, economic, and social parameters, whereas more narrowly defined concepts are mostly concerned with environmental issues such as optimal resource and environmental management (*McCracken and Pretty, 1990*). The notion that sustainable agricultural systems “maintain output in spite of major disturbance, such as caused by intensive stress or large perturbation” (*Conway, 1985*) is of particular relevance in the current concerns with the possible impacts of climate change on agroecosystems.

2. Observed climate change

The Intergovernmental Panel on Climate Change (IPCC) was established in 1988, by the World Meteorological Organization (WMO) and the United Nations Environment Program (UNEP), to assess scientific information on climate change, as well as its environmental and socioeconomic impacts, and to formulate response strategies. Climate change is defined by the IPCC as any change in climate over time, whether due to natural variability or as a result of human activity (*IPCC, 2007b*). Evidence from observations of the climate system has led to the conclusion that human activities are contributing to a warming of the Earth’s atmosphere. This evidence includes an increase of 0.74 ± 0.18 °C in global average surface temperature over the last century, and an even greater warming trend over the last 50 years than over the last 100 years. Eleven years of the 12-year period between 1995 to 2006 are among the 12 warmest years since the instrumental record of global surface temperature was started in 1850 (*IPCC, 2007b*). Furthermore, higher temperatures along with decreased precipitation have been associated with observations of more intense and longer droughts over wider areas since the 1970s.

Changes in climate have also been manifested in altered precipitation patterns. Over the last century, the amount of precipitation has increased significantly across the eastern parts of North America and several other regions of the world (*IPCC, 2007b*). Many land areas have likely experienced an increase in the number and intensity of heavy precipitation (5 cm of rain or more) events (*IPCC, 2007b*). About half of the increase in total precipitation observed nationally in the United States has been attributed to the increase in intensity of storms (*Karl and Knight, 1998*).

During the 20th century, the changes in temperature and precipitation described above caused important changes in hydrology over large regions. One change was a decline in spring snow cover. This trend was observed throughout

the Northern Hemisphere starting in the 1920s and accelerated in the late 1970s (*IPCC*, 2007b). Less snow generally translates to lower reservoir levels. The earlier onset of spring snowmelt exacerbates this problem. Snowmelt started 2–3 weeks earlier in 2000 than it did in 1948 (*Stewart et al.*, 2004).

Another manifestation of changes in the climate system is a warming in the world's oceans. The global ocean temperature rose by 0.10 °C from the surface to 700 m depth from 1961 to 2003 (*IPCC*, 2007b). Warming causes seawater to expand and thus contributes to sea level rise. This factor, referred to as thermal expansion, has contributed 1.6 ± 0.5 mm per year to global average sea level over the last decade (1993–2003). Other factors contributing to sea level rise over the last decade include a decline in mountain glaciers and ice caps (0.77 ± 0.22 mm per year), losses from the Greenland ice sheets (0.21 ± 0.07 mm per year), and losses from the Antarctic ice sheets (0.21 ± 0.35 mm per year) (*IPCC*, 2007c).

Other observations at smaller geographic scales lend evidence that the climate system is warming. For example, in the Arctic, average temperatures have increased and sea ice extent has shrunk (*IPCC*, 2007b).

3. *Future climate change*

Climate change projections indicate it to be very likely that hot extremes, heat waves, and heavy precipitation events will continue to become more frequent. Looking ahead, the *IPCC* (2007a) expects the warming in the 21st century to be greatest over land and at the highest northern latitudes. For the next two decades a warming of about 0.2 °C per decade is projected. Increases in the amount of precipitation are very likely in high latitudes, while decreases are likely in most subtropical land regions. For many parts of Africa the length of the growing period is projected to decrease over time (*Thornton et al.*, 2006) and projected losses in yield amount to 50% by 2020 for some countries (*IPCC*, 2007a).

Annual average river runoff and water availability are projected to increase by 10–40% at high latitudes and in some wet tropical areas, and decrease by 10–30% over some dry regions at mid-latitudes and in the dry tropics. The areas suitable for rainfed agriculture are expected to significantly decrease affecting adversely the land productivity potential of the continent (*Fischer et al.*, 2002).

4. *Climate change impacts*

An emerging but growing body of literature indicates that over the past three decades, the changes in the climate system described above—including the anthropogenic component of warming—have caused physical and biological changes in a variety of ecosystems (*Root et al.*, 2005; *Parmesan*, 2006; *IPCC*, 2007a) that are discernable at the global scale. These changes include shifts in genetics (*Bradshaw and Holzapfel*, 2006; *Franks et al.*, 2007), species' ranges,

phenological patterns, and life cycles (reviewed in *Parmesan*, 2006). Most (85%) of these ecological responses have been in the expected direction (e.g., poleward shifts in species distributions), and it is very unlikely that the observed responses are due to natural variability alone (*IPCC*, 2007a).

Croplands, pastures, and forests that occupy 60 percent of the Earth's surface are progressively being exposed to threats from increased climatic variability and climate change. Abnormal changes in air temperature and rainfall and resulting increases in frequency and intensity of drought and flood events have long-term implications for the viability of these ecosystems (*FAO*, 2007).

IPCC (2007a) detailed many impacts on global and regional agriculture which impacts depend on the specific location and the magnitude of the warming.

- In general, the report states that increases in the frequency of droughts and floods are projected to affect local crop production negatively, especially in subsistence sectors at low latitudes.
- Globally, the potential for food production is projected to increase with increases in local average temperature over a range of 1–3 °C, but above this range, food production is projected to decrease.
- At lower latitudes, especially in the seasonally dry and tropical regions, crop productivity is projected to decrease for even small local temperature increases (1–2 °C), which would increase risk of hunger.
- Crop productivity is projected to increase slightly at mid- to high latitudes for local mean temperature increases of up to 1–3 °C depending on the crop, and then decrease beyond that in some regions.
- With the virtually certain likelihood of warmer and more frequent hot days and nights, there are projected to be increased insect outbreaks impacting agriculture, forestry, and ecosystems.
- Adaptations such as altered cultivars and planting times allow low- and mid- to high-latitude cereal yields to be maintained at or above baseline yields for modest warming.

They are too many region-specific climate change impacts on agricultural production to describe. For example, in many parts of Africa, it seems that warmer climates and changes in precipitation will destabilize the agricultural production. This is expected to undermine the systems that provide food security (*Gregory et al.*, 2005). *IPCC* (2007a) indicates that crop yields could decrease up to 30% in South Asia by the end of the century even if the direct positive physiological effects of CO₂ are taken into account. Several global studies indicate a probability of 10–40% loss in crop production in India with increases in temperature by 2080–2100 (*Rosenzweig et al.*, 1994; *Fischer et al.*, 2002; *Parry et al.*, 2004). From an analysis of climate risks for crops in 12 food-insecure regions conducted to identify adaptation priorities, based on statistical

crop models and climate projections for 2030 from 20 general circulation models, *Lobell et al.* (2008) conclude that South Asia and Southern Africa are two regions that, without sufficient adaptation measures, will likely suffer negative impacts on several crops that are important to large food-insecure human populations.

In the Atlantic south, Continental south and Mediterranean zones of Europe, the greatest risks are reduced crop yields and conflicts over reduced water supply (*AEA Energy and Environment*, 2007). But in the Alpine, Boreal, Atlantic, and Continental north agro-climatic zones, a lengthened growing season and an extension of the frost-free period may increase the productivity of some crops and enhance the suitability of these zones for the growth of other crops. However, these changes will only be possible if there is sufficient water available (*AEA Energy and Environment*, 2007). Climate change is affecting many species attributes, ecological interactions, and ecosystem processes. Habitat change is already underway in some areas, leading to species range shifts, changes in plant diversity which includes indigenous foods and plant-based medicines (*McClellan et al.*, 2005).

5. Climate change and sustainability

Sustainable agricultural systems remain productive over time (*Senanayake*, 1991) and should provide for the needs of current, as well as future generations, while conserving natural resources (*NRC*, 1991). The enhancement of the environmental quality and careful use of the resource base on which agriculture depends is viewed as a requisite to sustained agricultural productivity (*ASA*, 1989).

One important environmental force is climate, which can change over the long term and whose variation (with or without climatic change) has major implications for farming and sustainability. Agriculture's sensitivity to climate is influenced both by the nature of climatic variation and the nature of farming. Disasters are "caused" by the juxtaposition of a vulnerable activity and particular climatic conditions. For example, lack of economic activity and poverty renders African countries, especially the poorest communities in these countries, disproportionately vulnerable to climate change impacts.

The issues of climate change and sustainability have become well known worldwide, following the adoption of the United Nations' Agenda 21 and the United Nations Framework Convention on Climate Change (UNFCCC) at the 1992 Earth Summit in Rio de Janeiro, Brazil. Development, equity, and sustainability are integral elements of sustainable development. Hazards associated with climate change have the potential to undermine progress with sustainable development (*Berke*, 1995; *Wang'ati*, 1996). Therefore, it is important for sustainable development initiatives to explicitly consider hazards and risks associated with climate change (*Apuuli et al.*, 2000). The capacity to

mitigate and adapt to climate change, and the associated mitigation and adaptation costs, depend critically upon the underlying development path, which in turn would be significantly influenced by sustainable development policies and actions.

Swart et al. (2003) point out that climate change and sustainable development have been addressed in largely separate circles in both research and policy. Nevertheless, there are strong linkages between the two in both realms. They argue that since the feasibility of stabilizing greenhouse gas concentrations is dependent on general socio-economic development paths, climate policy responses should be fully placed in the larger context of technological and socio-economic policy development rather than be viewed as an add-on to those broader policies.

Robinson et al. (2006) argue that manifold linkages exist between climate change and sustainable development, and that the focus has typically been on examining sustainable development through a climate change lens, rather than vice versa. They refer to the work of a panel of business, local government, and academic representatives in British Columbia, Canada, who were appointed to advise the provincial government on climate change policy. The panel found that sustainable development may offer a significantly more fruitful way to pursue climate policy goals than climate policy itself. Hence it is important to understand clearly the concept of sustainable agriculture and how it might help in coping with the projected climate change.

6. Climate change mitigation and adaptation

Climate change adaptation includes both short- and long-term responses to climate change, whereas mitigation refers to methods of reducing greenhouse gas emissions.

6.1. Climate change mitigation

When the topic of climate change is usually discussed, the focus is on the impact of the future climate changes on the agricultural sector. However, there is another aspect of climate change and agriculture, and that is the contribution of GHG emissions from agricultural sources (*Das, 2004; Desjardins, 2004; Smith et al., 2007; Desjardins et al., 2007*). According to the IPCC AR4, agriculture accounted for 10–12% (5.1 to 6.1 Gt CO₂-eq/yr) of total global anthropogenic emissions of greenhouse gases GHGs (*Smith et al., 2007*). In separating the contribution from each GHG, agriculture accounted for about 60% of global anthropogenic emissions of N₂O and about 50% of CH₄.

Table 1 shows the percentage of world GHG emissions from agriculture by source in 2000 (*Vergé et al., 2007*). This analysis for this table focused only on

methane and nitrous oxide emissions. *Vergé et al.* (2007) state that carbon dioxide emissions from agriculture are mainly due to changes in land use such as clearing forests for agricultural development. Nitrous oxide emissions from agricultural soils represent the largest source of GHG emissions from agriculture. Nitrous oxide is produced in the soil during the process of converting ammonia to nitrate (nitrification) by soil microbes and by the conversion of nitrate into gaseous nitrogen (denitrification). Methane emissions by enteric fermentation (by-product of livestock digestion) is the second largest, and methane emissions from the fermentation of decomposing organic matter from rice paddies is the third. These three sources account for 86.2% of the GHG emissions from global agriculture. Globally, agricultural CH₄ and N₂O emissions have increased by nearly 17% from 1990 to 2005 (*Smith et al.*, 2007).

Table 1. Percentage of world GHG emissions from agriculture by source in 2000 excluding CO₂ (*Vergé et al.*, 2007)

Source	World GHG emissions from agriculture (%)
Agricultural soils (N ₂ O)	41.4
Enteric fermentation (CH ₄)	30.1
Rice (CH ₄)	14.7
N fertilizers (N ₂ O)	7.3
Manure management (CH ₄)	3.4
Manure storage (N ₂ O)	3.1

6.1.1. Mitigation strategies

The IPCC AR4 (*Barker et al.*, 2007) defines mitigation as the technological change and substitution that reduces resource inputs and emissions per unit of output. Although several social, economic and technological policies would produce a reduction in emissions with respect to climate change, the term mitigation is defined as implementing policies to reduce GHG emissions and enhance sinks. The IPCC AR4 Working Group III Chapter on Agriculture (*Smith et al.*, 2007) noted that the most prominent mitigation options of GHG emissions in agriculture are improved crop and grazing land management such as improved agronomic practices, nutrient use, tillage, and residue management, restoration of organic soils that are drained for crop production, and restoration of degraded lands. Other options that offer significant mitigation potential include improved water and rice management; set-asides, land use change such as the conversion of cropland to grassland and agro-forestry; as well as improved livestock and manure management. The AR4 chapter on agricultural mitigation stresses that a practice effective in reducing emissions at one location may be less effective or even counterproductive elsewhere. Therefore, there is

no universally applicable list of mitigation practices and that practices need to be evaluated for individual agricultural systems based on climate, soil, social issues, and historical patterns of land use and management.

Most of the mitigation strategies involve reducing nitrous oxide and methane emissions in agriculture. With regards to reducing CO₂ emissions in agriculture, increasing energy efficiencies in the transportation and building sector are important, but soil carbon sequestration is a mitigation strategy in which agriculture can directly play a significant important role. The IPCC (*Smith et al.*, 2007) stated that soil carbon sequestration can provide an estimated 89% contribution to the total mitigation potential, while mitigation of CH₄ emissions and N₂O emissions from soils only account for 9% and 2%, respectively, of the total.

Desjardins (2004) provided an overview of agricultural practices to reduce GHG which include the following categories: livestock management; animal waste and nutrient management; crop management; soil management; and energy. *Edwards* (2007) notes that organic agricultural practices can reduce GHG emission in agriculture. These practices include the systematic application of manure and compost from animal and crop residues; crop-legume rotations; green manure with legumes; and agroforestry with multipurpose leguminous trees.

The AR4 report noted that the interactions between mitigation and adaptation in the agricultural sector need to be examined but differ in their spatial and geographic characteristics (*Smith et al.*, 2007). The report goes on to state that in many regions, non-climate policies related to economics, agriculture, and environment will have a larger impact on agricultural mitigation than climate policies. Also, current GHG emission rates may increase due to future population growth and changing diets. The report concluded that there is significant potential for GHG mitigation in agriculture and that current initiatives suggest that synergies between climate change policies, sustainable development, and improvement of environmental quality will be in the forefront in realizing mitigation potential in agriculture.

