Adv. Geosci., 11, 85–92, 2007
www.adv-geosci.net/11/85/2007/

Advances in Geosciences

Impacts of global change on water-related sectors and society in a trans-boundary central European river basin – Part 1: project framework and impacts on agriculture

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Received: 29 January 2007 – Revised: 20 April 2007 – Accepted: 22 May 2007 – Published: 15 June 2007

Abstract. Central Europe, the focus region of this study, is a region in transition, climatically from maritime to continental and politically from formerly more planning-oriented to more market-oriented management regimes, and in terms of climate change from regions of increasing precipitation in the west and north of Europe to regions of decreasing precipitation in central and southern Europe. The Elbe basin, a trans-boundary catchment flowing from the Czech Republic through Germany into the North Sea, was selected to investigate the possible impacts of global change on crop yields and water resources in this region.

For technical reasons, the paper has been split into two parts, the first showing the overall model concept, the model set-up for the agricultural sector, and first results linking eco-hydrological and agro-economic tools for the German part of the basin. The second part describes the model set-up for simulating water supply and demand linking eco-hydrological and water management tools for the entire basin including the Czech part.

1 Introduction

Global and continental studies (IPCC, 2007; Eisenreich, 2005; EEA, 2004, 2005) suggest a mean temperature increase of about 1.0 K to 5.5 K for Europe over the 21st century. The trend in precipitation is not so clear, but most Global Circulation Model (GCM) results driven by IPCC emission scenarios agree in that the observed increase in precipitation for north and west Europe and the observed decrease for south and parts of central Europe will continue and partly intensify under scenario conditions (Houghton et al., 2001; IPCC, 2007).

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However, these general trends may differ regionally due to local circulation pattern and orographic conditions (Houghton et al., 2001), which cannot be reproduced by GCMs having a spatial cell size of 1 to 3 degrees. This is why a regionalization of the global results is so important for investigation of adaptation measures, which normally are implemented at the regional scale. In addition, in most studies the climate change impact was investigated for the hydrological regime, land use and water-related sectors (e.g. agriculture and water management) separately, applying different and incompatible tools, and without addressing the possible feedbacks and inherent uncertainty of the results (Bronstert, 2004).

This study, carried out in the framework of the German GLOWA-Elbe project (see also Wechsung et al., 2005), tries therefore to describe the methodology to develop and apply transient climate and land use change scenarios which are consistent in terms of climate and socio-economic conditions, taking into account possible feedbacks, to investigate the climate and land use change impacts on water resources, and to quantify the uncertainty of water availability. Many water conflicts in the basin occur because of the low water availability per capita in the basin (about 680 $m^3\,a^{-1}$), the second lowest of the large river basins in Europe.

2 Methods

2.1 The modelling concept

This section will describe the model set-up developed to analyse the main pressures on the water resources in the Elbe basin, climate change and land use change respectively.

The climate scenario taken as future climate boundary condition was produced by the GCM ECHAM 5 (Roeckner et al., 2003), which was driven by the IPCC SRES

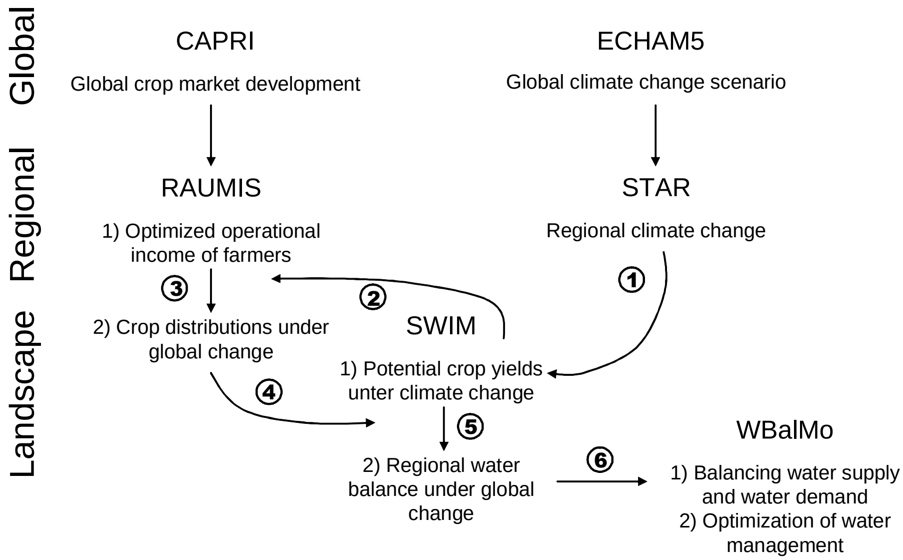

Fig. 1. Flow chart of the modelling procedure.

