A Decision Support System for Foresight and Potentials in Rural Areas under Regional Climate Change

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Keywords: *decision support system, climate change, spatial simulation, spatial evapotranspiration, yield estimation, expert knowledge, interaction between sectoral models, interactive control by the user*

EXTENDED ABSTRACT

Climate change means not only an increase of the mean temperature, but also a change in atmospheric CO_2 content and in precipitation as well as an increase of extreme weather events such as an increase of dry periods in spring and summer, thunderstorms with intensive rains, or heavy rain falls in late summer and winter. Climate change directly influences the water availability in a region and indirectly ecosystems functions and agricultural production. A computer information system can help to plan human activities to compensate for the effects of climate change. Such a system ought to provide information about the estimated local weather, the effects on the water balance, effects on the agricultural crop production, the development of ecosystems, etc. This information should be provided in such a way that it can be used not only to evaluate the traditional agricultural production but also the impacts of new production techniques such as energy production using wind power, solar radiation or energy crops. These new production methods together with the use of genetically modified organism (GMOs) bring a secondary effect to the region that influences the economic situation of the farmers, i.e. an influence on the social development on the one hand and on the other hand changes in ecosystem services. A decision support system has to take account of both effects. The system design and first applications were described and discussed.

1. INTRODUCTION

Sustainable development of rural areas requires highly productive and environmentally sound agriculture. Climate change is expected to affect agriculture very differently in diverse parts of the world (Parry et al. 1999). The resulting effects depend on current climatic and soil conditions, on the direction of change and on the availability of resources and infrastructure to cope with change. Considerable study has gone into questions of just how farming might be affected in different regions, and by how much, and whether the net result may be harmful or beneficial. There is further uncertainty regarding the physiological response of crops to carbon dioxide enrichment in the atmosphere. The problem of predicting the future course of agriculture in a changing world is caused by the fundamental complexity of natural agricultural systems and by the socioeconomic systems governing world food supply and demand (Rosenzweig and Hillel 1998). Another common result is that a changed landscape water balance increases the risk of water deficiency for non-production ecosystems (Wessolek and Asseng 2006). Unfortunately the case studies, mostly based on roughly discriminated land use types, e.g. cropland/grassland/forest with a low spatial resolution (Rounsevell et al., 2006) or their assessment is confined to only a few important crops (wheat, maize, rice, sorghum, etc.). Those scenario studies can help to compare different future situations but they exclude the people who live in the region as regional players and they focus only on agriculture.

A decision support system (DSS) opens up new possibilities to include different landscape aspects (water, soil, biota, etc.) that are influenced by climate change. These aspects interact over the same region or spatial flows in the area. For example agricultural production is affected by the soil water content in the area but also affects the soil water content itself. This influences the water level of lakes in the region and in the long run the habitat quality for plants and animals. One great challenge for a DSS is the complexity of these interactions in a landscape. Another challenge is to account for the possible reaction and adaptation of the players (farmers, conservationists etc.) in a region. These interactions are demonstrated in Fig. 1. Additional information about processes on the regional scale such as potential wind- and water erosion, spatial evaporation etc. should be supplied. On the farm scale, information about agricultural yield, nitrogen leaching etc. must be provided.

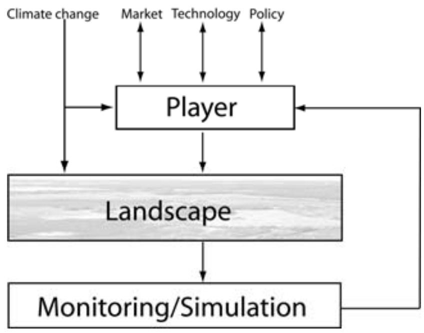

Figure 1. Landscape as a control system driven by climate change and activities of regional players

2. THE STUDY AREA *QUILLOW*

The study area *Quillow* is the watershed area of the river Quillow with about 168 square kilometres. The study area is located in the Uckermark region west of the town of Prenzlau in Northeast Germany (State of Brandenburg and State of Mecklenburg-Western Pomerania, see Fig. 2) and is comprised mostly of agricultural land use (77%). Within the DSS, the area, which belongs to 15 villages, is divided into 54,000 grid cells (100 x 100 meters, 180 x 300 elements in the north-south/east-west direction). Within each grid cell homogeneous conditions (soil, land use, etc.) are assumed.