6.2. *Climate change adaptation*

As described earlier, climate change is expected to present new combinations of risks and potentially grave consequences. The secondary changes induced by climate change are expected to undermine the ability of people and ecosystems to cope with extreme climate events and other natural hazards. According to *Thomas* (2008), the world's drylands will face not only increasing temperatures with climate change but more importantly also disruptions to their hydrological cycles resulting in less and more erratic rainfall that will exacerbate the already critical state of water scarcity and conflicts over water allocation. In many regions of Africa, where small farmers depend on natural environment for their livelihoods, the high levels of poverty combined with rather poor infrastructure

increases the vulnerability of local communities to climate change. Adaptation is a key factor that will shape the future severity of climate change impacts on food production (*Easterling et al., 2007*) and is most relevant when it influences decisions that exist irrespectively of climate change, but which have longer-term consequences (*Stainforth et al., 2007*).

According to *FAO (2007)*, the two main types of adaptation are autonomous and planned adaptation. Autonomous adaptation is the reaction of, for example, a farmer to changing precipitation patterns through changing crops or planting dates. Planned adaptation measures, on the other hand, are conscious policy options or response strategies, often multisectoral in nature, aimed at altering the adaptive capacity of the agricultural system, or facilitating specific adaptations. Judicious use of water using supplementary irrigation systems, more efficient irrigation practices, and the adaptation and adoption of existing and new water harvesting technologies have been suggested as appropriate strategies to cope with these problems.

6.2.1. Adaptation strategies

Human adaptation to climate change impacts is increasingly viewed as a necessary complementary strategy to mitigation—reducing greenhouse gas emissions from energy use and land use changes in order to minimize the pace and extent of climate change (*Klein et al., 2007*). Because adaptive strategies undertaken will have associated effects on carbon dynamics, it is important to consider carbon impacts of any proposed adaptive strategy.

In agriculture, forestry, livestock operations, water resources management, public health, and other fields impacted by climate change, there are typically a multiplicity of adaptation measures that may be taken (*Table 2*). In any given situation or context, though, the choice of adaptation measures may be difficult and constrained by their expense, the lack of knowledge on how to implement them, traditional beliefs, cultural practices, and others. Notwithstanding these impediments, farmers and others at risk from climate change (and including variability and extremes) can be provided with external help in a number of ways: insurance or other forms of financial assistance and risk spreading; drought relief in the form of cash or kind; information and advice; information and guidance; free or cheap seeds or replacement seed for seeds consumed, and so on (*Yohe et al., 2007*). These are actions that can be taken to reduce exposure, vulnerability, or risk. For example, farmers in regions subject to drought can select the time of planting appropriate to their cropping systems.

For Europe, *AEA Energy and Environment (2007)* identified priority risks at the sector and farm level in the assessment of impacts and evaluated a number of possible adaptation responses (at both sector/policy level and farm level) with respect to the following issues: technical feasibility, potential costs of implementation, cost-effectiveness, ancillary benefits, and cross-sectoral implications

(e.g., water, tourism, energy). Adaptation measures were further categorized as technical (e.g., introduction of new cultivars), management (e.g., changes in cropping patterns, soil, landscape, water), or infrastructural (e.g., changes in drainage, irrigation systems, access, buildings).

Table 2. Available adaptation measures

Sectors	Adaptation measures
Agricultural cropping	Choice of crop and cultivar: Use of more heat/drought-tolerant crop varieties in areas under water stress; Use of more disease and pest tolerant crop varieties; Use of salt-tolerant varieties; Introduce higher yielding, earlier maturing crop varieties in cold regions. Farm management: Altered application of nutrients/fertilizer; Altered application of insecticide/pesticide; Change planting date to effectively use the prolonged growing season and irrigation; Develop adaptive management strategy at farm level.
Livestock production	Breeding livestock for greater tolerance and productivity; Increase stocks of forages for unfavorable time periods; Improve pasture and grazing management including improved grasslands and pastures; Improve management of stocking rates and rotation of pastures; Increase the quantity of forages used to graze animals; Plant native grassland species; Increase plant coverage per hectare; Provide local specific support in supplementary feed and veterinary service.
Fishery	Breeding fish tolerant to high water temperature; Fisheries management capabilities to cope with impacts of climate change must be developed.
Development of agricultural biotechnologies	Development and distribution of more drought, disease, pest and salt-tolerant crop varieties; Develop improved processing and conservation technologies in livestock production; Improve crossbreeds of high productivity animals.
Improvement of agricultural infrastructure	Improve pasture water supply; Improve irrigation systems and their efficiency; Improve use/store of rain and snow water; Improve information exchange system on new technologies at national as well as regional and international level; Improve sea defense and flood management; Improve access of herders, fishers and farmers to timely weather forecasts.

Source: Yohe et al. (2007)

In a synthesis of research on adaptation options in Canadian agriculture, Smith and Skinner (2002) identified four main categories of adaptation options: (i) technological developments, (ii) government programs and insurance, (iii) farm production practices, and (iv) farm financial management. Most adaptation

options were identified as modifications to on-going farm practices and public policy decision making processes with respect to a suite of changing climatic (including variability and extremes) and non-climatic conditions (political, economic, and social).

7. Conclusions

Western governments currently prioritize economic growth and the pursuit of profit above alternative goals of sustainability, health, and equality. Climate change and rising energy costs are challenging this consensus. The realization of the transformation required to meet these challenges has provoked denial and conflict, but could lead to a more positive response which leads to a health dividend; enhanced well-being, less overconsumption, and greater equality (McCartney *et al.*, 2008).

There is a need for better assessment of risks associated with variable and uncertain environmental conditions. This likely would involve documentation of climatic variation (temporal and spatial) so that probabilities of climatic conditions can be better estimated. This is different from mapping “normal” conditions, and it should focus on those climatic variables that are pertinent (for example, moisture during critical time periods) rather than readily available (such as mean annual temperature). This assessment of risks should include consideration of variation in other relevant external forces, including economic and policy conditions.

There is also a need for developing and promoting enterprises and management practices that are adaptive and sustainable in the variable and uncertain environment. Evaluations of existing and potential production systems according to their ability to sustain production and economic returns, as well as the consideration of policy vehicles (i.e., alternatives to the set of policies likely to be withdrawn) that might promote more sustainability, would help address this need.

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Some perspectives on agricultural GHG mitigation and adaptation strategies with respect to the impact of climate change/variability in vulnerable areas

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Abstract—It is generally agreed that agricultural activities contribute to greenhouse gas (GHG) build up in the atmosphere which influences climate change and climate variability. Worldwide agriculture is responsible for about 13 percent of the total anthropogenic emissions. The scientific community has placed considerable efforts on developing ways to mitigate this effect through improvements in agricultural management practices. Improved management practices such as precision farming, implementation of less intensive tillage, changes in crop rotation, improved feed quality for better digestibility, improved manure handling, better water management of rice paddies, and biofuel/bioheat production are commonly employed as a means to mitigate GHG emissions. Even with all these mitigation measures, climate change is likely to have a wide range of effects on agricultural systems and we must adapt to these changes to ensure that agricultural production is not only maintained but is increased to support a growing world population. In some areas shifts in crop zones are expected, whereby cool season crops may be replaced by warm season crops and new cropping zones may open up for production. Most adaptation scenarios are likely to influence GHG emissions. Production of bioenergy crops, particularly lignocellulosic crops can, in some cases, provide a means to both mitigate net CO₂ emissions and adapt to a changing climate and world energy needs. There are numerous potential mitigation strategies to reduce GHG emissions from agriculture, but their effectiveness depends on climate, soil, and economic conditions which vary across regions. Process-based models can potentially act as a useful tool for examining the influence that climate change may have on mitigation and adaptation efforts. However, there are gaps in knowledge regarding processes that govern GHG emissions and much uncertainty regarding future trends in climate. In this paper the DeNitrification-DeComposition (DNDC) model was used to investigate the influence that a changing climate might have on GHG emissions in agricultural systems. Results indicate that N₂O emissions will be highly variable across different landscapes, and that net CO₂ emissions will generally increase, particularly in cooler regions. In regions with an average annual temperature of less than 10 °C, enhanced soil carbon decomposition due to increased temperatures is expected to cause a loss of approximately 70 kg CO₂ ha⁻¹ y⁻¹ by 2100.

Key-words: greenhouse gas, mitigation, adaptation, climate change, model

1. Introduction

Mitigating greenhouse gas (GHG) emissions and adapting to climate change will give rise to economic and environmental constraints. The agricultural sector is responsible for approximately 10–13% of total global anthropogenic emissions of GHGs (5.1 to 6.1 Gt CO₂-eq y⁻¹ in 2005), and most of these emissions are in the form of CH₄ and N₂O (*Carter et al.*, 2007). Agricultural CH₄ and N₂O emissions have increased by nearly 17% from 1990 to 2005. Although net CO₂ exchange from agriculture soils is approximately at equilibrium, substantial mitigation potential exists in sequestering atmospheric CO₂.

The mitigation of GHG in agricultural systems is undoubtedly not the primary concern for farmers. Increased production costs and a need to maintain or re-establish sustainable agricultural systems are the driving forces for the agricultural sector. However, if concentration of GHGs continue to increase, the vulnerability of agriculture to changes in climate will be significant. Due to economic constraints, farmers in developing nations are considerably more vulnerable to climate change than those in developed countries. Implementation of long-term mitigation measures should help to minimize the impacts of climate change and reduce this vulnerability. There is an extensive range of potential agricultural mitigation measures for most regions, but the full potential to reduce GHG emissions will only be realized if economic and policy incentives are given. Due to the inevitability of climate change, adaptation of agricultural systems is also required to maintain or increase production.

There are some difficulties in assessing the potential impacts of future climate change on mitigation and adaptation strategies for agriculture. Empirical data cannot always be extrapolated to forecast future changes in GHG emissions from agriculture as the impacts of climate change are often dynamic. The use of process-based models, that have been verified against measurements, present a means of quantifying changes in GHG emissions from agricultural systems under future climate change scenarios. In this paper we will review the status of agricultural mitigation strategies that can potentially reduce GHG emissions under a changing climate. We will also review how adaptation measures can influence GHG emissions. Additionally, we will demonstrate how process based model can be used to predict changes in GHG emissions from agriculture under future climate.

2. Mitigation of agricultural GHG emissions through improved management practices

Numerous mitigation measures have been proposed to reduce GHG emissions from agricultural systems (*Smith et al.*, 2008a). Typically, the most promising practices are those that sequester carbon. *Smith et al.* (2007a) estimated that 90% of the total potential comes from sink enhancement. Mitigation measures that

are particularly effective at reducing one GHG may, however, increase emissions of another thus it becomes important to quantify the emissions of CO₂, CH₄, and N₂O, simultaneously. In certain cases a change in albedo may also be an important factor in determining total radiative forcing of a management practice (Janzen *et al.*, 2008).

It is also important that mitigation measures be of long duration. Some practices may sequester soil carbon for a few years before reaching a new equilibrium with no further storage of carbon. Additionally, any sequestered soil carbon is vulnerable to being lost by either a change in practice or by a change in climate. Soil carbon may also be depleted in the future due to enhanced organic matter decomposition under a warming climate (Smith *et al.*, 2008b). Adaptation measures to minimize climate change impacts on crop production using improved water, soil, and disease management may also hamper mitigation efforts and fuel further changes in climate. Therefore, it is important to quantify the impact of adaptation measures. The impacts of land management, crop management, and livestock management on GHG emissions are discussed below.

2.1. Land management

Changes in land management can reduce GHG emissions by enhancing the removal of CO₂ and to a smaller extent CH₄ from the atmosphere. N₂O emissions can also be highly influenced by changes in water and nutrient management. Land management practices that impact GHG emissions include changes in tillage, nutrient, and water management, as well as the management of organic soils and degraded land (Table 1).

Reduction in the frequency of tillage is a widely accepted means to reduce carbon loss from soils. Advances in farm machinery and weed control methods have made this a viable strategy in many areas. Reduced tillage results in less water loss, less soil erosion, and a lower rate of organic matter decomposition. Soil disturbance through tillage aerates the soil and mixes residues into the profile providing substrates for enhanced decomposition of organic matter. The benefit of a reduction in tillage depends largely on climate and soil type. It is usually more beneficial in dryer soils which are not susceptible to water logging and disease. A reduction in the frequency of tillage can also affect N₂O emissions. Globally, the effects are not consistent, but in some areas a pattern can be discerned. For instance, in the semiarid regions of western Canada N₂O emissions are generally reduced (Helgason *et al.*, 2005), whereas in the humid east emissions often increase.

After years of intensive agriculture many soils have become less productive and thus fertilizer N use has been increased to compensate. Improved cultivars and management have also led to a higher fertilizer N requirement. Unfortunately, a large fraction of fertilizer N that is applied to crops remains unused or leaches out of the field and is subject to being transformed and

emitted as N₂O. Improving N use efficiency by crops can yield both environmental and economic benefits. Frequent soil N testing is likely the most straightforward technique to improve nutrient management, although the cost of testing sometime limits its application. Applying the appropriate amount of nitrogen maximizes crop production and decreases N₂O formation. The use of slow release fertilizers, coated fertilizers, and nitrogen inhibitors has the potential to reduce N₂O production. Broadcast application of fertilizer often results in excess fertilizer application. Alternative fertilizer application techniques such as banding, precision, and deep placement can help alleviate over fertilization issues.

Table 1. Land management practices that reduce greenhouse gas emissions

Mitigation category	Practice	Impact on GHG emissions			Correlation of mitigation to adaptation
		CO ₂	CH ₄	N ₂ O	
<i>Land management</i>					
Tillage management	Reduction in tillage	↓↑		↓↑	Positive: Reduced tillage also helps maintain soil water and reduces soil erosion
	No tillage	↓↑		↓↑	
	Zone tillage	↓↑		↓↑	
Nutrient management	Slow release fertilizers or nitrogen inhibitors	↓		↓	Positive: Efficient N management means less energy use and cost per unit of food production
	Improved N scheduling to minimize loss	↓		↓	
	Reduce leaching and volatile losses	↓		↓	
	Placement of N (banding)	↓		↓	
	Timing of organic residue additions	↓↑	↓	↓	
Water management	More efficient irrigation (Trickle, subsurface)	↓		↓↑	Positive: Practices which conserve water often reduce GHG emissions and help maintain crop production as an adaptive measure
	Drainage in humid areas	↓		↓	
	Keeping soil cropped to rice dry in off season	↓↑	↓	↓	
	Deficit irrigation	↓↑		↓	
	Mulching with crop residue during fallowing	↓		↓↑	
	Draining wetland rice during the growing season (one to several times)	↓↑	↓	↓↑	
Managing organic soils and degraded land	Avoid drainage of wetlands	↓	↑	↓↑	Positive: Reclamation of degraded land can create a sustainable source of food production
	Maintain shallower water table in org. soils	↓		↓↑	
	Re-vegetation of organic soils	↓		↓↑	
	Improve fertility of degraded soils	↓		↓↑	
	Apply organic substrates to degraded soils	↓		↓↑	
	Retain crop residues and conserve water	↓		↓↑	

Although water management is not considered to be one of the more prominent mitigation options in agriculture, the potential benefits of acting as both a mitigation practice as well as an adaptation option are attractive. Mitigation of GHGs through water management is most applicable in regions where irrigation and drainage management is prevalent. Globally, irrigated rice production accounts for nearly 75% of all rice produced. Continuous flooding of rice paddies has been discussed as a potential mitigation measure that reduces the N₂O emissions in comparison to fields that use mid-season drainage

management (Zheng *et al.*, 2000). Considering that nearly 80% of the land area currently dedicated to rice production in China uses midseason drainage (Li *et al.*, 2002), the potential for mitigation of N₂O emissions is significant. Note that low denitrification rates occur either when soils are saturated or at low in water content. If continuous flooding is not an option, then techniques that reduce the frequency and magnitude of irrigation events could also decrease the production of N₂O emissions, i.e., deficit irrigation, trickle, and subsurface (Doerge *et al.*, 1991). The use of crop residues as mulch can limit both evaporation losses as well as improve soil quality through the incorporation of organic matter along with reducing the impact of soil erosion (Dahiya *et al.*, 2007; Bilbro and Fryrear, 1994).