(International Panel on Climate Change Special Report Emissions Scenario) A2 (Houghton et al., 2001). The A2 storyline and scenario family describes a very heterogeneous and regionally oriented world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in continuously increasing population. Economic development is primarily regionally oriented and per capita economic growth and technological change more fragmented and slower than in other storylines.

The global results were regionalized using the statistical downscaling model STAR (STAtistisches Regionalmodell, Werner and Gerstengarbe, 1997), taking the most reliable result of GCM simulations, the temperature, as driver for regional changes (point ① in Fig. 1). The GCM gives a temperature increase of approximately 2.1 K until 2050. Based on this assumption, 100 long term transient time series of the possible future climate (2000–2055) were calculated in a way that they reflect the temperature given by the scenario as well as the observed regional climate pattern (Orlowsky, 2006). The anticipated scenario increase in temperature can be, due to the robustness of the temperature signal with only small differences of temperature increase in the different IPCC scenarios until 2050, regarded as representative for the model region and different IPCC SRES scenarios (Gerstengarbe and Werner, 2005).

The second step is to derive a land use change scenario consistent with the socio-economic story line of the regional climate change scenario. The basic assumption was here that land use changes in the Elbe basin will mainly affect arable land. Following this assumption, the eco-hydrological model SWIM (Soil and Water Integrated Model, Krysanova et al., 2005) was used to calculate potential crop yields under climate change for the seven main crops cultivated in the study area (② in Fig. 1). The climate change realizations taken are the median variant of the 100 scenario realizations produced by STAR and the minimum and maximum variant in terms of basin averaged water supply under scenario conditions (Wechsung et al., 2005).

The changes in crop yield are used by the agro-economic model RAUMIS (Regional Agricultural and Environmental Information System, Henrichsmeyer et al., 1996) to optimize the potential operational income of farmers in the study area under *climate* change and to calculate corresponding county specific crop distributions (land use scenario variant A) (③ in Fig. 1). The second input are global crop market conditions as defined by the underlining IPCC storyline and produced by the global and regional agro-economic model CAPRI (Britz, 2004). These were the input for RAUMIS to optimize the potential operational income of farmers under *socio-economic* change in a second land use scenario (land use scenario variant B). The spatial aggregation level of the simulations is the administrative level of counties.

The county specific cropping structure derived by RAUMIS have to be transformed into crop rotations for each spatial element considered in the eco-hydrological model SWIM (④ in Fig. 1), which are much smaller than the average county area, and which are not defined by administrative boundaries but built based on information about the environmental characteristics of the basin (the so-called hydrotopes or Hydrological Response Units, HRUs). This was done by implementing a crop generator in the model SWIM (Wechsung et al., 2005).

The next task is to transform the regional climate and land use change into altered hydrological quantities (⑤ in Fig. 1). This was done by running SWIM 100 times, each

