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THE ROLE OF WATER RESOURCES IN AGRICULTURAL LAND USE MODELING: AN EXTENSION OF THE LAND USE MODEL *KLUM*

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Abstract

Key words

land use, modeling, water resources, integrated assessment

Introduction

Land use constitutes one of the essential links between biosphere and anthroposphere, and appears as both, driver and target of changes in global environment (Heistermann *et al*., 2006). Changes in land use directly influence biogeochemical and water cycles, and thus affect nutrient balances, hydrologic systems, and biodiversity. They influence climate, as they govern large parts of anthropogenic greenhouse gas emissions, and may alter the albedo. Land use changes also affect the socioeconomic environment and determine the economic revenue of land-intensive agricultural production. Overall, a vital feedback loop of the interaction between human society and natural environment is built, as the underlying land use decisions are triggered by environmental properties and motivated by socio-economic drivers (Lambin *et al*., 2003).

Agricultural land use currently accounts for 34% of the terrestrial earth's surface and can be divided into 22% of pasture, and 12% occupied by either annual or permanent crops (FAO, 2006). For the human population, crops are the main food source (Heistermann, 2006). Within the next 50 years, the world population will grow by about 65% (Wallace, 2000). Together with an increasing demand on natural resources and food products, climate change is likely to add an additional pressure to agricultural systems. Thus, a great emphasis has to be placed on the resilience, adaptability and sustainability of these systems (Dolman *et al*., 2003).

Future agricultural water management will be determined by growing water scarcity, competition for water use and growing concerns about its environmental impacts (van Hofwegen, 2006). The latter include salinization, water-logging of soils, water pollution, and depletion of water resources. These changes have a negative feedback on crop agriculture in terms of long-term reduced biophysical potential for agriculture, up to threats to human health. Additionally, fundamental interest has to be put on the question of how to use and balance water resources between food and environmental security (Rockström *et al*., 2004).

Agriculture accounts for approximately 70% of the current human water withdrawal (Lotze-Campen *et al*., 2004). Without irrigation, agricultural yield increases that have fed the growing population would not have been possible (Rosegrant *et al*., 2002a). About 20% of the total arable cropland is under irrigation, producing 40% of the global harvest. Within the last 40 years, global irrigated agriculture almost doubled. Future yield increases necessary to secure food availability will also have to be partly based on irrigation, which is expected to expand by 40% within the next 30 years (Bruinsma / FAO, 2003).

The fact that transboundary watersheds, which are home to about 40% of the world's people, account for at least 60% of the world's freshwater (Gerlak, 2004) highlights the close relationship between water management, transboundary policies and agricultural development, and the need for multi-scale assessments.

Integrated global land use modeling and issues of irrigation: an overview

Land use models are used to analyze the complex structures of linkages and feedbacks related to land use change, and to gain knowledge on the impacts and importance of the different driving forces and processes. An overview on the different classifications and methodological approaches in land use modeling, as well as for differences between large- and small-scale modeling is given in Heistermann *et al*. (2006).

Global land use models are often disciplinary, tending to emphasize economic or geographic aspects, or they are very comprehensive and thus not appropriate as a coupling tool (Ronneberger *et al*., 2005). “Economic approaches are strong in the formalisation and quantification of drivers on the demand side while geographic approaches are rather suited to account for the supply-side limitations of land resources. Integrated models are expected to combine these strengths” (Heistermann, 2006). However, integrated land use models often apply empirical, rule-based methods, neglecting economic motivation and dynamic market feedbacks (Ronneberger, 2006).

Irrigation and water scarcity are mostly considered as a consequence of land use decisions, rather than as decisive factors in farm-based crop production. Moreover, the share of irrigated crops is often based on estimations or observations of infrastructurally well-developed areas, but not on economically motivated decisions by the farmer. Another challenge is the consideration of crop- and country-specific irrigation methods.

The *FARM* model (Darwin *et al*., 1996) includes an economic CGE framework and accounts for 3 crop commodities (wheat, other grains, non-grain crops) in 8 world regions. Classes of “land productivity” are determined by the length of the growing season, based on temperature and precipitation. Water is explicitly modeled as a primary production factor for the crops, livestock and service sectors, under consideration of the regional water supply.

The *ACCELERATES* framework (Rounsevell *et al*., 2006) includes very detailed management options to analyze farm level impacts on continental scale (NUTS2 regions). It contains various agricultural model parameters to project water resource use and irrigation, e.g. irrigation infrastructure availability, irrigation efficiency, water input costs. Water-limited crop yields and “minimum requirements for cumulated monthly precipitation” are determined. Moreover, a concept of vulnerability and the quantification of ecosystem capacity indicators are crucial features with regard to achieving a feedback loop between land use and environmental processes.