Increasing demand for food production from agriculture has caused farmers to reclaim organic soils and degraded land. Serious obstacles exist, however, before these areas are suitable for agriculture. Organic soils tend to be acidic and inherently have low fertility. The topsoil is typically very shallow and susceptible to erosion. The application of manure and the burning of crop residues are not always sufficient to keep degraded soils viable for continuous agriculture, so alternative nutrient additions are sometimes unavoidable. The application of phosphorus (P) can usually overcome the fertility constraints inherent in these types of soils but not without introducing a high cost to farmers. The opportunity to sequester soil carbon and increase the area of productive agricultural land should not be ignored. However, due to the inherently high cost of reclaiming these infertile soils, governments may need to provide incentives.

2.2. Crop management

Crop management includes practices that enhance removals of CO₂ from the atmosphere by improving crop selection, using rotations that include high input crops, changing to permanent cover or trees, reducing bare fallow, retaining crop residues, and avoiding biomass burning (Table 2). These practices stand to promote carbon sequestration by absorbing more CO₂ from the atmosphere and increasing carbon inputs in the soil.

Crop management can also contribute to reduce N₂O and CH₄ emissions through reduction of fertilizer inputs, using rice cultivars with low exudation rates, organic agriculture, and adjusting timing of planting, harvesting, and fertilizer additions.

Another way to mitigate GHG emissions is to replace fossil fuels with biofuels. Currently much effort is focused on bioenergy production using wheat and maize. It is debatable whether or not biofuel production using existing mainstream crop cultivars mitigates GHG emissions. There is also a major concern that biofuel production will displace agricultural land that would otherwise be used for food production. This is particularly a concern for third

world countries where inexpensive food sources are necessary. However, much research is going into new forms of biofuel production using crop residues, lignocellulosic crops, or grasses and shrubs which can, in some cases, be grown on marginal or abandoned land. *Smith et al.* (2008a) predicted that biofuel production could reduce GHG emissions by over 600 Mt CO₂-eq y⁻¹ at a market price of USD/20/t CO₂-eq.

Table 2. Crop management practices that reduce greenhouse gas emissions

Mitigation category	Practice	Impact on GHG emissions			Correlation of mitigation to adaptation
		CO ₂	CH ₄	N ₂ O	
<i>Crop management</i>					
Residue management	Retain crop residues	↓		↓↑	Positive: Crop residues are retained to reduce evaporation/water loss
	Avoid burning	↓		↓↑	
Change in land cover	Reduction in fallowing	↓		↓↑	Negative: Farmers may be required to increase fallow to store water in dryer conditions
	Cropland to Permanent grass/trees	↓		↓	
	More forage in rotations	↓		↓	Negative: Increased demand for food production may require more intensive agriculture
	Grassed waterways/field margins/shelterbelts	↓↑		↓↑	
Improved crops/crop management	Improved varieties to enhance production	↓		↓↑	Positive: Increased crop production usually enhances soil carbon inputs
	Rice cultivars with low exudation rate	↓↑	↓	↓↑	
	Reduced fertilizer/pesticide inputs	↓↑		↓↑	
	Organic agriculture	↓↑		↓↑	
	Use catch or cover crops	↓		↓	
	Adjust fertilizer rate to crop needs	↓		↑	
Bioenergy	Biofuels from common crop cultivars	↓↑		↓↑	Positive: Biofuel production is an adaptation measure to meet global energy demands
	Biofuels from crop residues	↓		↓↑	
	Biofuels from Lignocellulosic crops	↓		↓↑	Positive or negative: In some cases Biofuel crops may replace existing crops that become no longer suitable for production but in other cases they displace land that is needed for mainstream production
	Bioheat from grasses and shrubs	↓		↓	

2.3. Livestock and manure management

Approximately 16% of the global atmospheric CH₄ emissions originate from livestock. The two main sources are enteric fermentation (83%) and manure management (17%) (*FAO*, 2007). It is well documented that the GHG emissions associated with livestock production are substantially higher than for crop production. Mean values of approximately 0.3 kg CO₂-eq per kg of soybean and 0.4 kg CO₂-eq per kg of corn have recently been calculated for these two crops in Canada. The GHG emission per kg of meat is substantially larger. The high emissions from livestock provide opportunities for reducing GHG emissions (*Table 3*). Emission intensities have been reduced in countries that have moved

towards intensive production. For example, in Canada *Vergé et al.* (2008) reported a reduction of 5.9 kg CO₂-eq per kg of live weight for beef from 1981 to 2006. Gains in animal productivity as well as changes in animal management practices have contributed to this reduction in GHG emission intensity. Anaerobic digesters can also be used as an energy source thereby displacing emissions from fossil fuels. Other manure handling techniques such as more frequent applications to the field and mechanically separated solids, and handling manure in solid form can also reduce GHG emissions.

Table 3. Livestock and manure management practices that reduce greenhouse gas emissions

Mitigation category	Practice	Impact on GHG emissions			Correlation of mitigation to adaptation
		CO ₂	CH ₄	N ₂ O	
<i>Livestock and manure management</i>					
Grazing management	Grazing intensity and timing	↓↑	↓↑	↓↑	Positive: Improved grazing systems increase productivity
	Fertilizer or organic amendments	↓		↓↑	
	Irrigation (energy requirement)	↓↑		↑	
	Nutrient management	↓		↓	
	Reduce frequency of fires	↓	↓	↓↑	
	Species introduction	↓		↓↑	
Livestock management	Feeding more concentrates		↓	↓	Positive: More efficient feeding can enhance productivity Negative: In some areas breeds of livestock will need to be more resilient to heat and water stress. The dietary needs may be restricted by these requirements
	Adding more oilseeds to diet		↓	↓	
	Special agents and dietary additives		↓		
	Long-term management and improved breeding		↓	↓	
	Reduce confinement	↓	↓		
Manure and biosolid management	Anaerobic digestion to retrieve CH ₄ as an energy source		↓	↓↑	Positive: There are technologies which capture energy from manures
	Handling manure in solid form		↓	↓	
	More efficient use as nutrient source	↓		↓	
	Cooling of manure in lagoons or tanks, use of solid covers, mechanically separated solids, capturing emitted CH ₄		↓	↓↑	

3. Agricultural adaptation to limited water resources

Based on current climate model assumptions, it is predicted that there will be major shifts in global precipitation patterns and evaporation losses (*UNEP, 1997; Carter et al., 2007*). Since many regions are already water stressed, any further declines in water resources would have an immediate impact on agroecosystems. Farmers would be forced to adopt water management techniques to ensure that agricultural productivity is minimally impacted. *Debaeke and Aboudare (2004)* identified six practices that farmers in dry land areas will need to employ to cope with future water limitations. These are: (1) increasing stored soil water at sowing to increase water availability, (2) increasing soil water extraction by crop by maximizing root extraction, (3) reducing the magnitude of soil evaporation

and drainage, (4) optimizing the seasonal water use pattern during the growing season, (5) increasing crop tolerance to water stress, and (6) irrigating crops at the most-sensitive growth stages. These practices aim to improve water use efficiency by crops.

In soils that have low organic matter contents, the addition of farmyard manure or use of bio-fertilizers can help improve the soil structure and water holding capacity of these soils. Alternate deep tillage techniques can also increase soil water at sowing by encouraging water infiltration and by promoting deep root development. The deep tillage breaks up the sub soil which is often not ideal for root development. Stubble-mulch and minimum-tillage techniques can increase infiltration and lower evaporation. Evaporation of water was found to be reduced by 34–50% by leaving crop residues on the surface (*Sauer et al.*, 1996). The supply of water through irrigation at critical growth phases, deficit irrigation, would ensure that farmers can maintain productivity even when water resources are limited. Deficit irrigation can be accomplished by reducing the irrigation depth, refilling only part of the root zone, reducing the irrigation frequency, and various furrow wetting techniques (*Ali and Tualukder*, 2008).

Most of the water management practices mentioned are pertinent for dry land farming systems, but water management will also be important for rice production in many of the more humid regions. China and India produces much of their rice on irrigated lowlands which have relatively high water requirements. Irrigation water could be saved without yield loss by applying alternate wetting and drying or flush irrigation to rice systems, but in some cases this may increase N₂O emissions.

4. Modeling mitigation strategies to reduce GHG emissions

Future trends in climate will change the rate of GHG emissions from agroecosystems and will influence the effectiveness of mitigation strategies. We need to develop tools for estimating emissions under a changing climate. Due to limited data and the extreme number of variables in agricultural systems, it is difficult to extrapolate measured data to predict changes. In some cases, particularly for certain adaptation measures, no GHG emissions data are available.

The use of process-based models as prediction tools offers many advantages as they can simulate the highly diverse soils, farm management, and climatic conditions found in agroecosystems. They can simultaneously provide the interactions between all the GHG emissions and predict emissions over space and time. However, the biggest issue in using process-based models in various situations is that many of the processes observed are not fully understood. Therefore, process-based models require continuous development and verification to increase the confidence in the results.

Several researchers have used models to estimate GHG emission factors for different soils, crops, and climates (*Smith et al.*, 2001; *Desjardins et al.*, 2004;

Grant et al., 2004), but few have attempted to estimate the effect of climate change on these factors. Changes in climate are accompanied by many possible changes in agricultural management, whereby the length of the crop growing season may change, crop cultivars may change, it may no longer be viable to grow certain crops, different rates of fertilizer will need to be applied, irrigation or drainage may be required, and pest management strategies may need to change. The effect of climate on our agroecosystems in the future is highly uncertain, partly because our ability to predict climate change is uncertain. *Smith et al.*, (2008b) using the Century model found that climate change had little effect on no-till C sequestration factors, but had some influence on permanent cover factors. Both the SRES B2 and IS92a climate scenarios resulted in greater loss of soil C towards the end of the century. *Smith et al.*, (2007b) estimated ranges of emission factors for changes in agricultural management. The estimates were derived from empirical data and process-based models such as Daycent (*Del Grosso et al.*, 2001) and DNDC (*Li*, 2000). Based on these factors they estimated approximately 6000 Mg CO₂-eq y⁻¹ as the global mitigation potential by 2030 and an economic potential of 1500–1600, 2500–2700, and 4000–4300 Mt CO₂-eq y⁻¹ at carbon prices of 20, 50, and 100 USD/t CO₂-eq. No doubt there is much uncertainty involved in this process, but it is important to quantify the various mitigation options.

Adaptation methods and sometimes even mitigation measures may change with time as the climate becomes warmer, more arid, or more variable. For this review paper we also carried out a short study to serve as an example of how models may be applied to assess the effects of climate change on GHG emissions in some areas around the world. Ten locations were chosen across contrasting climatic zones, soils, and crops (*Table 4*). The purpose of this exercise was to gain a better understanding of how a changing climate might affect GHG emissions and not to fully characterize any given area.

Simulations were performed in a manner similar to that by *Smith et al.*, 2008b. To generate future climate, 20 years of historical weather data (1970–1999) from a station at each of the 10 locations was used. A historical year was randomly selected from this 20-year period for each of the 100 years from 2000–2100. Thus each year from 2000 to 2100 had the same distribution and frequency of weather events as historical data. Seasonal changes in precipitation and temperature over time were applied based on estimates from the IPCC report on Climate Change: Impacts, Adaptation and Vulnerability (*Carter et al.*, 2007). In this report AOCM predictions of seasonal changes in mean temperature and precipitation for the A2 emission scenario were estimated and averaged from 15 recent AOCM simulations to the end of the 21st century for 32 regions. We used the average of these ranges to indicate changes in temperature and precipitation for the ten chosen locations and applied the change in temperature and precipitation linearly over the time period from 2000 to 2100. Simulations were carried out both with and without CO₂ fertilization. A

nonlinear rate of CO₂ fertilization was assumed based on the A2 scenario. Generalized agricultural management, including fertilizer application rates and scheduling, planting, and harvest dates, and tillage scheduling were used for each location. We created a few new crop profiles by adjusting optimum grain and total biomass and degree days to maturity such that the DNDC model could better match biomass production.

Table 4. Estimated change in yield from 2090–2100 in comparison to baseline yields from 1970–1999 using the DNDC model for the A2 climate change scenario

Location	Crop type	Average annual precipitation (cm)	Average annual temperature (°C)	Change in precipitation (%)	Change in temperature (°C)	Change in yield (CO ₂ fertilization) (%)	Change in yield (no CO ₂ fertilization) (%)
Australia	WF	29	17	-4.6	3.2	-6	-15
Canada	W	39	6	3.6	4.0	6	-4
Canada	W	47	2	18.1	5.2	-1	-7
India*	R/W	66	23	4.8	3.5	17	-3
China*	W/M	68	14	11.5	4.1	24	1
Germany	W	81	8	-19.1	3.9	-3	-19
Africa	M	92	28	1.3	3.4	-24	-25
Canada	M	99	6	5.5	4.3	21	-5
Brazil	M	121	27	-4.0	3.8	9	-3
China	R/R	146	17	11.5	4.1	-6	-13

W – wheat, F – fallow, R – rice, M – maize; / denotes two crops in same year ; * denotes irrigated systems

Crop yields were simulated under the A2 climate change scenario both with and without CO₂ fertilization. The resulting change in yield over the last 10 years from 2090–2100 in comparison to baseline yields from 1970–1999 is shown in Table 4. The average overall yield across the ten locations showed no change under the climate scenario when CO₂ fertilization was included, however, yield declined in simulations with no increase in CO₂ fertilization. Considering that recent research indicates some crops may reduce their rate of respiration and slow growth under higher temperatures (Gill *et al.*, 2002), we may not expect them to respond to increased CO₂ fertilization. Note that for the site in Mali, Africa a small increase in temperature resulted in a sizable decline in yield. This is because production at this location is already seriously hampered by poor soil quality, and the DNDC model indicates that any more stress could result in detrimental effects on crop yield.