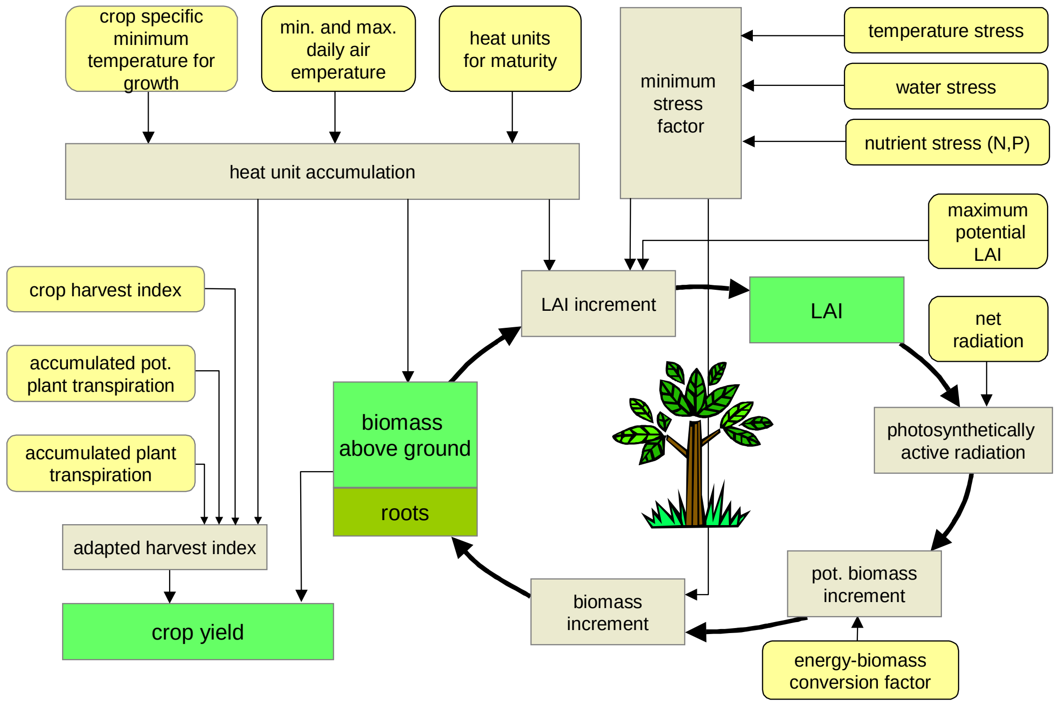

Fig. 2. The vegetation module in SWIM and its parameter demand. The parameters are partly tabulated values (e.g. the crop harvest index, maximum potential LAI, biomass energy ratio and the crop specific minimum and optimal temperature for growth), and partly calculated daily (e.g. the heat units and the temperature, water and nutrient stresses).

time forced by another realization of the climate change scenario, and with the land use scenarios as spatial boundary condition. These hydrological quantities are then used by the water management model WBalMo® (Water Balance Model) to balance natural water yield and water demand at about 2000 sites, where in total 114 reservoirs and about 2500 water users are connected. One result of the balance procedure is water availability for water users. Types of them are: thermal and hydropower plants, municipal water supply, industry, irrigation and sub-irrigation for agriculture, water transfer by channels or pumping stations, inland fishery and navigation. Thereby, water availability can be improved by optimizing water demand and water management.

The final step is to analyze the results in cooperation with relevant actors and to evaluate possible adaptation measures. Shown in the first part of the paper are crop yields simulated for the entire basin by SWIM and socio-economic impacts on crop distributions calculated by RAUMIS for the German part of the basin, taking changes in crop yields as one boundary condition besides changes in the global agro-markets. The second part describes the model link SWIM–WbalMo® and illustrates possible water conflicts taking into account the total trans-boundary basin.

2.2 The basin under study

The river Elbe is the most easterly located large river flowing into the North Sea (catchment area of 148 268 km^2). Approximately 52% of the catchment area are covered by arable land, 29% by forest, 6% by settlements and industry and 5% by lakes, mining pits and other land use forms.

Climatically, the Elbe basin is at the interface of maritime climates in the northwest (more than 1000 mm annual precipitation) and continental climates in the central southeastern part of the basin (annual precipitation below 500 mm). The long-term mean annual precipitation over the whole basin is 703 mm in the period 1951–2000 (corrected), and the long-term mean discharge at the estuary is 877 m^3 s^{-1} with an average inflow from the Czech Republic of 315 m^3 s^{-1} (Prange et al., 2000). The per capita water supply is only 680 m^3 a^{-1}, being one of the lowest in Europe.

2.3 The model SWIM

The eco-hydrological model SWIM is an offspring of the commonly known SWAT model (Soil and Water Assessment Tool, Arnold et al., 2004) and integrates the relevant eco-hydrological processes including water flow, nutrient transport and turn-over, vegetation (crop) growth and land use, and water management needed to investigate climate and land use change impacts on hydrological systems and

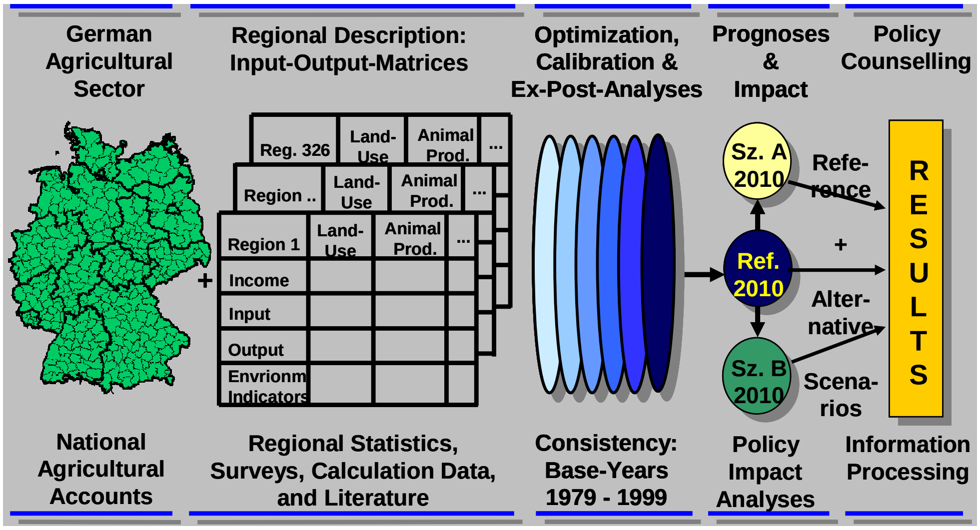

Fig. 3. Methodological design of RAUMIS.

vegetation at the subbasin scale. The smallest aggregation scheme is the so called hydrotope, whereby each unique combination of the underlying geographical maps (soils, landuse, etc.) forms one hydrotope class. Vertical flows of water and nutrients are calculated at the hydrotpe scale and are then aggregated for each subbasin.