The *IMAGE* model (Alcamo *et al*., 1994; Alcamo *et al*., 1998) is an integrated assessment model (IAM) and enables long-term dynamical predictions. A broad range of biophysical, anthropogenic and socio-economic land use determinants is applied to account for demographic, technological, economic, social, cultural, and political interactions. Different land use sectors are considered, including their possible expansion or shrinkage in land. The potential distribution of crops follows the rule-based AEZ-approach with a “constraint-free rain-fed crop yield”. Trade and market interactions are not dynamically represented by the underlying economic demand module (Heistermann *et al*., 2006). Several feedback loops between land use and environmental degradation are established or planned (e.g. water erosion, biogeochemical and hydrological changes).

The simulation of the dynamics of irrigated and potentially irrigated areas within the *LANDShift* modeling framework, and an integrated assessment against the background of changing climate and soil conditions is given by Heistermann (2006). *LandSHIFT* (Alcamo & Schaldach, 2006) is a geographical land use model and provides a process-based simulation of global crop distribution, with distinction between rain-fed and irrigated crops. The model accounts for freshwater availability and inter-sectoral competition. The economic part is contributed by the *IMPACT* model (Rosegrant *et al*., 2002b). Irrigation costs are not explicitly considered.

Economic analyses on water represent a highly complex subject due to the wide range of facets and systemic effects of the substance. Primary topics in water resource management include e.g. demand estimations, water valuation, externality modeling accounting for issues of efficiency, and regulatory analysis (Swanson & Xepapadeas, 2003). A variety of water pricing methods have been developed, depending on natural and economic conditions. They differ in their implementation, the institutions they require, and the information on which they base. For more discussion on issues of water resource economics and water pricing see Johansson (2000).

Buchanan & Cross (2002) state that all factors used to estimate irrigation costs vary with location, e.g. the equipment and techniques for water supply and the operation of irrigation systems. Additionally, the chosen irrigation method must account for the particular crop requirements, which in turn also vary with the biophysical background. Of further economic importance regarding irrigation decisions is the fact that the development of irrigation infrastructure and the supply of irrigation water has become increasingly expensive (Johansson, 2000).

Yuan et al. (2003) discuss and economically evaluate different systems auf rainwater harvesting in semiarid regions. Von Westarp *et al*. (2004) compare the performance of different irrigation methods (low-cost drip irrigation, conventional drip irrigation, hand-watering) under different irrigation regimes to meet rising food demand in the Middle Mountains of Nepal.

Another important aspect in the context of growing water scarcity is the debate on irrigation water efficiency due to huge amounts of water being wasted (Wallace, 2000). Karagiannis *et al*. (2003) present an economic approach to measure irrigation water efficiency, based on the concept of input-specific technical efficiency such as the ratio of minimum feasible and observed water use. As the measured irrigation water efficiency is conditional on production technology and the observed levels of output and other inputs, information can be gained on how much water use could be decreased without altering the output produced and the quantities of other inputs used.

***KLUM-W*: Model background and aims**

Within this work, we present the extension of the global integrated land use model *KLUM* (Ronneberger, 2006) in terms of integrating irrigation. *KLUM* is a tool to dynamically couple global state-of-the-art economy and vegetation models. In the past, coupling was implemented with the CGE model *GTAP-EFL*, a refined version of the *GTAP-E* model (Burniaux & Truong, 2002; Hertel, 1997) and the DGVM *LPJ-C* (Criscuolo, 2006).

A balanced representation of essential economic and biophysical aspects makes KLUM appropriate to project global crop patterns. Due to its simplicity and flexibility the model enables online coupling, as well as long-term projections. The crop allocation process is based on profit maximization, assuming risk aversion and decreasing returns to scales. The aggregated allocation can be fed back to the CGE as production-specific land endowments, and to the DGVM to improve carbon cycle simulation (Ronneberger *et al*., 2006a; Ronneberger *et al*., 2006b).

Management practices are not explicitly accounted for yet. The extended *KLUM-W* version (“*KLUM-Water*”) integrates irrigation by means of crop-specific irrigation demands and respective irrigation costs. The inclusion of irrigation in *KLUM* is important for several reasons: The former model uses “potential yields” to simulate crop allocation. Water scarcity was neglected, i.e. no constraints on water availability were included. Furthermore, costs for irrigation to reach the applied potential yields were not included in the optimization algorithm.