Nitrous oxide emissions were extremely variable at several locations. Fertilizer rate was not adjusted to account for changes in growth which could result in over- or under-fertilization. At a subhumid location in Canada over-fertilization was not an issue. These results demonstrate the potential tradeoff that can occur between N₂O and CO₂ emissions (Fig. 1). At this location CO₂ flux from soils is increased due to enhanced decomposition of organic matter

under higher temperatures. The denitrification process, on the other hand, is limited as soil-water availability declines and as a result less N₂O emissions occur. Some climate change studies have only looked at the effect of a changing temperature on GHG emissions but it is also of importance to examine the effects of a changing water regime. In semiarid and subhumid locations adaptation efforts will be required to maintain crop yields. Such measures might include selecting crops with improved water use efficiency, or a change in irrigation, or residue management. These changes should decrease soil carbon loss but will have variable effects on N₂O emissions.

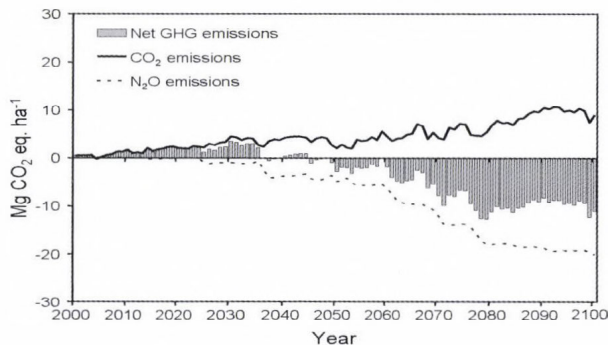


Fig. 1. Estimated influence of climate change on CO₂/N₂O emissions from a wheat crop in subhumid Canada, 2000–2100.

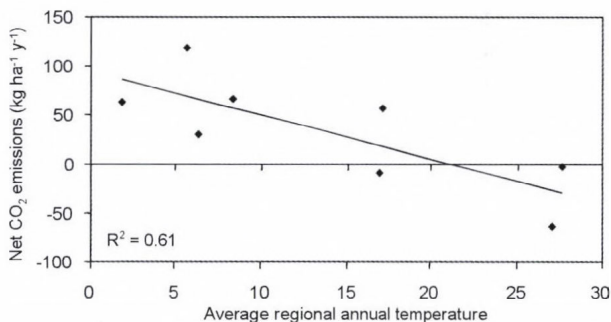


Fig. 2. Estimated effect of climate change by 2100 on CO₂ exchange from agricultural systems for a wide range of annual temperatures (see Table 4 for information on country selected).

An increase in temperature through climate change can result in enhanced soil organic matter decomposition and loss of soil carbon, which may offset some of the mitigative efforts. The results using the DNDC model indicate that soil carbon will be lost in cooler climatic zones but may be gained slightly in warmer regions (Fig. 2). In tropical regions soil carbon is often already in a degraded state, thus further

increases in temperature have little effect. Furthermore, an increase in average annual temperature from 2 to 7 degrees will have more of an effect on decomposition than an increase from 28 to 33 degrees, largely because there are more frost free days, and the soil thaws much earlier in the spring.

5. Conclusions

Greenhouse gas emissions from most agricultural systems could be reduced, however, the extent to which reduction will occur is limited by policy, economics, and a need for more food production. Gaps in knowledge regarding the potential of various mitigation measures limit our ability to make recommendations. Policy and economic incentives will be needed to promote mitigation of GHG from agricultural sources. Reducing agricultural production that requires a large amount of energy input per unit of food (e.g., meat and milk) could substantially reduce GHG emissions. Biofuel production can be a viable adaptation and mitigation measure, but practices such as residue removal or growth of crops on marginal land should be promoted to avoid competition with mainstream agriculture. It is essential to assess long-term consequences of mitigation and adaptation strategies, determine how these actions are affected by climate, and develop strategies to combat climate change. Integration of mitigation and adaptation frameworks into sustainable development planning is required, especially in developing countries. It is imperative for countries to take a proactive and collaborative role in planning national and regional programs on mitigation and adaptation to climate variability and climate change.

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Developing an adaptation strategy for sustainable agriculture

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Abstract—Agriculture is one of the most important economic sectors of global society. Agricultural production continues to expand into forest lands and marginal crop areas in an attempt to keep pace with the ever-increasing world population. Environmental damage is increasing, including erosion, salinity, desertification, deforestation, threats to biodiversity, and water scarcity. Moreover, climate change/variability is having a profound influence on agroecosystems, posing serious threats to food security, human health, and protection of the environment. Thus, comprehensive agrometeorological adaptation policy guidelines, focusing on preparedness, mitigation, and adaptation measures to support sustainable agricultural development, are needed to cope with the impacts of climate change/variability. Adaptation policy can not be an effective “stand alone” strategy, but should be incorporated into a broader policy objective. For example, adaptation to climate change should be a part of a broader socio-economic policy such as agricultural, forest, water resources, natural resources, or coastal-zone management policy. Poorer countries that will require resources to improve capacity in order to cope with impacts, undertake specific adaptation measures.

Key-words: climate change, sustainable agriculture, adaptation, preparedness, policy

1. Introduction

Farmers must cope with natural disasters and extreme weather events as part of their everyday farm management strategy to harvest their crops and raise their livestock. Droughts, floods, heat waves, and tropical cyclones, among other natural hazards, have enormous (and sometimes devastating) impacts on agriculture and the socio-economic well-being of the agricultural community. Thus, an important challenge for agrometeorologists is to develop or improve preparedness and adaptation strategies, especially in vulnerable regions where food and fiber production is most sensitive to vagaries of weather and climate. Equally important, however, are to find the ways and means to translate these

strategies into meaningful products and services for local farming and extension systems; and, to help build the capacity to disseminate appropriate and timely information for the entire user community.

2. Preparedness, mitigation, adaptation, and emergency relief measures

It is within this framework that an effective agrometeorological adaptation policy is needed for the agricultural community to cope with natural disasters and climate change/variability. A disaster can be defined in terms of a natural hazard times the vulnerability. The natural hazard is an extreme weather or climate event such as drought, flood, heat wave, tropical cyclone, or other catastrophe such as wildfire, avalanche, earthquake, or tsunami. Vulnerability represents the social factors including land use practices, environmental degradation, water use trends, technology, urbanization, population growth, and population shifts.

Farmers have to cope with disasters and climate extremes throughout the growing season. Actions can be taken at the farm level to help farmers implement preparedness measures to cope with disasters, including better early warning communication and response systems. Feasible mitigation measures can help reduce vulnerability. Specific mitigation measures implemented by federal, state, or regional governments include drought monitor programs, water supply augmentation, public awareness/education programs, technical assistance on water conservation, water conservation programs, and emergency response programs. Specifically for agriculture, crop irrigation efficiency studies and scheduling, soil moisture monitoring, irrigation technology management, drought-tolerant crops, and innovative cultivation techniques to reduce crop water use are the primary mitigation measures. Adaptation strategies are measures or long-term plans to reduce the vulnerability of the agricultural or coastal communities to the natural hazards. These adaptation strategies need to be both proactive to address long-term coping strategies as well as reactive to provide resilience in the short-term.

A comprehensive framework to cope with natural disasters, which focuses on preparedness, mitigation, and adaptation, as well as emergency relief measures after a disaster strikes, is the ultimate goal of any policy initiative to support sustainable agricultural development efforts. There are other factors involved in this framework that have a significant impact on the ability to recover from climate extreme events. For example, with a shift from productive to marginal agricultural area, the impact of drought or flood on agriculture becomes a much more difficult challenge for climate sensitive farming and ranching, if remedial measures are not taken. The aim of this strategy is to move away from a mainly reactive approach to a disaster event (responding to a natural hazard that turns into a disaster) to a new paradigm based on a more

comprehensive approach that include preventive measures, mainly aimed at reducing the likelihood that a natural hazard translates into a disaster.

Adaptation can help farmers to minimize or reduce the negative impacts of climate extremes on activities and ecosystems, and, perhaps to take advantage of potential beneficial changes (*Rosenzweig, 2007*). The response that can be taken may be directly by individual farmers based on a set of technology and management decisions available. These systems include shifting the crop calendar (planting, input schedules), cultivar changes, and crop rotation changes. Another response requires a concerted action facilitated by climate-specific regulations and incentives from local, regional, and national policies. These options include land use incentives, irrigation infrastructure, water management, regulations, and germplasm development programs. Both adaption responses are essential for sustainable agricultural systems.

3. Framework for an adaptation strategy

The development of adaptation policy must begin by identifying both the hazards and vulnerabilities, which then can be used to identify particular disaster scenarios. The disaster scenarios must account for all scales, ranging from actions to managing the local manifestations of global climate disaster, through to global measures to reduce hazards, and to reduce vulnerability. Ways and means of dealing with integrated climate disasters (or natural disasters) need to include the following elements: (1) adaptation to ensure that future developments reduce rather than increase potential disasters; (2) actions to mitigate the losses associated with disasters; and (3) measures to ensure that disasters do not reoccur after a disaster event. These measures should take into account both potential impacts on socio-economic and environmental systems in the local area.

Integrated planning and actions dealing with climate change (or natural disasters) allow the affected community to move beyond preparedness and contingency response and develop adaptation/response strategies to cope with climate change, variability, and extremes. Action must be taken at all governmental levels (international, national, and local) in order to deal with climate disasters and to move the policy from concept to practice. At the international level, an integrated international framework can promote partnerships for coping strategies, which incorporates elements of and builds on existing frameworks for addressing climate change, disaster reduction, desertification and others. At the national level, integrated climate disaster strategies, plans, and programs need to be built on the same institutional and administrative mechanisms as disaster risk management activities in order to address adaptation strategies for climate change (*Sperling and Szekely, 2005*).

Burton et al. (2002) describes a step-by-step formulation of an adaption policy. The process to develop an adaptation policy for natural disasters and

future climate change begins by assessing current local vulnerabilities to present day climate, including its variability and extremes, and the ways that existing policy and development practice serve to reduce vulnerability.

The assessment of current vulnerability requires an understanding of key background information. What has been the recent pattern in climate variability and extremes? Are there any trends in their recent history of climate variability and extreme events, and if so, are there any discernible atmospheric oceanic features that can be attributed to the trends?

The next step in the policy development process involves the design of policy initiatives and alternatives, and their assessments and prioritization. In evaluating this phase of the exercise, some thought must be given to future conditions, including climate change and changes in the socio-economic environment, based on available evidence and/or sound reasoning. What are the prospects for economic and sustainable agricultural development? What are the prospects for adaptation and how much can vulnerability be reduced? What are the constraints and limitations to public policy for adaptation? What are the costs of adaptation measures and what benefits can be anticipated?

Adaptation policy can not be an effective “stand alone” strategy, but has to be incorporated into a broader policy objective. For example, adaptation to climate change in agriculture should be a part of a broader agricultural policy. The same applies to forests, water resources, coastal zone management, public health, natural ecosystems, infrastructure, and human settlements. Relevant policies are not limited to such socio-economic sectors, but can also include policies for dealing with natural hazards and coping with natural disasters (floods, droughts, tropical and extra-tropical storms, etc.). Governments may have national policies or special policies that are directed to regional developments, including rural and urban-centered regions or river-basins.

An assessment of current policy in agriculture, for example, will normally take into consideration the broad strategic objectives for agriculture in the national socio-economic and development context. Is the aim to expand commercial agriculture for export-led development? How much importance is given to local food security and the maintenance and improvement of agriculture-based livelihoods? Such policies also influence choice of crops and many other agricultural practices at the farm level. Of specific interest in the case of agriculture are other policies in related areas of natural resources and environmental management such as watershed protection and rehabilitation, soil erosion, soil salinity, the use of genetically modified crops, and so forth.

Costs of production are likely to rise in a changing climate, as producers adjust crop varieties and species, scheduling of operations, and land and water management techniques. Successful adaptation to climate change/variability may involve significant changes to current agricultural systems in order to maintain sustainability. Some of these changes may be costly. There may be a need for investment in new technologies and infrastructure; new irrigation

systems may be required for aridity or precipitation instability, damages from flooding may increase in many regions, there may be greater application and/or development of new agricultural chemicals, particularly herbicides and pesticides. However, with respect to agricultural chemicals, environmental concerns and increasing problems with chemical pollution (discussed earlier) limit its successful application.

Adaptation is, in fundamental ways, inherently local, meaning that both natural disasters and climate change/extremes have their direct impacts mostly at the local level. Thus, response measures must be tailored to local circumstances. However, for these efforts to be robust, or, in many cases, even possible, they must be acted upon, guided, and supported by the national policies and strategies. For some countries, these, in turn, need to be facilitated through international measures.

The adaptation strategy for a country refers to a general plan of action for addressing the impacts of natural disasters and climate change and climate variability, including extremes. This requires a combination of coordinated policies and measures with the primary objective of reducing the country's vulnerability. The comprehensive strategy should be aimed at the national level, but addressing adaptation factors across all sectors, regions and vulnerable populations of the country. Policies refer to objectives, together with the means of implementation, with the goal to strengthen food security, for example.

Ways and means to achieve this objective may be to enhance farmer advice and information services, improved application of agricultural research and development, better seasonal climate forecasting services for agricultural applications, and sustainable agricultural development systems. Measures are focused actions aimed at specific issues. Measures can be individual interventions or they can consist of packages of related measures. Specific measures might include actions that promote the chosen policy directions such as implementing an irrigation project, setting up a farmer information, advice, and early-warning programme, developing a new scheme for crop insurance, establishing a system of grain storage to protect against drought or crop failure, or providing incentives to grow a specific crop. Each of these measures may contribute to the local, regional, and national goal of food security.

Easterling et al. (2004) discussed the strategy of "proactive adaptation" as opposed to reactive adaptation. In the reactive strategy, measures take effect after the climate event or disaster strike. In the reactive approach, coping with disasters or climate change/extremes can be very costly in terms of emergency response measures. For example, there is the possibility that irreversible impacts such as species extinction or unrecoverable ecosystem changes can occur. Unacceptable high agricultural losses and damages that expose lives and property to intense storm damages can also occur.

Proactive adaptation, unlike reactive adaptation, is forward-thinking and takes into account the inherent uncertainties associated with anticipated change.

Successful proactive adaptation strategies are, therefore, flexible; i.e., they are designed to be effective under a wide variety of potential climate conditions, to be economically justifiable (i.e., benefits exceed costs) and to increase adaptive capacity. Preparedness is the cornerstone for a proactive adaptation strategy.