This semi-distributed modelling concept allows for the consideration of the spatial heterogeneity while saving computation time. Due to the fact that the first part of the combined paper deals with land use changes and crop yields, the vegetation module of SWIM is explained in more detail below, whilst hydrological processes are explained in the second part. The model has been extensively validated for the hydrological processes in the Elbe basin (Hattermann et al., 2004, 2005). A full description of the model including the functionality of the different modules can be found in Krysanova et al. (1998).

Vegetation processes (plant growth, water and nutrient uptake) are simulated dynamically on a daily time step in SWIM, while distinguishing between up to 72 different plant types. They are simulated using a simplified EPIC approach (Williams et al., 1984). Having a dynamic representation of plant processes in the model is the precondition to take into account their type and age specific response to land use management and climate variability, which gives a more realistic feedback on environmental change in the river basin. Typical examples are winter wheat and most other cereals cultivated in Europe (mostly C3 plants), which have their temperature optimum between 12°C and 15°C and therefore are not promoted by the anticipated change in temperatures, and maize, which has its temperature optimum around 20°C and hence will benefit from the increase in temperature.

Plant growth is driven by intercepted photosynthetic active solar radiation PAR (see Fig. 2). The potential increase in biomass is afterwards adjusted by multiplying PAR with a plant specific biomass-energy ratio. The potential increase is adjusted further if one of the plant stress factors for water availability, nutrient availability or temperature is less than 1. Leaf area index is a function of heat units and biomass, and is different for two phases of the growing season (see Krysanova et al., 1998).

2.4 The agro-economic model RAUMIS

The Regional Agricultural and Environmental Information System (RAUMIS) represents the whole German agricultural sector and has been developed by Henrichsmeyer et al. (1996) for continuous usage in the scope of medium and long-term agricultural and environmental policy impact analyses. Figure 3 gives an overview of the methodological design of RAUMIS. The model consolidates various agricultural data sources and generates base model data with the national agricultural accounts as a framework of consistency. It comprises more than 50 agricultural products, 40 inputs with exogenously determined prices, and reflects the whole German agricultural sector with its sector linkages.

According to data availability, the spatial differentiation of RAUMIS is presently based on administrative bodies. A continuous spatial distribution of agricultural production is approximated by some 326 regions basically on a county level (“Landkreise” in Germany). These regions are treated as single “region enterprises” that autonomously reach their production decisions. Hence, adjustments of production at the national level are based on aggregated responses of “region farms”.

Adjustments caused by changes in general conditions such as agricultural policies are determined using a mathematical programming approach with a nonlinear objective function.

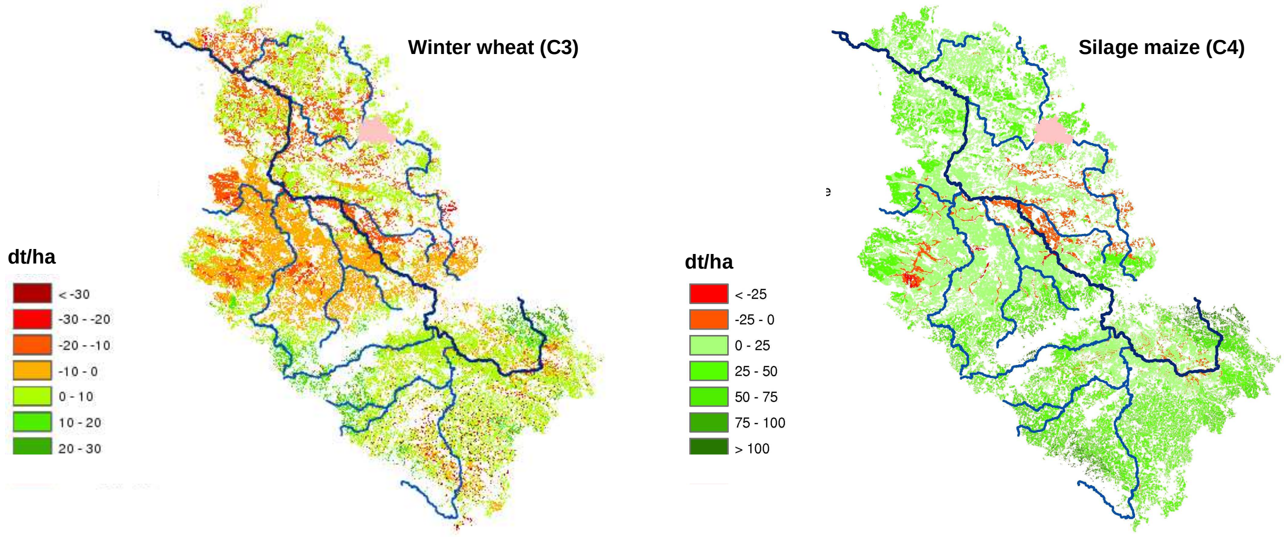

Fig. 4. Changes of mean annual crop yields under climate conditions of 1961–1990 (reference) to 2021–2050 (scenario) for a moderate climate change.