Figure 2. Location of the study area Quillow

For the study area, grid information are available for soil type (99 soil association groups), slope steepness, substratum, hydromorphy and topography (DEM 25). Additional maps for medium climatic data and landuse are available for this region.

The meteorological standard data (temperature, sunshine duration/global radiation, precipitation) for the study area are taken from the meteorological station Prenzlau for the past years as current weather data and also for the future time period up to 2050 as climate scenario data according to Gerstengarbe (2003).

3. METHOD

The interactive DSS which is under construction consists of the control unit including the graphical user interface and the models. Vertically the DSS is organized in three Pillars (see Fig. 3).

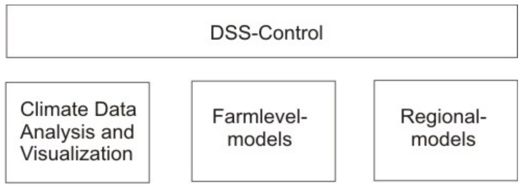

Figure 3. Preliminary structure of the interactive DSS

The climate data analysis and visualization (Pillar 1) contains information on possible future weather conditions and also a climate database containing data with higher spatial resolution provided by the Institute for Meteorology of the TU-Dresden within the project "LAND CARE 2020" (LandCaRe2020, 2007). Here daily resolved weather data such as temperature, precipitation, solar radiation etc. are stored for the time period 1950-2050. From this data one can, for example, estimate the entry dates of important ontogenesis stages of agricultural crops for the entire growing season (Fig. 4).

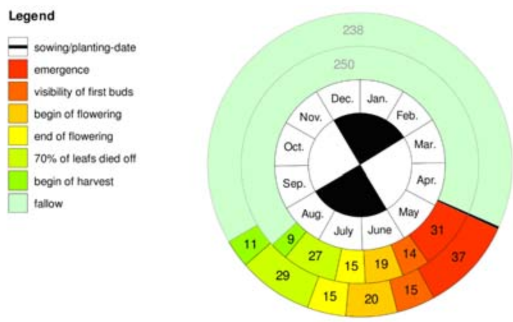

Figure 4. Visualization of the climate-change impact on ontogenesis stages of agricultural crops (in this case potatoes) as a comparison between 1965-1975 (outer ring) and 2025-2035 (inner ring)

Additional information is provided about extreme precipitation events stored as a list containing date and intensity. This information is needed to calculate the risk of total yield loss, for instance.

In Pillar 2 the farm-level models include models for the yield prediction of agricultural crops for arable land as well as grass land. These models serve as an entry point for the farmer to estimate the crop yield without delivering precise management data. If precise management data (soil tillage, fertilizer regime, sowing, plant protection etc.) are available the farmer can use a soil-vegetation-atmosphere transfer (SVAT) model to get more detailed information such as above-ground biomass, nitrogen and water uptake by plants, nitrogen leaching, water, nitrogen and carbon in the soil, percolation of water etc. (Mirschel et al. 2003). Additionally, an economic evaluation of agro-management strategies is possible, based on information about the yield income and the costs of the cropping measures.

In Pillar 3 regional models provide a basis for the simulation of regional processes such as wind and water erosion or evapotranspiration. Regional models must cope with coarse information to calculate a result that covers the whole region. The evapotranspiration model BAGLUVA (BAGLUVA, 2003) is such a regional model which distinguishes only between two different agricultural land use types. If there is more information about the cropping system and the agro-management then the output of the SVAT model can be used to substitute the coarse output of the BAGLUVA model.

4. STEAKHOLDER PARTICIPATION AND SYSTEM DESIGN

At the beginning of the project two workshops were organized to meet the stakeholders (farmer, regional politicians, ecologists, etc.) of the two study areas. We learned that they do not only want to know the result of a single spatial simulation run, but they want a statistics-based statement of many simulation runs. A second demand by the stakeholders concerned the interactive use of the DSS, to play with it in a similar manner as a computer game. This permits checking different alternatives under different weather conditions. The third demand of the stakeholders was the possibility to use a simulation result as input for further simulations, the prerequisite being simulation interconnectivity. These demands led to a system design shown in Fig. 5.