4. Formulation of an adaptation strategy for sustainable agriculture

All countries should have national adaptation strategies with a broad view of future development paths and expected impacts of climate on agriculture, forests, fisheries, and other natural resources. The policy review needs to include the management of extreme weather events as well. It must be proactive, emphasize risk management, and preparedness as the cornerstone of its strategy, but must include emergency relief measures as fail-safe response steps.

Developed countries are well advanced in both resources and planning for adaptation strategies. However, even in the developed countries, there is a wide range of progress, with some very limited action plans to a few with well developed national adaptation strategies. Developing countries are more vulnerable and less able to adapt to changing climate. They also have a greater dependence on agriculture and natural resources for subsistence-level economies. There is a tendency for many of these nations to have larger variations in weather; lower availability of critical resources such as water, productive land, production inputs, and capital. These vulnerabilities and limitations pose serious constraints on the ability of developing countries to cope with climate change and natural disaster issues.

The key issue is how governments and the international community can work together to assist developing countries with adaptation strategies and measures that are effective for local communities. The constraints are numerous, including expense, lack of knowledge on how to implement measures, and countervailing beliefs and cultural practices (Yohe *et al.*, 2007). Notwithstanding these impediments, farmers and others at risk in the local community from changing climate and natural disasters can be provided with external help. The provision of technical information, advice or guidance can be made more readily available through extension services in agricultural services; the provision of weather and seasonal climate forecasts and warnings can be improved; drought and flood emergency relief measures can be readily implemented; and insurance or other forms of risk management measures can be instituted. Adaptation measures need to be formulated into public policy. For example, with agricultural policies in place on crop and livelihood diversification, how drought and other climate variability or climate change influences agriculture can be factored into policy choices.

Knowledge is fundamental to any adaptation strategy. Knowledge is dynamic; it accumulates through observation, monitoring, and analysis; it can

also degrade over time if the learning process is neglected; and research and development must be continually supported to ensure literacy and education levels improve and/or basic societal infrastructure does not decay. Education raises awareness, and over time, it changes societal values. Examples are consumer information, public awareness campaigns, and professional development. Monitoring, observation, and communication systems have to be created or strengthened for climate-related parameters, for indicators of climate change and impacts (e.g., sea-level rise, changes in species composition of ecosystems, extreme events monitoring, and for enhanced agroclimatic observations).

Technological change is a principal route of many recent human adaptations. Innovations in transportation, agriculture, and information systems have advanced adaptive capacity. However, while these advances have taken place in developed countries, developing countries have not benefited from these innovations. Thus, a major gap is still to be bridged. Science, research, and development (R&D) and technological innovations are needed to enable responses to natural disasters/climate change in general, and to enable specific responses to extreme events/climate variability, including economic valuation of adaptations, technological adaptations (development of drought or salt-resistant crop varieties), and investigations of new sources of groundwater and better resource management. It may be necessary to adapt existing technologies to fit with the adaptation demands; e.g., the development of more energy-efficient, low-cost desalination plants and new technologies to combat saltwater intrusion.

Adaptations can be divided into two categories: autonomous and planned adaptations (*Easterling et al, 2007*). Autonomous adaptation is the ongoing implementation of existing knowledge and technology in response to the changes in climate experienced, and planned adaptation is the increase in adaptive capacity by mobilizing institutions and policies to establish or strengthen conditions favorable for effective adaptation and investment in new technologies and infrastructure.

Examples of autonomous adaptation options include: altering inputs such as varieties and/or species to those with more appropriate thermal time and vernalization requirements; wider use of technologies to “harvest” water, conserve soil moisture and to use water more effectively; water management to prevent waterlogging, erosion, and nutrient leaching in areas with rainfall increases; altering the time or location of cropping activities, diversifying income by integrating other farming activities such as livestock raising; improving the effectiveness of pest, disease, and weed management practices through wider use of integrated pest and pathogen management; and, using seasonal climate forecasting to reduce production risk.

Options for effective planning and capacity building for adaptation include: policies to maintain climate monitoring and for effective communication of this information, including surveillance of pests, diseases, and other factors directly

affected by climate; policies to support research, systems analysis, extension capacity, and industry and regional networks that provide information; need to invest in or develop technical options to respond to projected changes; where there are major land use changes, there may be a role for governments to support any transition; and, developing new infrastructure, policies and institutions to support management and land use arrangements by addressing climate change in development programs.

Risk and disaster management is another essential component of proactive adaptation. Proactive adaptation may necessitate periodic reassessment of the adequacy and preparedness of relief systems and programs, particularly in light of changing frequency and intensity of extreme events. Governments and insurance companies provide relief for such extreme climate events as hurricanes and tropical cyclones, floods, and droughts. Emergency plans, extreme events relief, and recovery measures also belong to this type of adaptation measure. Updating risk insurance rate tables may require anticipation of future climate/natural disaster risk changes. Proactive adaptation, therefore, may include fire mitigation programs such as prescribed burns and land use controls.

National drought policy has taken on even more importance with severe drought episodes in the late 1980's. Adaptation measures can also be grouped according to whether they are focused on one or more economic sectors (i.e., agriculture or multiple sectors). An example of a sectoral measure would be the introduction of improved agricultural varieties. In agriculture, for example, reduced rainfall and higher evaporation may call for drought tolerant crop varieties in a growing area. It may require a local, regional, and national drought policy to be implemented for long-term planning. Multi-sectoral measures include the use of improved watershed and coastal management methods, and more efficient irrigation management techniques. Multi-sectoral measures relate to the management of natural resources that span sectors; e.g. agricultural, water management, or river basin management. A third adaptation measure is called cross-sectoral measures, which includes such measures as the promotion of public awareness, agroclimatic research, and data collection. Sectoral measures may relate to specific adaptations that could be affected by natural disasters/climate change.

Science and technology have provided the knowledge and tools for the development of adaptation strategy formulation; a key component in the ultimate success in this framework is the engagement of stakeholders; i.e., individuals, local community groups, organizations (governmental agencies or non-governmental organizations and their networks). Relevant stakeholders need to be brought together to identify the most appropriate forms of adaptation. Furthermore, understanding the role of stakeholders in the decision-making process will assist in the implementation of adaptation policies.

Thus, an outline of an adaptation strategy for agriculture considers the following issues:

- (1) Complete monitoring systems will allow policymakers to develop and adjust adaptation strategies based on sound observational data bases. Agrometeorologists can take a more active role in this aspect, as noted earlier in the discussion of the socialization of agrometeorology. It is becoming increasingly important to communicate and disseminate meaningful and appropriate information to the user community at the right time and in the right format for decision-making.
- (2) Risk/disaster management measures include the development of early warning systems, in particular for extreme events like cyclones, droughts, floods, and ENSO occurrences. The success of this type of measure depends upon good communication systems and cooperation among users.
- (3) In many cases, flexibility, durability, and resiliency to climatic variability and change can be enhanced via changes in infrastructure design characteristics. Agriculture extension services can be more proactive with farmers to inform them about changes in crop varieties and practices that may be better suited to changing climate conditions.
- (4) Adopt preparedness measures and emergency response measures to help mitigate the impact of climate extremes and climate change.
- (5) Avoid agricultural expansion into marginal lands, coastal lowlands, or other poor cropping areas that are prone to desertification, coastal erosion, or prone to flooding.
- (6) Promote technological innovations that fit adaptation demands and will benefit both developed and developing countries, if possible.
- (7) Public policy provides substantial guidance in adaptation formulation and strategy at the national level, and, planning and implementations at the local level. Coordination at all levels is absolutely essential for emergency preparedness and disaster planning.
- (8) In summary, the ecosystem approach to adaptation measures involves the integrated management of land, water and other resources that promotes their conservation and sustainable use in an equitable way.

5. Education and training

It is essential to promote greater community education and training opportunities to meet the needs of the public, which correspond with the development of more robust warning systems, the increasing capacity to respond rapidly to disasters, and the recognition for comprehensive adaptation strategies in the community to

cope with natural disasters and climate change. Some general focus areas include:

- Develop community awareness and self-management programs in relation to hazard management. The emphasis is on equipping community groups exposed to certain types of hazards with the knowledge to manage that hazard;
- Provide training programs in the effective use of agro-climate information, including climate predictions (which have the potential not only to help minimize heavy losses in poor years, but also to maximize yields in good years) and vulnerability scenarios;
- Promote communication strategies between stakeholders, including effective use of the media. Good services and methodologies are ineffective unless the user understands and applies the information provided. At the same time, it is important that users be able to feed back how the information can be improved (*Wright, 2005*).

Finally, the introduction of natural disaster/climate change and climate variability issues at different levels of the educational system must be in an ongoing process to help build capacity among stakeholders to support adaptation in the future and to develop appropriate research activities and a greater awareness among citizens. Furthermore, campaigns to raise public awareness and disseminate information in order to involve a broad array of stakeholders are necessary. These campaigns can also be an opportunity for adaptation decision-makers to better understand the perception and views of the public on the issues.

6. Conclusion

There are many illustrations of potential coping strategies each with challenges and uncertainties. There can be no generic strategy that can be formulated as a suitable solution for wide applications in diverse areas. However, the goal is to establish guidelines to meet the specific needs of the user community that be incorporated in the development of adaptation policy framework and adaptation measures.

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Effect of climate change on growth potential in the mountainous region of southeast Norway

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Abstract—The COUP–ENGNOR ley crop modeling system was calibrated on relevant yield data from field trials in southern Norway. This parameterized version was used to compare the potential ley production at Fokstua (62°N; 970 m a.s.l.) for the period 1961–1990 with that of a Hadley A2 climatic scenario for the period 2071–2100. The impact of a climatic change, which projects a temperature increase by 2–3 °C, and a lengthening of the growing season by approximately 1.5 months, is an appreciable increase in production potential, especially as to fodder quality and feed unit yield. This is due to a new harvesting regime, which favors an early first cut and thus allows two seasonal cuts. The impact of the increased production potential of the mountainous districts of southern Norway towards the end of this century are considered, including the value of ley plant breeding towards optimal combination of late seasonal growth with maximum winter hardiness.

Key-words: climatic scenario, crop model, cultivar, ley, mountainous area, regrowth, timothy, wintering

1. Introduction

A large part of the reclaimable land reserves in Norway lies in the mountainous areas of the southeastern parts at altitudes from 600 to 1000–1100 m a.s.l. In the marginal agroclimatic zones corresponding to this region, less than 30 percent of the arable soil is so far taken into cultivation for the whole country (Grønlund, 1990). In the most marginal zone, corresponding to approx. 900–1100 m a.s.l. in South Norway, at most some 15 percent of the potentially arable land is cultivated. These areas, in spite of their extremely short growing season, might still give a satisfactory dry matter (DM) yield when used for fodder production by a hardy perennial grass crop. One reason for the low utilization is that a satisfactory (DM) yield depends on one late cut, and thus to the cost of feed

quality whether expressed as net energy (feed unit) or protein concentration in harvested DM. Both these quality traits decrease strongly with advancing grass development stage.

As the temperature climate ameliorates, cultivation will be possible and more profitable than today at higher altitudes, thus opening considerable areas in southeast Norway for increased food production. We have explored potentials and possible challenges by extending fodder production to higher altitudes in a future climate.

2. Materials and methods

The analytical tool of this work was the COUP–ENGNOR crop modeling system, in which the COUP model (Jansson and Karlberg, 2001) simulates soil moisture and crop water uptake based on daily values of global radiation, temperature, precipitation, relative air humidity, and wind speed. These data were the inputs to simulations of plant production by the ENGNOR model (Baadshaug and Lantinga, 2002), which calculates total and harvestable ley yield from the temperature, radiation, and soil moisture supply. The present model has been calibrated to weekly observations of growth rates of first and second growth of timothy at the University Experimental Farm. This has allowed a reliable description of the reduced regrowth capacity of the extremely hardy timothy cultivar Engmo (Fig. 1). In this study, the extrapolations into future climates were based on a regionally downscaled Hadley A2 scenario for the site Fokstua (62°N; 970 m a.s.l.) (Engen-Skaugen, 2007).

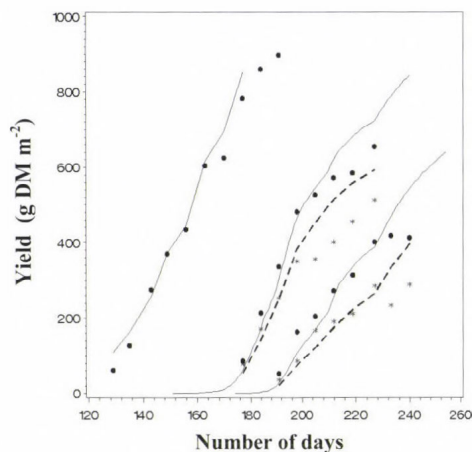


Fig. 1. Calibration of the ENGNOR ley crop model (curves) using first (left), and second growth rate observations (middle and right) at the University Experimental Farm (dots or stars) for two timothy cultivars, Engmo and Grindstad.

3. Results

The Hadley A2 scenario indicates only minor changes in the precipitation, whereas the air temperature (*Fig. 2*) will increase by 2–3 °C, implying a lengthening of the growing season by approximately 1.5 months. The effect of this change on the yield potential is seen from the comparison between the estimates for the 1961–1990 period and those of the 2071–2100 scenario (*Fig. 3*). The benefit of the climatic change may not be too striking when measured as a mere DM yield increase. The most important gain may be that of fodder quality, since the future climate will make possible two harvests in a season, a management regime which is not practical at this altitude in the present climate. The superior quality of young grass, especially as to net energy concentration, is more than ever appraised by milk and meat producers.

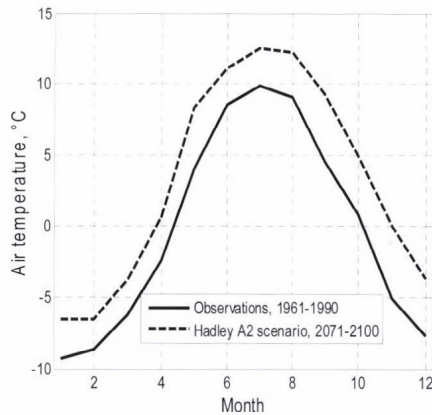


Fig. 2. Air temperature of the Hadley A2 scenario for the period 2071–2100 of Fokstua in southern Norway (62°N; 970 m a.s.l.), as compared with the observations during 1961 to 1990.

The results in *Fig. 3* are relevant for the timothy cultivar Grindstad, which is usually not considered as sufficiently winter hardy for the high altitudes. When choosing a more hardy cultivar, Engmo, to secure maximum winter survival, the yield gain from the warmer climate will be reduced (*Fig. 4*), due to the less vigorous second growth of this cultivar.