This method uses an algorithm to model responses of producers to changes in relative profitability of production activities subject to technical, political and economic constraints. The calculated optimal production plan generates the maximum feasible farm income which is the objective function of this approach.

However, the derived optimal production plan does not necessarily match exactly with the actual production being observed ex-post because of imperfect information about the true coefficients. This problem is overcome by applying the technique of positive mathematical programming (Howitt, 1995). The approach provides substantial advantages with respect to the long-term forecasting behaviour of the model. In the projection phase a variety of exogenous variables such as implicit costs resulting from positive mathematical programming, input-output coefficients, yields, capacities, and prices are forecast. Updates are partially based on trend and yield dependent regression analyses as well as on estimates provided by experts particularly relating to prices and the development of farm structures.

Comparative static policy impact analyses for a future target year require a scenario of reference because various parameters are changing in the long-run in addition to the variations of policy measures being investigated. Typically, the scenario of reference is a projection of the development under “business as usual”. Deviating from the reference scenario, alternative policies and regulations are imposed on the model keeping all other parameters and constraints constant. This procedure separates the policy impacts on agricultural production, land-use and agricultural income as deviations from the scenario of reference.

In RAUMIS, a set of agri-environmental indicators is linked to agricultural production. Currently, the model comprises indicators such as fertilizer surplus (nitrogen, phosphorus, and potassium), pesticides expenditures, a biodiversity index, and corrosive gas emissions. These indicators help to evaluate direct and indirect environmental impacts of policy driven changes in agricultural production. Regarding diffuse water pollution the indicator “nitrogen surplus” is of particular importance.

3 First results

3.1 Crop yields under climate change

Crop yields show a non-uniform sensitivity to changes in temperature and precipitation, depending on regional characteristics of climate change and crop species. The differences are the highest comparing C3-plants like winter wheat and C4-plants like maize (see Fig. 4) having a different CO_2-metabolism. Over all, C4-plants have a higher potential biomass production under climate change as investigated in GLOWA. This is induced by the increase in temperature mainly, whereas they are adapted to low water availability, and decreases in maize yield are only simulated where the decrease in precipitation is the strongest. The C3-plants show an increase in yields where the precipitation is increasing or where the precipitation is still high under climate change and where the temperature increase generates longer vegetation periods, but the overall sensitivity to water availability is higher than for the C4-plants.

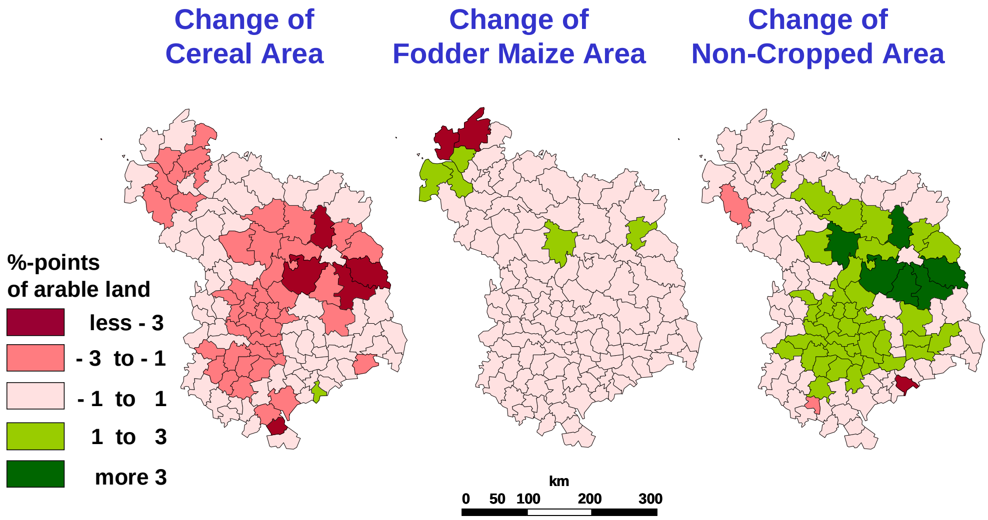

Fig. 5. Climate change driven regional adjustment of agricultural land use changes in the target year 2020.