The user interacts with the system using a graphical user interface (GUI). He can obtain plots, reports etc. as a result of his inputs. The simulation control allocates the inputs, organizes all data using the spatial and relational databases, selects the different models, and starts the simulation runs. After the simulation runs the results will be collected and sent to the GUI to generate single or aggregated reports. As the start of such an DSS the simulation system SAMT (Spatial Modeling and Analysis Tool) developed by the Institute of Landscape Systems Analysis of the ZALF Müncheberg was used (Wieland et al. 2006).

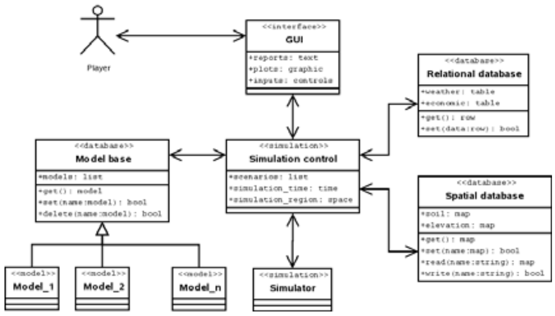

Figure 5. Software design of the DSS "LANDCARE 2020"

5. EXAMPLES

To explain the interconnectivity of the different pillars of the DSS mentioned above, a simple example will be examined in more detail.

In one scenario, a farmer wants to produce winter wheat for energy production because of its possible profit. In a first step of his simulation the farmer needs information about the distribution of precipitation during the vegetation period since this is the most critical climate factor in his region. In a second step, he can use a crop-yield model to determine the crop yield with and without irrigation. Irrigation can help to improve crop yields, but requires additional investments and may also produce negative feedbacks to the water balance of the study area. If the farmer needs irrigation water from the ground water or surface water bodies such as lakes or rivers, he must negotiate these demands with other players in the area (tourism, fishermen, ecologists etc.). From the point of control theory, this is a hierarchical control system that is nowadays solved using a multiagent system (Weiss, 2000). In the DSS the multi agents are simulated by models of different scales.

BAGLUVA – a spatial evapotranspiration model

BAGLUVA is an evapotranspiration model well validated for Germany. The model is extensively documented (BAGLUVA, 2003) so that only a short introduction is given here.

The purpose of the model is to calculate the climate water balance $R = \overline{P_{korr}} - \overline{ET_a}$ for a whole region.

The basis of the algorithm is the following differential equation given by Bagrov (1954):

$$\frac{d\overline{ET_a}}{d\overline{P_{korr}}} = 1 - \left(\frac{\overline{ET_a}}{\overline{ET_{\max}}} \right)^n$$

Here $\overline{ET_a}$ is the actual evapotranspiration calculated using the corrected precipitation $\overline{P_{korr}}$ and the availability of energy expressed by $\overline{ET_{\max}}$. $\overline{P_{korr}}$ is a function of the precipitation and adjustment factor (Richter 1995) to take into account the specific measuring equipment of the German Weather Service (DWD). The $\overline{ET_{\max}}$ can be calculated using the grass reference evapotranspiration (Wendling 1995) and a factor *f* to correct for the land use influence. *Fh* as part of *f* takes into account the influence of the slope of the region. The parameter n accounts for the water storage both in the soil and stored by interception.

The algorithm of the BAGLUVA model performs the following steps:

1. Selection of the land use from the land use map “Corine” (Corine 2000)
2. Selection of the soil parameter “plant useable field capacity” (nfk) of the soil from the soil map and of soil water content (Θ_{nfk}) at nfk.
3. Calculation of different parameters $n = \mathrm{Fct}_2(\Theta_{nfk}, \text{land\_use}, Fh)$
   $f = \mathrm{Fct}_2(\Theta_{nfk}, \text{land\_use}, Fh)$ with $\overline{ET_{\max}} = f \cdot \overline{ET_0}$
4. Calculation of $\overline{ET_a}$ using the BAGROV equation.

The climate water balance (*R*) is the difference between $R = \overline{P_{korr}} - \overline{ET_a}$. *R* influences both the ground water reservoir, i.e. the ground water level and the regional water outflow.

$$\frac{d}{dt}\left(reservoir\, storage \right) = R - outflow$$

In a simulation example for the study area, the mean value of *R* for the time period 1965-1975 compared to the time period 2025-2035 can be estimated. A histogram plot of the means using a bootstrap procedure (Efron et al. 1993) with 20,000 runs was produced to compare the distributions of the means of *R* (see Fig. 6). Information about the probability of *R* is important for risk calculations of an effective regional water management.