4. Discussion

The main limiting factors for agriculture in the marginal areas are the length of the growing season and the winter survival of perennial fodder crops, which usually are the only ones which can be grown. The expected increase of the

seasonal temperature has a considerable positive effect on future plant production potential. However, the same is not necessarily in the case of wintering conditions. The main problems might be warm spells during the winter, which will be more frequent, and imply increased risks of ice crust formation on the grass fields. Therefore, in the case of timothy ley culture, the hardy cultivar Engmo will still be a highly actual choice, to the cost of reduced seasonal yield (*Fig. 4*), whenever more than one harvest is practiced.

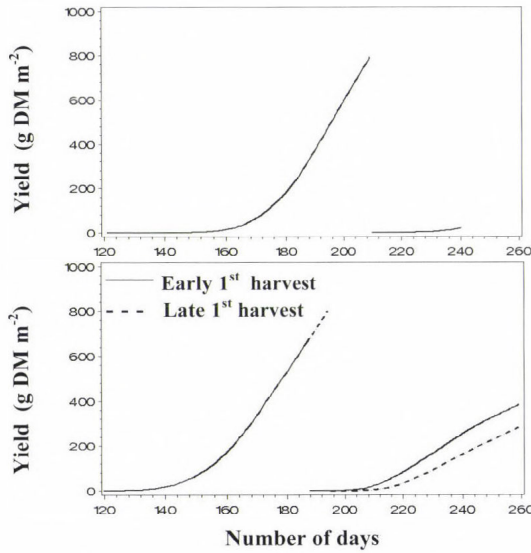


Fig. 3. Estimated yields of the Grindstad timothy ley at Fokstua (62°N; 970 m a.s.l.) for the period 1961–1990 (upper part) and for the scenario period 2071–2100 (lower part), using the ENGNOR crop growth model.

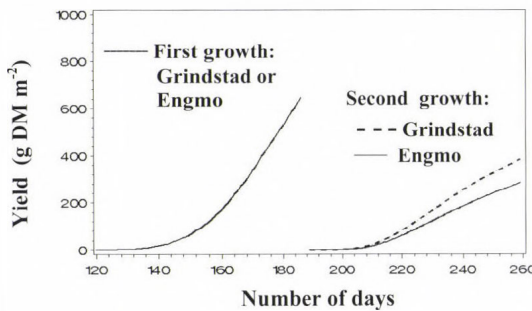


Fig. 4. Estimated yields of a timothy ley at Fokstua (62°N; 970 m a.s.l.) for the period 2071–2100 for the two contrasting timothy cultivars Grindstad and Engmo.

5. Conclusions

The projected climatic change will strongly increase the agricultural production potential of the mountainous areas of Norway. But, for a full benefit of the climatic change, the eternal challenge to the grass breeders still remains: to combine vigorous growth in the late growing season (see *Fig. 4*, Grindstad) with maximum winter hardiness (Engmo).

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Drought analyses of agricultural regions as influenced by climatic conditions in the Slovak Republic

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Abstract—Drought analysis of the Slovak territory was based on evaluation of climatic conditions during the growing season limited by daily mean air temperature $T > 10$ °C. Precipitation total (R in mm), and potential (E_0 in mm) and actual (E in mm) evapotranspiration were calculated for this period. Consequently, climatic index of drought ($E_0 - R$) and evapotranspiration deficits ($E_0 - E$) were evaluated on the background of agricultural productive regions. Climatic data from the database of the Slovak Hydrometeorological Institute in Bratislava in period of years 1960–1990 were used for evaluating the reference climate condition. Climatic stations used for GIS analyses were selected from the point of view of altitude, limiting plant production areas (up to 900 m a.s.l. – this altitude represents acreage 45,000 km²) and spatial distribution. Climate change conditions were generated by general circulation model CCCM for emission scenario SRES B2.

According to the results, agricultural regions of the Slovak Republic will become more sensitive in conditions of climate change on drought occurrence as compared with climate conditions of the last normal period 1961–1990. While 5 categories of drought conditions were recognized on the territory of the Slovak Republic in the reference period 1961–1990, additional two very dry categories can be recognized in agricultural regions of Slovakia according to climatic indices of both drought and evapotranspiration deficit. This fact has serious effects on potential acreage of some crops. High totals of potential evapotranspiration can evoke occurrence of drought more frequently. This fact should be taken into account in the future on the levels of both crop selections and water saving rotations.

Key-words: climatic index of drought, evapotranspiration deficit, precipitation, drought, growing season, Slovakia

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1. Introduction

Climatic conditions become the most important factor influencing variability of field crop yields in Slovakia today. Increase of annual mean air temperature by about 1 °C was occurred on most of climatic stations in Slovakia during last century. On the other hand, annual precipitations decreased by about 10% on lowlands of Slovakia (Danubian and east Slovakian lowlands) during this period. Precipitation totals varied also in mountainous regions, but no significant trend was found during last century (Lapin *et al.*, 2001). Increase of air temperature and shortage of precipitations create also conditions for drought occurrence, especially on lowlands of Slovakia. According to the outputs of the general circulation models (GCM), this trend is also supposed for future climate. Those facts call for analysis of drought occurrence in conditions of climate change on territory of the Slovak Republic.

According to the natural climate variability and the duration of drought, several levels of drought can be defined (Hayes *et al.*, 1999; Heim, 2002). For example, the difference between potential evapotranspiration and precipitation totals during growing season limited by mean air temperature $T \geq 10$ °C was defined as climatic index of drought for conditions of Central Europe. This index was frequently used in many works for evaluation of drought conditions (Ditmarová *et al.*, 2006; Dubrovský *et al.*, 2005; Hlásný and Baláž, 2008; Tomlain, 1997; Trnka *et al.*, 2007). This index was also used for agroclimatic regionalization of the Slovak Republic during the periods of 1931–1960 (Kurpelová, *et al.*, 1975) and 1961–1990 (Šiška and Špánik, 2008).

Evapotranspiration, as an important component of water balance, is also frequently used for evaluation of drought conditions in Slovakia. Spatial distribution of potential evapotranspiration was related to water needs of ecosystems (Tomlain, 1979; Škvarenina *et al.*, 2008), actual evapotranspiration was correlated to yield of some field crops (Matejka and Huzulák, 1995; Vidovič and Novák, 1987). Difference between potential and actual evapotranspiration defined as evapotranspiration deficit can be a good parameter for evaluating the drought condition of the landscape on agricultural level.

The aim of the paper is to evaluate drought occurrence in climate change conditions by means of GIS in Slovakia.

2. Material and methods

Climatic data from the database of the Slovak Hydrometeorological Institute (SHMI) in Bratislava were used for calculation of present climate (1×CO₂) in this paper. Climatic stations used for GIS analyses were selected with respect to agricultural productive types, altitude (up to 900 m a.s.l. – upper range of plant production), and spatial distribution. Evaluated acreage represents 45,000 km² –

90% of total area of Slovakia. Climatic data of the period 1961–1990 for 11 stations given in *Table 1* were used. These climatic stations represent 4 Slovak agroclimatic regions (productivity types).

Table 1. Agricultural regions and related climatic stations

Agricultural regions (productive type)	Altitude (m a.s.l.)	Climatic stations	Altitude (m a.s.l.)
Maize	< 200	Somotor	100
		Hurbanovo	115
		Nitra	143
		Piešťany	165
		Kamenica n/C.	178
Sugar beet	200 – 300	Rimavská Sobota	214
		Prievidza	260
		Košice	230
Potato	300 – 500	Bardejov	304
		Sliač	330
Mountainous	>500	Liptovský Hrádok	640

Temperature and drought characteristics were evaluated for growing seasons limited by daily mean air temperatures $T > 10.0$ °C, henceforth signed by GS10. Daily mean air temperature sums (TS in °C), precipitation totals (R in mm), potential evapotranspiration (E_0 in mm), and climatic index of drought ($E_0 - R$ in mm) were calculated for GS10. Potential (E_0) and actual (E) evapotranspiration were calculated according to Budyko-Zubenok method (cit. in *Tomlain, 1979*).

In this study, two indices were selected for spatial evaluation of drought conditions for the territory of Slovakia: the climatic indices of drought and evapotranspiration deficit.

Since drought conditions are frequently observed during the whole growing season, calculation was applied for the whole growing season (GS10 period).

Climatic index of drought was calculated as:

$$K_{GS10} = E_0 - R, \quad (1)$$

where E_0 is the potential evapotranspiration during GS10 and R is the rainfall during GS10.

Evapotranspiration deficit was calculated as:

$$\Delta E_{GS10} = E_0 - E \quad (2)$$

where E_0 is the potential evapotranspiration during GS10, and E is the actual evapotranspiration during GS10.

Onset and end of GS10 were established according to numeric analyses (Nosek, 1972). GS10 is limited by biological temperature minimum of thermophil plants (by daily mean air temperature of $T \geq 10.0$ °C).

A raster model of geodata was applied for the spatial evaluation of the climatic parameters. Through the interpolation, the spatial change of the individual average meteodata was calculated. The method of regularized spline interpolation with tension and kriging was applied. Global radiation, air mean temperature, and precipitation for $2 \times \text{CO}_2$ climate were generated by general circulation model CCCM 2000 (Lapin *et al.*, 2001). Consequently, potential and actual evapotranspirations were calculated.

Finally, by comparing the spatial distribution of the climatic indices of drought and evapotranspiration deficit for $1 \times \text{CO}_2$ and $2 \times \text{CO}_2$ scenarios, climate sensitivity of the agricultural regions of Slovakia to drought occurrence was evaluated.

3. Results

3.1. Duration of growing season

The main growing season (GS10) is limited by the onset and end of daily mean air temperature $T > 10$ °C, and it is the period when drought conditions are frequently observed.

The onset and end of GS10 in altitudinal profile of Slovakia are given in Fig. 1. As resulted from trend lines of the onset and end of GS10, the onset of GS10 would start significantly earlier by about 28 days in climate conditions of the $2 \times \text{CO}_2$ climate in the whole altitudinal profile as compared to climate conditions of the $1 \times \text{CO}_2$ climate. The end of the GS10 period will be delayed by about 14 days under the $2 \times \text{CO}_2$ climatic conditions as compared to the $1 \times \text{CO}_2$ climatic conditions.

The duration of the GS10 of the maize region related to the reference period $1 \times \text{CO}_2$ is 175 days or which represents about 34% of total acreage of agricultural regions. Those conditions will occur on 80% of the total agricultural regions acreage in $2 \times \text{CO}_2$ climatic conditions and the duration of GS10 can exceed 200 days in the Danubian lowland, east Slovakian lowland, and Zahorie lowland. Duration of GS10 influences positively photosynthetically active period of maize and, therefore, also biomass creation. On the other hand, a longer duration of GS10 also increases the potential risk for drought occurrence.

3.2. Precipitation (R)

Generally it is supposed, that the precipitation total increases in $2 \times \text{CO}_2$ climatic conditions. Except for the GCM (CCCM 2000), this fact is influenced also by a

rising duration of GS10. An increase of R by about 60 mm in the lowlands of southern and eastern Slovakia and by 79–134 mm in northern Slovakia will probably not be sufficient. All regions should receive more than 390 mm precipitation during GS10 in $2\times\text{CO}_2$ climatic conditions, and a raising rainfall could favorably influence the yield of some crops (e.g., maize and other cereals). The distribution of precipitation generated by the GCM in the context of rising air temperatures and consequently increasing crop water demands during GS10 will, however, very probably result in increasing occurrence of drought conditions reducing yields of field crops.

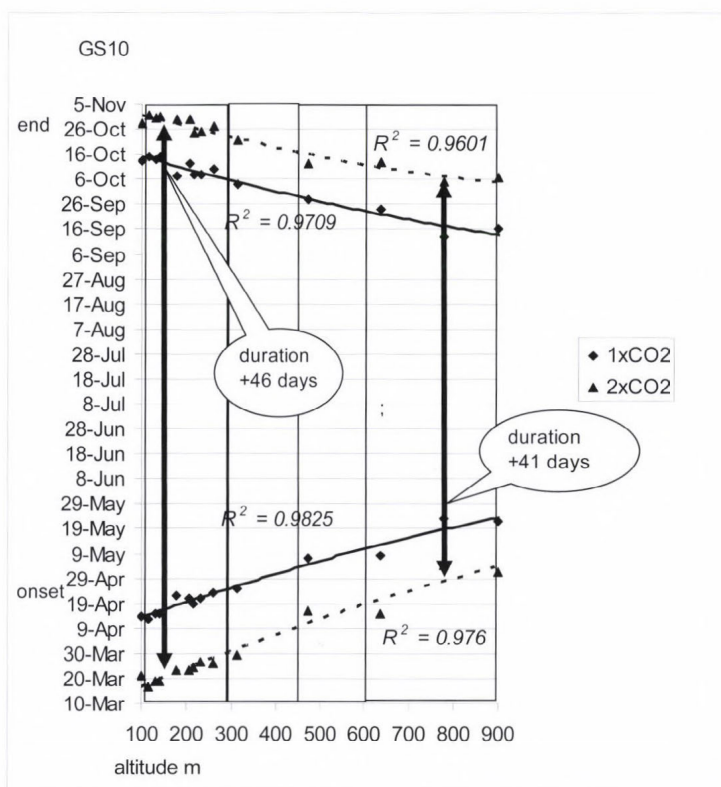


Fig. 1. Onset and end of growing seasons GS10 in dependence on altitude for $1\times\text{CO}_2$ and $2\times\text{CO}_2$ climates.

3.3. Changes of evapotranspiration characteristics

Evapotranspiration as a significant element of environmental water balance is a suitable indicator for moisture balance in any space and time scale. While

potential evapotranspiration can be used as an indicator for estimating of water demand of the maximum productivity of ecosystems (Šiška, 1992), the exact estimation of actual evapotranspiration can lead to an actual assessment of biomass production (Vidovič and Novák, 1987).

Our study shows that potential evapotranspiration of $E_0 > 450$ mm during the GS10 period in the whole agricultural area, and even E_0 exceeding 700 mm, can be expected in the warmest areas of Slovakia (south of Danubian lowland, and the lowest areas of east Slovakian lowland). Such high E_0 totals call for the need of effective management with water resources and for building irrigation systems in most of the territory of Slovakia to eliminate negative effects on yield production.

3.4. Climatic index of drought

Climatic index of drought (K) was applied for the first time as index of agroclimatic regionalization of Slovakia by Kurpelová *et al.* (1975). The difference between potential evapotranspiration and precipitation during summer months was taken into account. Because drought conditions are frequently observed during the whole growing season, K was recalculated for the whole GS10 period (Šiška and Špánik, 2008).