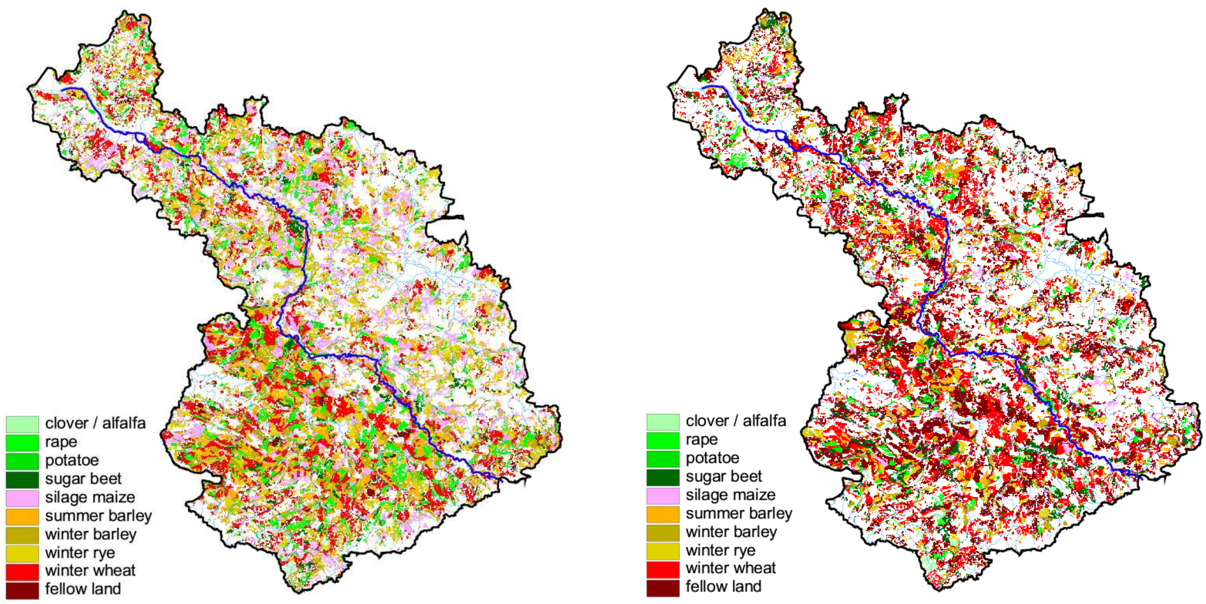

Fig. 6. Crop distribution under baseline (left) and liberalization of European crop markets (right).

3.2 Land use management under climate change (RAUMIS results)

In line with the methodological approach of RAUMIS (see Fig. 3) policy measures are analyzed and assessed comparing their impacts to a scenario of reference. The scenario of reference is a medium term projection of the development until the year 2020 under policies of Agenda 2000.

In a first step the climate change driven variation of potential crop yields calculated by SWIM for the time period 2016–2025 are applied to crop yields of RAUMIS activities in the baseline for the target year 2020 (note that the results depicted in Fig. 4 show a different comparison including CO_2 effects). In a second step, the intensity of production, e.g. the use of fertiliser, plant protection, and machinery, is adjusted. In a final step, RAUMIS calculates a new optimal cropping structure according to the changed relative profitability of activities.

According to the model results the acreages of oilseeds and cereals are reduced by 4–5% and 3% respectively. As a consequence of decreasing yields for most of the crops a profitable cultivation at the acreage level of the base line cannot be maintained in many regions. Hence, the non-cropped area increases by about 12%. Mainly affected are less fertile

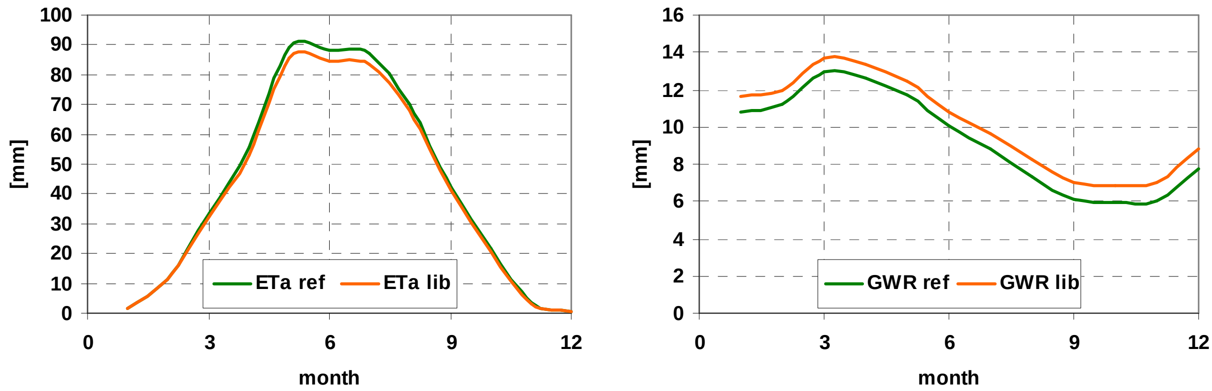

Fig. 7. Simulated changes for monthly actual evapotranspiration (left) and groundwater recharge (right) as a basin wide integral for the German part of the Elbe catchment (ten year average, induced only by changes in crop rotations as defined by RAUMIS, see Fig. 6