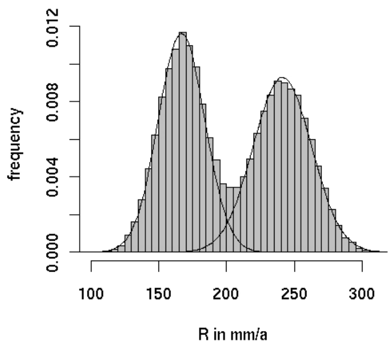

Figure 6. Distributions of the mean of R in comparison between two time periods, 2025-2035 (left) and 1965-1975 (right)

In the study area the ground water reservoir decreased continuously over the last 30 years. These measurements (until 2000) correlate well with the calculated *R* for this area.

YIELDSTAT – a model for spatial crop yield estimation

For a year-specific spatial estimation of crop yields, the climatic water balance calculated for every part of the grid map plays an essential role. Instead of only arable land as one uniform land-use type used in the BAGLUVA model, here the types of usage of the arable land are taken into account in more detail: different agricultural crop types are considered for the calculation of the crop type specific potential evapotranspiration (ET_p) which is calculated according to Wendling (1991). In combination with the map of corrected precipitations (P_{korr}) the spatial climatic water balance can be calculated for each grid in the study region. Based on the combination of this climatic water balance information with site, soil, and land use map information it is possible to estimate the yields for all main agricultural crops grown in the study region as basis for a further monetary or economic evaluation of all arable land within the study region. The use of the semi empirical statistical model YIELDSTAT is sensitive to the most important climatic values. It can be used for the impact assessment of climate change on yields of a broad spectra of agricultural crops. The YIELDSTAT model is a three-stage algorithm with an additive combination of the three algorithm parts. In the first part the natural basic yield is estimated based on the yield matrix according to Kindler (1992). The natural basic yields depend on crop type (17 different agricultural crop types and 2 grassland types (intensive, extensive)) and 56 site types according to the Medium Scale Site Map (MMK) for arable land (Schmidt and Diemann 1991). In the second part of the algorithm the basic natural yield is corrected giving positive or negative yield extra charges in dependence on concrete site specific characteristics like stoniness, slope steepness, altitude, hydromorphy, soil quality index, growing temperature according to Adler (1987), mesoscalic climatic zones according to Adler (1987) and climatic water balance for the cropping period using crop type-dependent extra charge functions which are described in Mirschel et al. (2003) for winter cereals and in Mirschel et al. (2006b) for winter rape. Because the development of the two algorithm parts is based on observation data from the seventies and eighties only, the genetic and plant breeding level as well as the agro-management level of this time period is taken into account. So on the basis of a 20-year (1980-2000) crop-yield statistic of the Federal State of Brandenburg (Germany) a site and crop variety invariant linear yield trend was calculated (0.121 t ha^{-1} y^{-1} for winter wheat, 0.081 t ha^{-1} y^{-1} for winter rye, 0.11 t ha^{-1} y^{-1} for triticale, 0.030 t ha^{-1} y^{-1} for winter rape, 1.118 t ha^{-1} y^{-1} for sugar beet). The estimation of the fertilizing CO_2-effect on crop yields is based on six years of data from the FACE experiment of the Federal Research Centre of Agriculture in Brunswick (Weigel et al., 2005) for winter barley, sugar beet, winter wheat and ray grass, which show an average of a 10.7 % yield increase at 550 ppmv CO_2 level. For other CO_2 – levels a linear conversion is carried out.

To take into account fuzzy information about real agro-management level changes in time, area- or region-specific fuzzy approaches for nitrogen fertilization and plant protection are connected to this crop yield estimation model.

The combination of the YIELDSTAT model with the “Spatial Analysis and Modeling Tool (SAMT)” produces yield maps.

For demonstrating the effect of climate change on the yield of agricultural crops only changed climate conditions are taken into account. All other important factors influencing crop yields like the time-dependent effects on plant breeding or in agro-management are not considered in this example. Here, for simulations, the plant breeding and agro-management levels for 1990s were assumed as well as a constant atmospheric CO_2 content typical for the middle of the 1990s. Further assumptions are average fertilizer and plant protecttion regimes for the study area *Quillow*. For a better comparison with other simulation results, the simulation runs with YIELDSTAT were realised with winter wheat only for the same two different time periods, 1965-1975 and 2025-2035, like in the simulations with the BAGLUVA model mentioned above.