The supposed air temperature increase and consequent increase of GS10 duration influence the E_0 increase in the $2\times\text{CO}_2$ climate on the whole area of Slovakia. During GS10, E_0 will increase in the lowlands of Slovakia by 160–170 mm, i.e., by 27–30%, on uplands by 106 mm, i.e., by 34%. $E_0 > 500$ mm can be expected in all agricultural regions of Slovakia, $E_0 > 750$ mm can be expected in the warmest regions of Slovakia (south of Danubian lowland and east Slovakian lowland). Such high E_0 totals during the relatively short GS10 period (compared to GS5) will increase the potential of the occurrence of drought periods. Effective management of water resources can, therefore, eliminate the negative influences of evaporation demand on agricultural production in the majority of regions in Slovakia.

K_{GS10} is changing in the whole altitudinal profile of Slovakia significantly. The original classification scale of drought-wet conditions proposed by Kurpelová *et al.* (1975) was based on 50 mm differences of the index. According to this criterion, 5 categories of drought conditions can be defined for the reference ($1\times\text{CO}_2$) climate. Most of the agricultural acreage belongs to the areas where wet conditions prevail in altitudes above 550 m. According to the calculations based on CCCM outputs, those conditions can be found in future in altitudes higher than 700 m. Other two categories of drought can be defined, where the deficit of water exceed 250 mm during GS10 (Fig. 2). These two new categories of drought will cover the most productive regions of the Slovak Republic – the Danubian and east Slovakian lowlands that represent the maize region productive type.

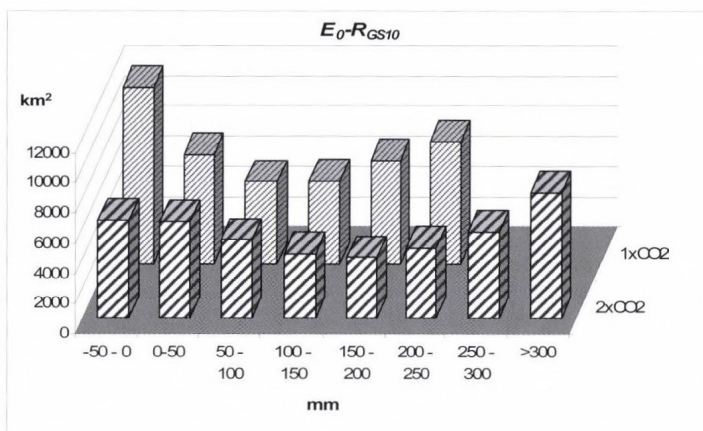


Fig. 2. Spatial distribution of climatic index of drought (K) during GS10 for $1\times\text{CO}_2$ and $2\times\text{CO}_2$ climates in Slovakia.

3.5. Evapotranspiration deficit

Evapotranspiration deficit ΔE as an important compound of water balance was also used for evaluation of drought conditions in Czechoslovakia (Tomlain, 1979). Except for meteorological factors, the calculation of actual evapotranspiration takes into account also soil water content and therefore, this parameter can better reflect drought conditions of agricultural regions.

According to the index ΔE , the territory of Slovakia looks even more vulnerable to drought than according to the previous index K . While $\Delta E \leq 100$ mm was calculated for sites with altitude over 300 m for the reference climate $1\times\text{CO}_2$, those conditions will be found in altitudes above 500 m for the $2\times\text{CO}_2$ climate (Table 2). These values represent potato and mountainous productive regions.

Table 2. Climatic index of drought ($E_0 - R$) and evapotranspiration deficit ($E_0 - E$) related to agricultural productive regions for $1\times\text{CO}_2$ and $2\times\text{CO}_2$ climates in Slovakia

Agro regions	$E_0 - R$ [mm]		$E_0 - E$ [mm]	
	$1\times\text{CO}_2$	$2\times\text{CO}_2$	$1\times\text{CO}_2$	$2\times\text{CO}_2$
Maize	150 – 250	250 – 360	130 – 220	240 – 350
Sugar beet	75 – 150	150 – 250	70 – 130	140 – 240
Potato	0 – 75	-20 – 150	30 – 70	90 – 140
Mountainous	<0	<-20	<30	<90

The classification scale of drought-wet conditions of this index is also based on 50 mm differences. According to this criterion, 5 categories of drought

conditions can be defined for the reference ($1\times\text{CO}_2$) climate. As resulted from calculations based on CCCM outputs, two new very dry categories of drought can be introduced, where $\Delta E \geq 250$ mm (Fig. 3). Except for the Danubian and east Slovakian lowlands, these two categories of drought will cover also valleys of Slovakian rivers up to altitudes of 300 m. On the other hand, the acreage of agricultural regions, where $\Delta E < 50$ mm, will diminish under conditions of climate change.

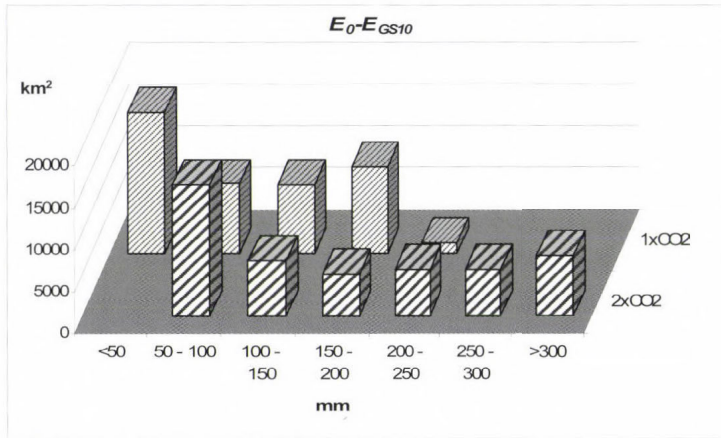


Fig. 3. Spatial distribution of evapotranspiration deficit ($E_0 - E$) during GS10 for $1\times\text{CO}_2$ and $2\times\text{CO}_2$ climates in Slovakia.

4. Conclusions

Drought conditions of agricultural regions were analyzed by climatic (climatic index of drought) and agroclimatic (evapotranspiration deficit) indices for the Slovak Republic.

It was found that the duration of the growing period (GS10) influences also the potential for drought occurrence.

According to both indices, two very dry and hot regions can be classified where the deficit of water exceed 250 mm. These two categories of drought will cover the most productive regions of the Slovak Republic – the Danubian and east Slovakian lowlands that represents the maize productive areas.

According to the evapotranspiration deficit, the agricultural regions of the Slovak Republic are more vulnerable under conditions of the applied climate change scenario as compared with *K*. $\Delta E \geq 250$ mm, except for Danubian and east Slovakian lowlands, will probably be recorded also in valleys of rivers up to altitudes of 300 m. Agricultural regions, where $\Delta E < 50$ mm, will probably disappear under conditions of this climate scenario in Slovakia.

According to K_{GSI0} , most of the agricultural acreage belongs to areas where wet conditions prevail in altitudes above 550 m a.s.l. in the $1\times\text{CO}_2$ reference climate. As resulted from calculations based on CCCM outputs, those conditions will be found in altitudes higher than 700 m.

Except for agroclimatic planning issues, these facts should be taken into account in breeding strategies of new crop varieties suitable for the future climate of Slovakia.

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Consequences of climate change on some maize characteristics in Hungary

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Abstract—The influences of global climate change on sensible and latent heat fluxes of maize were studied by using the simulation model of *Goudriaan* (1977). Eight scenarios were made, an increase of CO₂ content until doubling the recent content was included in the scenarios. Some of the scenarios were developed by downscaling the *IPCC* (2007) report (A2 and B2) to Hungary, and the others by taking into account more serious weather changes. Surprisingly, the distribution of intercepted radiation among sensible and latent heat fluxes in the individual scenarios was not significantly modified. A given increase in ambient air temperature caused a lesser rise in crop temperature at cob level, demonstrating the compensation role of the canopy. The moderate rise in crop temperature indicated that the plants did not suffer significantly from lack of water in any of the scenarios. However, there was a variation during the diurnal cycle. The doubled CO₂ concentration alone increased the net carbon assimilation rate of maize by 40%. Photosynthesis decreased only in cases with warmings higher than 6 °C. Decreased precipitation counteracted the positive influence of elevated CO₂ on carbon assimilation.

In other scenarios the latent heat flux increased in comparison to control run. This justifies the existence of reserve soil water at Keszthely, even in on extra hot day during July.

Key-words: micro-meteorological model, simulation, maize canopy, global warming

1. Introduction

The plant canopy architecture determines the energy and mass exchange creating the canopy microclimate, which affects the plant physiological processes. Thus, there is a long series of impacts from changes in environmental factors to plant responses. To investigate such complex relationships, simulation

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models are the most suitable tools, because they draw attention to those fields where there is a lack of knowledge. The early works of *de Wit* (1965), *Monteith* (1973), *Shawcroft et al.* (1974), *Norman* (1979), *de Vries* (1975), and *Waggoner* (1975) can be considered as the beginning of crop growth simulation modeling. The first reflections on modeling were provided by *Passioura* at a relatively early date, in 1973. *Bouman et al.* (1996) has summarized the 30-year experience of the “Dutch school” dealing with the simulation modeling founded by *de Wit*, and outlined the way of further development.

The simulation models offer advantages in quantitative assumption of crop growth. Although the shortcomings of model application are well known, including limited accuracy of local climate change projections, the crop microclimate simulation model (CMSM) of *Goudriaan* (1977) provides complexity in crop-environment studies. The effect of increased atmospheric carbon dioxide concentration may be hypothesized by its direct effect as well as its effect on plant canopy temperature via evaporative cooling. The paramount importance of crop temperature is provided by the fact that it determines the intensity of physiological processes including photosynthesis through influencing intensity of biochemical processes. The aim of this examination was to present the expected changes based on various scenarios in crop temperature and intensity of photosynthesis to the area of Keszthely. The model results are illustrated by plants at fulfilled tasseling, a stage of phenological development that is certainly achieved in Keszthely in the month of July. Out of the three model layers regarding the energy distribution, we have chosen the middle one: the cob stratum in which physiological processes are the most intensive.

Topicality was grounded by the appearance of the latest climate scenarios published in *IPCC 2007 Report*, and its scenarios downscaled to Hungary (*Bartholy et al.*, 2007). At a certain part of the scenarios we used average changes (*Bartholy et al.*, 2007), while – due to the growing frequency of extreme weather phenomena – we have also drafted several notions regarding extreme hot days. However, due to the uncertain precipitation scenarios we have not widened this to the precipitation.

2. Material and methods

2.1. Source of model inputs

The model inputs are site- and plant-specific values (plant height, leaf density in different layers), soil characteristics (soil moisture content, physical soil properties), and hourly meteorological data (air temperature, global radiation, relative humidity, soil temperatures). The hourly meteorological elements were the driving variables of the model, which were transformed from the standard measurement level (Agrometeorological Research Station at Keszthely,

46°44'N; 17°14'E; 114.2 m above sea level) to the reference level required by the model. The automatic weather station equipped by Eppley pyranometer is a part of the observation network of the Hungarian Meteorological Service. Data from the preceding station back to 1961 are also included. The meteorological data measured under standard conditions were correlated to the reference level required by the model on the basis of former investigations by *Anda et al.* (2003). The leaf area and its density were measured in the field on 10 sample plants weekly, using a LI-3000A type leaf area meter. The soil moisture content in the upper 1 m was also measured in the field with thermo-gravimetric method at 10 cm intervals every 10 days.

Our test plant was a maize hybrid for which we have more than 30-year data with weekly observations of plant height, leaf area index, leaf breadth, density, etc. These values and relative water content of crop were parameters of the model. The observed soil water content also covers more than 30 years with weekly soil sampling and gravimetric determination of soil water down to a depth of 1 m for every 10 cm layer. Precipitation projections were converted into local soil water content expressed in terms of soil water potential, which in turn is the model input regarding crop water supply. The water, as a basis material of photosynthesis and a cooling substance for transpiration, determines crop energy balance together with the intensity of photosynthesis. Physical properties of the soil (heat capacity, heat conductivity, soil surface resistance, starting value of soil heat flux, diameter of soil particles) were the parameters of the model. The former and current atmospheric CO₂ concentrations as parameters were taken into account on the basis of the local measurements by *Dunkel* (1982) and the national measurements of *Haszpra* (2007). More details on plant and other data samplings are found in an earlier publication of *Anda* (2006).

A one-day detailed study by canopy simulation will only be presented for an “average day” in July. Weather, crop, and soil data for July between 1961 and 1990 served as a reference in our simulation. We chose the month July for demonstration because the intensity of maize physiological processes is the highest during July. The one day resolution attributes to model construction. In some scenarios the influence of extreme hot days is also included in the study.

2.2. *The applied scenarios*

The **first scenario**, called the control scenario, is the same as presented in the *IPCC* (2007) Report. Mean values of July during 1961–1990 and a CO₂ concentration published by *Haszpra* (2007) at 340 ppmv were applied. Soil water potential was –7 bar.

The **second scenario**, called 1997–2006, represents the changes of recent years by data from 1997–2006. According to the last climate normal of Keszthely, the summer air temperature has been significantly higher by 0.6 °C

as compared with the monthly mean of July of the period 1901–2000. Accumulated precipitation of the same month has decreased by about 10–15% in Keszthely, though it is not statistically significant. The soil water potential was equal to -7.7 bar. We estimated the atmospheric CO_2 concentration to be 380 ppmv on the basis of the background measurements.

The **third scenario**, called $2\times\text{CO}_2$, represents the impacts of the rising ambient air CO_2 concentration alone. We doubled the present CO_2 gas concentration (760 ppmv), and the meteorological inputs remained the same as in the control scenario. With this we estimated the expected change due to increased CO_2 concentration to the time period 2071–2100.

In scenarios four to eight – beside doubling the current CO_2 level (760 ppmv) – we gradually increased the air temperature and decreased the precipitation values compared to the basic run (1961–1990). The **fourth scenario**, called $3.8^\circ\text{C}/-15\%$, is based on the B2 scenario (IPCC, 2007). Mean summer temperature in Keszthely is estimated to rise by 3.8°C and precipitation to decrease by about 15% (soil water potential: -9 bar).

The **fifth scenario**, called $4.8^\circ\text{C}/-25\%$, used the summer data of the A2 IPCC (2007) scenario for 2071–2100, downscaled to Hungary by the above mentioned method. It has estimated a stronger warming of $+4.8^\circ\text{C}$ and a 25% decrease in precipitation. We have noted that standard deviation is rather high in both scenarios ($\pm 15\%$), which implies strong uncertainty. The soil water potential was settled to -10 bar.

In the **sixth scenario**, called $6.0^\circ\text{C}/-25\%$, we increased the average air temperature by 6.0°C together with a 25% decrease in precipitation. This 6°C rise is close to the value of the upper limit value (6.4°C , annual average) in the IPCC Fourth Assessment Report (2007). The soil water potential was -9 bar.