regions of the Spree and Havel catchments (see Fig. 5). In these regions a comparatively low yield decrease leads to substantial increases of idling which is of considerable importance already in the base line.

In Fig. 5 the changes of cereal, fodder maize and non-cropped area are related to the total arable land in order to demonstrate the effects in regard to the landscape. The extent of land use changes varies regionally due to the regional differences of the cropping structure as well as regional varying crop yield changes. However, the changes fall mostly within the range of ±3% of arable land and thus will not be perceptible in the landscape.

Due to the lower yields and reduced acreages the cereal production decreases by about 10% in the German Elbe basin. Potential impacts of the cereal market, i.e. an expectable price rise, is not considered since climate change-driven yield increases in Germany or the EU may compensate the losses in the Elbe basin. However, when comparing with the baseline farmers in the Elbe basin incur income reductions of approx. 6%.

3.3 Changes in landscape water balance due to changes in land use pattern

Changes of the landscape water balance due to changes in agriculture as given by the model RAUMIS have been simulated using SWIM after transferring the results to the hydrotope scale of SWIM. The crop distributions are illustrated in Fig. 6 for one example year, where one map gives the land use under the reference scenario or baseline, and one the land use under liberalization (no subsides for crops).

Under liberalization, large areas having low precipitation and soils with low water holding capacity become fallow land. Important is the further treatment of these areas: keeping them as extensive grassland would decrease the overall evapotranspiration (basin wide total decrease ≈4%) and increase of groundwater recharge (basin wide total increase ≈10%), while development of forest would lead to an increase of evapotranspiration, pending on tree composition and age structure (Wattenbach et al., 2005). The monthly changes are the highest during the summer months, but the seasonality is more pronounced for evapotranspiration then for groundwater recharge, due to the fact that groundwater recharge is buffered by soil percolation (see Fig. 7).

4 Summary and conclusions

A projection of future land use development under climate change impacts is only possible with an interdisciplinary model network that considers the complexity of natural and economic relationships. This becomes evident regarding the different regional impacts of climate change.

The first results of the simulations show that traditional cropping zones may shift due to varying crop yields. This can have stronger impacts on agriculture in fertile than in less fertile regions. However, the impacts of land use changes on the Elbe basin wide water balance are relevant to save water resources: an integrated land use and water management planning can be applied to save water resources and increase, e.g. groundwater recharge, important in view of climate change scenarios projecting mostly dryer conditions in the basin.

The results also show that the differences of the spatial resolution of the models require the development of a module that allocates agricultural land use from the RAUMIS region farms (administrative units) to homogenous natural sites units. Depending on the availability of data, in particular land use information from remote sensing, a first step is to extend the model RAUMIS to a lower municipality level which is closer to the HRUs applied in SWIM.

An expansion and application of a similar model network to other catchments in Europe should in principle be possible without major problems.

Acknowledgements. The authors would like to thank their colleagues H. Apel and C. Hesse who reviewed the text for their support and B. Orlowsky for providing the climate data.

Edited by: K.-E. Lindenschmidt
Reviewed by: H. Apel and C. Hesse

References

Arnold, J., Williams, J., Srinivasan, R., King, K., and Griggs, R.: SWAT, Soil and Water Assessment Tool, Tech. rep., USDA, Agriculture Research Service, Grassland, Soil and Water Research Laboratory, Temple, Texas, 2004.

Britz, W.: CAPRI Modelling System Documentation, Final report of the FP5 shared cost project CAP-STRAT (common agricultural policy strategy for regions, agriculture, and trade), Universitt Bonn, Bonn, Germany, 2004.

Bronstert, A.: Rainfall-runoff modelling for assessing impacts of climate and land-use change, Hydrol. Processes, 18, 567–570, 2004.

EEA(2004): Impacts of Europe's changing climate – An indicator based assessment, European Environmental Agency (EEA), Copenhagen, Denmark, EEA technical report no. 2, 2004.

EEA(2005): Vulnerability and Adaptation to Climate Change in Europe, European Environmental Agency (EEA), Copenhagen, Denmark, EEA technical report no. 7/, 2005.