For the comparison of the results, a histogram plot of the mean of the yield distributions for both climate levels (1965-1975 vs. 2025-2035) was produced using a bootstrap procedure (Efron et al. 1993) with 20,000 runs (Fig. 7).

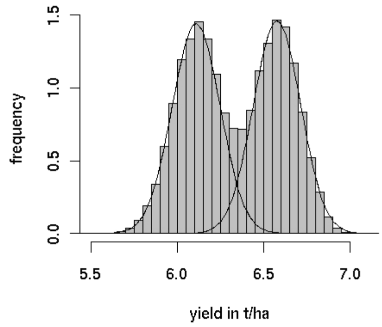

Figure 7. Distributions of the mean of the spatial winter wheat yield in comparison between two time periods, 2025-2035 (left) and 1965-1975 (right)

The histogram shows a significant difference between the mean of the yield levels. On the climate level 2030 the mean of the winter wheat yield in the study area is decreased by 0.48 t/ha in comparison to the mean of the yield on the climate level of 1970. These yield losses could be compensated using modern winter-wheat varieties (hybrid varieties) and improved cropping management (Mirschel et al. 2006a). On the one hand, such yield estimations are important for farmers to plan further successful cropping strategies (e.g. using or omitting irrigation) including an efficient regional water management. On the other hand the information are important for local politicians for the planning of further region-specific financial-support programs.

6. SUMMARY

The DSS LANDCARE 2020 combines three different information concepts (Pillars) to provide an integrated view of the agricultural landscape. The models represent specific aspects but interact together within a common study area. The combination of models of different scales produces an open system where the decision competences are distributed and must be performed by the different players such as farmers, ecologists, local politicians etc. The software components are organized as encapsulated modules that can run as separate processes in a LINUX environment. The open architecture of the software simplifies substitution of different models during the development process and later to adapt the DSS to future developments. The interactivity of the DSS LANDCARE 2020 opens up a wide range of possibilities to simulate different situations. The described examples for the estimation of regional evapotranspiration and spatial crop yields shows only the principal approach within the DSS. The DSS LANDCARE 2020 will contain some more models such as a SVAT-model, habitat models for plants and birds as well as wind and water erosion models. The combination of the sectoral views represented by the models and the integration for the same spatial region is one of the innovative parts of the LANDCARE 2020 project. Another innovative part is the interactivity of the DSS LANDCARE 2020 that gives the user the possibility to explore his very own solution space to get the information he needs, thus being able to decide. Additionally it affords new insight by providing information about the effects of his decisions not only for him but also for other players within the region.

7. CONCLUSIONS AND FUTURE DEVELOPMENTS

- It is impossible to forecast the future precisely. But one can simulate some possible future developments. On this basis we can prepare our reactions to future situations. It is, therefore, not only important to simulate possible landscape situations but it is more important to estimate the probability of the landscapes future reality.

- On the regional scale, decisions of one user will affect the possible choices of other users. That is caused by the complexity of the landscape as a whole system. Only a DSS that includes different modelling scales can help to cope with this complexity.

- The models in a landscape-related DSS are of different complexity and often include uncertain information. Fuzzy models and artificial neural networks are often the only approaches to fill the gap between expert knowledge and real data sets.

- The software basis for a landscape related DSS should be Open-Source software. This allows the inclusion of different modelling approaches including new modelling techniques like fuzzy models and artificial neural networks.

For the future development of the landscape related DSS, the players should be assisted to find an optimal solution for their problems.

8. ACKNOWLEDGEMENTS

This contribution was supported by the German Federal Ministry of Education and Research (project no.: 01 LS 05109), the German Federal Ministry of Food, Agriculture and Consumer Protection and the Ministry of Agriculture, Environmental Protection and Regional Planning of the Federal State of Brandenburg (Germany). Thank you to Mr. J. Kiesel, Ms. M. Voß and Ms. K. Luzi from the ZALF-Institute of Landscape Systems Analysis for their help to process the necessary grid maps and data for the Quillow catchment.

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