Keeping that in mind we performed a further increase in the degree of warming up by involving the 1.4 times product of the upper temperature rise (6.4°C) pertaining to Hungary (9°C) in the last two scenarios. To evaluate the effects of the uncertainty of precipitation projects, we assumed a weak decrease in precipitation (-10%) in the **seventh scenario** ($9^\circ\text{C}/-10\%$), and then a more significant drying (30% precipitation decrease) in the **eight scenario** ($9^\circ\text{C}/-30\%$). Their soil water potentials were -7.7 and -11 bar. The comparison of these latter two scenarios provided opportunity to quantify the impacts on plant growth of the different amounts of precipitation.

2.3. Model description

2.3.1. Energy balance of canopy layers

The advantage of present study, the use of Goudriaan's (1977) simulation model is that it could keep its high scientific level together with its relative simplicity. In 1989 the author himself published the critical evaluation and application

problems of the model (Goudriaan, 1989). The modified versions of the model (Chen, 1984; Goudriaan and van Laar, 1994) are also user-friendly and suitable for the better knowledge of the relationship between plant and environment and for providing the consequences of scenarios like global warming (Dióssy, 2008). The time step in the model is one hour.

The CMSM of Goudriaan simulates the canopy microclimate as a function of plant, soil, and weather characteristics. Plant stand plays important role in the model feedback as partly influenced by earlier weather. One of the advantages of the model is that short-term and long-term influences are also incorporated in its structure.

The amount of intercepted radiation was determined after Monsi and Saeki (1953). Partitioning of the intercepted radiation into sensible and latent heat fluxes was calculated on the basis of energy balance equations (Goudriaan, 1977):

$$0 = Rn - M - Q_H - \lambda E, \quad (1)$$

where Rn is the canopy net radiation [W m^{-2}], M is the metabolic storage [W m^{-2}], Q_H is the sensible heat flux [W m^{-2}], λE is the latent heat flux [W m^{-2}], and λ is the evaporation heat [kJ kg^{-1}].

The metabolic storage was neglected in the model. The sensible heat flux (Q_{Hi}) in the i th layer in the canopy is:

$$Q_{Hi} = \rho c_p \frac{T_{ci} - T_{ai}}{r_{aHi}}, \quad (2)$$

where T_{ai} is the air temperature in the i th layer [K], T_{ci} is the canopy temperature in the i th layer [K], r_{aHi} is the aerodynamic (boundary layer) resistance for sensible heat transfer in the i th layer [s m^{-1}], ρ is the air density [kg m^{-3}], and c_p is the specific heat of air [$\text{J kg}^{-1} \text{K}^{-1}$].

The latent heat flux (λE_i) in the i th layer can be calculated as follows:

$$\lambda E_i = \rho c_p \{e_s(T_{ci}) - e_s\} / [\gamma(r_{awi} + r_{ci})], \quad (3)$$

where $e_s(T_{ci}) - e_i$ is the difference between saturation vapor concentration at plant temperature and actual vapor concentration [$\text{m}^3 \text{m}^{-3}$], r_{awi} is the aerodynamic resistance for water vapor transfer in the i th layer [s m^{-1}], r_{ci} is the crop resistance in the i th layer [s m^{-1}], and γ is the psychrometric constant [$0.5 \text{ g m}^{-3} \text{K}^{-1}$].

After calculating the sensible and latent heat, the air temperature (T_{ai}) in the i th layer was estimated as:

$$T_{ai} = T_{ai-1} + Q_{Hi} r_i / \rho c_p, \quad (4)$$

where r_i is the characteristic value of resistance against heat in the i th layer [$s\ m^{-1}$] when $i=1$ (when canopy is considered as one layer) and (T_{ai-1}) is the air temperature for the reference level. When canopy is divided into more than one layer, the $i-1$ th layer means the bordering one. The crop temperature (T_{ci}) was calculated similarly to the air temperature:

$$T_{ci} = T_{ai} + (Q_{Hi} - Q_{Hi-1})r_{H,i} / \rho c_p. \quad (5)$$

2.3.2. Photosynthesis of the whole canopy

Rate of net CO₂ assimilation (F) was considered empirically as follows:

$$F_n = (F_m - F_d)[1 - \exp(-R_v \varepsilon / F_m)] + F_d, \quad (6)$$

where F_m is the maximum rate of net assimilation, F_d is the dark respiration, R_v is the absorbed short wave radiation (per LAI), ε is the slope of the curve of $F-R_v$ at low light intensities, or efficiency ($17.2 \cdot 10^{-9}$ kg J⁻¹ light in maize). Contrary to crop temperature and sensible and latent heat fluxes, the photosynthesis is calculated independently of energy balance and for the whole canopy only (Goudriaan, 1977).

The validation of the CMSM pertaining to the location of model building was performed by several authors (Stigter *et al.*, 1977; Singh and Jacobs 1995). The publication of Hiramatsu and Maitani (1984) firstly drew attention to the problems for simulation during the night hours. The Hungarian verification of the model regarding both the microclimate and several plant characteristics was performed by Anda and Lőke (2003, 2005) and Anda *et al.* (2001, 2002).

2.3.3. Assumption of crop water status

The water status of the canopy influences both the transpiration and photosynthesis by setting a lower limit to stomatal resistance. The relation between this lower limit and relative water content is given by Goudriaan (1977). The relative water content is calculated as the ratio of actual and maximum water contents. The value of maximum water content is based on leaf thickness ($2.5 \cdot 10^{-3}$ kg m⁻² times the leaf area index). The actual water content is an integral of water uptake minus transpiration rate (Penman, 1948). The first feedback is created by the relationship between transpiration and stomatal resistance. Another feedback functions through the water uptake, since lower water content of plants forces more water to flow from the soil. The soil water stress was supposedly set at -0.1 bar water potential, root resistance is a function of soil temperature, and plant stress is a function of the relative water content.

2.3.4. Statistical evaluation

We evaluated the significant differences between model runs by using paired t-test that was performed by the free version of *STATA 5.0* (1996) program package. The process reduces the two-sample t-test to one-sample test since there is no possibility of repetition (thus, of calculation of standard deviation) of the model runs. The test compares the mean value of the sample to an expected mean value. According to the null hypothesis, if the mean value of differences is 0 then the two samples are statistically the same. If the mean value of differences is not 0 then the control and the given scenarios are significantly different. The significance level was fixed at 5% in the course of the process.

3. Results and discussion

3.1. Energy use in the cob layer

The energy distribution for sensible and latent heat fluxes of the individual scenarios were not significantly modified in comparison to the control scenario, the difference to the control did not exceed 10% in any treatments (*Table 1*) which is in the range of error of the models as evaluated by *Singh and Jacobs* (1996), who diagnosed overestimations of 9 and 10% regarding the amount of simulated latent and sensible heat, respectively. It is worth noting that soil moisture reserves in Keszthely, even during the extremely hot days of July, were it is big enough to allow the latent heat to increase as compared with the control run. However, in case of more serious precipitation decrease they will supposedly be reduced and cause drastic fallback in latent heat (evapotranspiration depression).

Table 1. Ratio of the sensible and latent heat fluxes in maize on an average day in July at Keszthely

Scenario/ fluxes	1961– 1990	1997– 2006	2xCO ₂	3.8 °C/ –15%	4.8 °C/ –25%	6.0 °C –25%	9.0 °C/ –10%	9.0 °C/ –30%
Sensible heat (%)	32.3	32.2	35.4	32.1	32.4	31.4	26.0	29.3
Latent heat (%)	67.7	67.8	64.6	67.9	67.6	68.6	74.0	70.7

Though, the hardly changing energy ratios do not mean that the amounts of the sensible and latent heat were not modified by the different model runs as compared with the control runs. The changes produced by the individual scenarios are illustrated through the example of the latent heat. The narrowing of the stomata opening due to the doubled CO₂ concentration significantly

decreased the latent heat by 14.2%. A further significant difference could be found on extremely hot days (at the temperature change of +9 °C), when the degree of modification depended also on water supply. In the scenario with a modest decrease in precipitation (only 10%) the energy spent on evaporation significantly increased, by 30.2%. If the average precipitation was reduced by 30%, the amount of latent heat increased only by 13.9% due to a reduced amount of available water. A comparison of the daily water loss of the individual scenarios with that of the control run also credibly reflected the differences determined in latent heat (*Fig. 1*). Change in soil moisture influences the movements of stomata. Interaction in soil water and transpiration is taken into account by calculation of stomatal resistance.

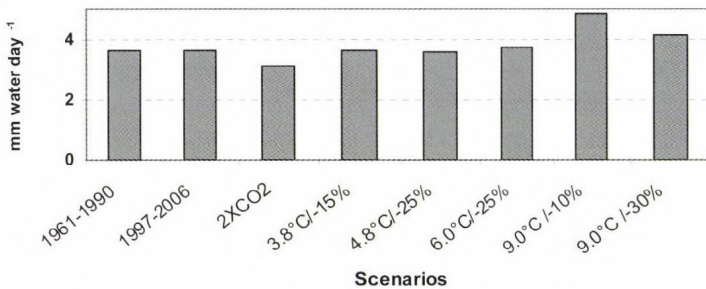


Fig. 1. Daily amounts of maize water losses (mm) in different scenarios at Keszthely during July.

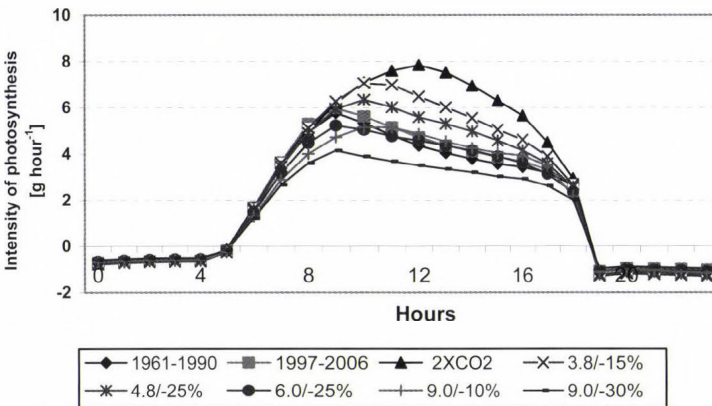


Fig. 2. Daily variation in the intensity of carbon assimilation in maize during July. Changes refer to 1961–1990.

Under the same weather conditions, the doubled CO₂ content significantly increased the net carbon assimilation rate of maize by 40% (*Fig. 2*). The balance

of the photosynthetic rate of the past decade was positive (+7.1%), and increasing carbon assimilation are predicted by the fourth and fifth scenarios (14 and 24%). Photosynthesis decreased only in cases with warmings higher than 6°C. A loss in photosynthesis will result from reduced amount of available soil water (precipitation); a good example of this relationship is the comparison of the two model runs with the same warming up of 9°C but with different precipitation. At a decrease of 10% the daily carbon assimilation rate was reduced by 13%, while with a 30% less rainfall the rate was reduced by more than 30%. The model application suggests that in Hungary the future limiting factor of outdoor maize production without irrigation might be the precipitation.

3.2. Crop temperature inside the canopy

The simulated plant and air temperatures of the scenarios showed similar diurnal pattern but at different temperature in levels (Fig. 3) given by Dióssy (2008). Air temperature was in all cases higher than leaf temperature as found also by Singh and Jacobs (1996), but the difference remained under 1°C. This indicates that the plants did not suffer significantly from lack of water in any of the scenarios.

In the past decade the crop temperature at cob level, similarly to that of the air temperature, rose significantly by 0.6°C. However, there was a variation during the diurnal cycle. From the second half of the night to the solar noon, the hourly rise in crop temperature was significantly higher for the past decade (1–1.5°C per hour) (Fig. 3). The difference between the temperatures of the control and second scenarios decreased during early afternoon, and in the late afternoon it stabilized between –0.2 and –0.7°C. Such a variation during the diurnal cycle was not found when comparing other scenarios with the values of the basic run of 1960–1990.

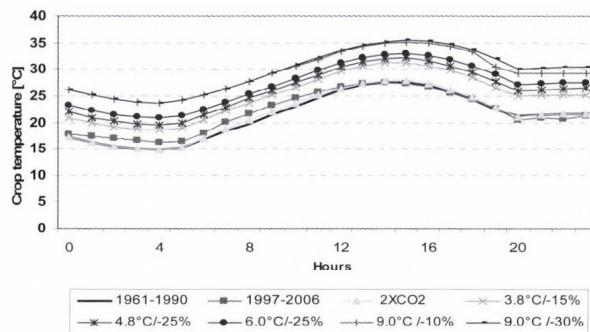


Fig. 3. Daily variations in maize crop temperature in the middle of the canopy (cob level).

The rise in plant temperature determined for the downscalings of the A2 and B2 scenarios to Hungary did not reach the rise of the ambient air

temperature. This means that the cooling effect of the canopy transpiration on plant temperature was significant. In the scenarios with a smaller warming up, the degree of cooling was lower, only a couple of tenths of a degree. With simulating a greater warming up (above 6 °C), the canopy compensating effect on plant temperature still worked, but it was significantly reduced. The cooling effect of the canopy that mitigates the increase in plant temperature as compared with that of the ambient air emerged even in the last two scenarios (seventh and eighth). The cooling effect was 0.9 °C in the seventh scenario with low precipitation reduction, and only about the half of that, namely 0.5 °C in the eighth scenario with greater reduction in rainfall.

The optimum crop temperature range for maize in July is somewhere between 22–24 °C on average under Hungarian climatic conditions. At present, in most of the seasons there is enough precipitation for plant cooling to not override this optimum temperature. During global warming, the air temperature rise may increase the leaf temperature above this optimum level. Reduced precipitation may disturb the present balance, and farmers have to adapt to the changes for example by choosing more suitable crops for the given environment. One of the best tools in the hands of the Hungarian farmers to mitigate future impacts of climate change seems to be the use of irrigation to a greater extent.

4. Conclusions

The ratio of sensible to latent heat flux remained almost the same of all different scenarios. At a magnitude of less than 10% this was comparable to the overestimations by the crop microclimate simulation model in earlier simulations. It does not have the meaning that the absolute values of future projections were the same as the latent heat flux of control run. The doubled CO₂ level narrows the pore opening by about 14%. This may be a positive effect of global warming on the water loss of plants at Keszthely, where the water is the limiting factor of non irrigated maize growing. The latent heat flux of additional scenarios increased in comparison to control run. This justifies the existence of the reserve soil water at Keszthely even in an extra hot day during July.

Reduced transpiration and thus plant cooling at elevated CO₂ produced a moderate rise in plant temperature of 0.2 °C (in the third scenario). A given increase in ambient air temperature caused a lesser rise in crop temperature at cob level (place of yield formation in maize), demonstrating the cooling role of the canopy transpiration. This effect was detected even in extreme hot days.

Photosynthesis decreased only in cases with warmings higher than 6 °C. The photosynthesis was reduced by one third on an extremely hot day with 30% reduction in rainfall. This decline in photosynthesis may result in serious yield depression.

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