Eisenreich, S.: Climate Change and the European Water Dimension, Tech. rep., European Commission: Joint Research Centre, Ispra, Italy, 2005.

Gerstengarbe, F. and Werner, P.: Simulationsergebnisse des regionalen Klimamodells STAR, in: GLOWA-Elbe I – Integrierte Analyse der Auswirkungen des globalen Wandels auf Wasser, Umwelt und Gesellschaft im Elbegebiet, edited by: Wechsung, F., Becker, A., and Grfe, P., vol. 95 of PIK report, ISSN 1436-0179, Potsdam Institute for Climate Impact Research, Potsdam, Germany, 2005.

Hattermann, F., Krysanova, V., Wechsung, F., and Wattenbach, M.: Integrating groundwater dynamics in regional hydrological modelling, Environ. Modell. Softw., 19, 1039–1051, 2004.

Hattermann, F., Wattenbach, M., Krysanova, V., and Wechsung, F.: Runoff simulations on the macroscale with the ecohydrological model SWIM in the Elbe catchment – validation and uncertainty analysis, Hydrol. Processes, 19, 693–714, 2005.

Henrichsmeyer, W., Cypris, C., Löhe, W., Meudt, M., Sander, R., von Sothen, F., Isermeyer, F., Schefski, A., Schleef, K.-H., Neander, E., Fasterding, F., Helmcke, B., Neumann, M., Nieberg, H., Manegold, D., and Meier, T.: Entwicklung eines gesamtdeutschen Agrarsektormodells RAUMIS96, Endbericht zum Kooperationsprojekt,Forschungsbericht für das BMELF (94 HS 021), unpublished, 1996.

Houghton, J., Ding, Y., Griggs, D., Noguer, M., van der Linden, P., and Xiaosu, D. (Eds.): Climate Change 2001: The Scientific Basis – Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), Cambridge University Press, Cambridge, United Kingdom, 2001.

Howitt, R.: Positive Mathematical Programming, Am. J. Agr. Econ., 77, 329–342, 1995.

IPCC(2007): Climate Change 2007: The Physical Science Basis, Summary for Policymakers. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, IPCC Secretariat, Geneva, Switzerland, 2007.

Krysanova, V., Mller-Wohlfeil, D.-I., and Becker, A.: Development and test of a spatially distributed hydrological/water quality model for mesoscale watersheds, Ecol. Model., 106, 261–289, 1998.

Krysanova, V., Hattermann, F., and Wechung, F.: Development of the ecohydrological model SWIM for regional impact studies and vulnerability assessment, Hydrol. Processes, 19, 763–783, 2005.

Orlowsky, B.: A statistical model for regional climate scenarios, in: Natural Systems and Global change, edited by: Kundzewicz, Z. and Hattermann, F., Research Centre for Agricultural and Forest Environment of the Polish Academy of Sciences and Potsdam Institute for Climate Impact Research, Poznan, Poland, and Potsdam, Germany, ISBN 83-89-887-58-4, pp. 28–34, 2006.

Prange, A., Furrer, R., Einax, J., Lochovsk, P., and Kofalk, S.: Die Elbe und ihre Nebenflsse – Belastung, Trends, Bewertung, Perspektiven, ATV-DVWK Forschungsberichte, Deutsche Vereinigung fr Wasserwirtschaft, Abwasser und Abfall e.V., Hennef, Germany, 2000.

Roeckner, E., Bäuml, G., Bonaventura, L., Brokopf, R., Esch, M., Giorgetta, M., Hagemann, S., Kirchner, I., Kornblueh, L., Manzini, E., Rhodin, A., Schlese, U., Schulzweida, U., and Tompkins, A.: The atmospheric general circulation model ECHAM 5. Part I: Model description, Tech. Rep. 349, Max Planck Institute for Atmospheric Science, Hamburg, Germany, 2003.

Wattenbach, M., Hattermann, F., Weng, R., Wechsung, F., Krysanova, V., and Badeck, F.: A simplified approach to implement forest eco-hydrological properties in regional hydrological modelling, Ecol. Model., 187, 40–59, 2005.

Wechsung, F., Becker, A., and Gräfe, P. (Eds).: GLOWA-Elbe I – Integrierte Analyse der Auswirkungen des globalen Wandels auf Wasser, Umwelt und Gesellschaft im Elbegebiet, PIK report 95, Potsdam Institute for Climate Impact Research, Potsdam, Germany, ISSN 1436-0179, 2005.

Werner, P. and Gerstengarbe, F.-W.: Proposal for the development of climate scenarios, Climate Res., 8, 171–182, 1997.

Williams, J., Renard, K., and Dyke, P.: EPIC – a new model for assessing erosion's effect on soil productivity, J. Soil Water Conserv., 38, 381–383, 1984.