With *KLUM-W*, the effects of changing water availability and irrigation costs on global crop allocation may be investigated. The goal is to depict actual irrigation decisions under a changing climatic, biophysical, and economic environment, accounting for a (quantitatively) sustainable use of resources in the context of increasing water scarcity and resource competition.

The applicability to investigate significant questions in the context of global change (e.g. feedbacks between irrigation volume and prices for water and energy, the compatibility of sustainable water use and crop demands, general impacts of climate change on the fraction of irrigated agriculture) means an improvement of the *KLUM*-inherent approach towards global land use modeling. This in turn may help to provide explanations on questions of future water-use and crop production.

Model setup and scenarios applied

Results

Discussion

Acknowledgements

This study is part of the research project TranSust.Scan ("Scanning Policy Scenarios for the Transition to Sustainable Economic Structures"), which is part of the Sixth EU Framework program on policy-oriented research (project no. 022773).

References

Alcamo, J., Kreileman, G.J.J., Krol, M., & Zuidema, G. 1994. Modelling the Global Society-Biosphere-Climate System: Part 1: Model Description and Testing. Water, Air, and Soil Pollution, 76, 1–35.

Alcamo, J., Leemans, R., & Kreileman, E. (eds). 1998. Global Change Scenarios of the 21st Century - Results from the IMAGE 2.1 Model. Elsevier Science Ldt.

Alcamo, J., & Schaldach, R. 2006. LandShift: Global Modeling to Assess Land Use Change. Paper presented at EnviroInfo2006, Graz, Austria, September 6-9, 2006.

Bruinsma, J. (ed) / FAO. 2003. World agriculture: towards 2015/2030 – An FAO Perspective. James & James/Earthscan.

Buchanan, J.R., & Cross, T.L. 2002. Irrigation Cost Analysis Handbook. Agricultural Extension Service, The University of Tennessee, PB1721. August 8, 2005.

Burniaux, J.-M., & Truong, T.P. 2002. GTAP-E: An energy environmental version of the GTAP model. GTAP Technical Paper 16.

Criscuolo, L. 2006. Assessing the Agricultural System and the Carbon Cycle under Climate Change in Europe using a Dynamic Global Vegetation Model. Reports on Earth System Science, 21. Max Planck Institute for Meteorology / IMPRS-ESM.

Darwin, R., Tsigas, M., Lewandrowski, J., & Raneses, A. 1996. Land use and cover in ecological economics. Ecological Economics, 17, 157–181.

Dolman, A.J., Verhagen A., & Rovers, C.A. (eds). 2003. Global Environmental Change and Land Use. Kluwer Academic Publishers.

FAO. 2006. FAOSTAT Database. Electronic version at http://www.fao.org [Accessed in December, 2006].

Gerlak, A.K. 2004. One Basin at a Time: The Global Environment Facility and Governance of Transboundary Waters. Global Environmental Politics, Vol.4/No.4, 108–141.

Heistermann, M. 2006. Modelling the Global Dynamics of Rain-fed and Irrigated Croplands. Reports on Earth System Science, 37. Max Planck Institute for Meteorology / IMPRS-ESM.

Heistermann, M., Müller, C., & Ronneberger, K. 2006. Land in Sight? Achievements, Deficits and Potentials of Continental to Global Scale Land Use Modeling. Agriculture Ecosystems and Environment, 114(2-4), 141–158.

Hertel, T.W. 1997. Global trade analysis. Cambridge.: Cambridge University Press.

Johansson, R.C. 2000. Pricing Irrigation Water: A Literature Survey. World Bank Policy Research Working Paper. The World Bank Washington, DC, Rural Development Department.

Karagiannis,G., Tzouvelekas,V., & Xepapadeas,A. 2003. Measuring Irrigation Water Efficiency with a Stochastic Production Frontier – An Application to Greek Out-of-season Vegetable Cultivation. Environmental and Resource Economics, 26, 57–72.

Lambin, E.F., Geist, H.J., & Lepers, E. 2003. Dynamics of land use and land cover change in tropical regions. Annual Review of Environment and Resources, 28, 205–241.

Lotze-Campen, H., Müller, C., Bondeau, A., Smith, P., & Lucht, W. 2004. How tight are the Limits to Land and Water Use? – Combined impacts of food demand and climate change. Paper to be presented at the 2004 Conference of the International Environmental Modelling and Software Society (iEMSs), 14-17 June 2004, Osnabrück, Germany.

Lovecraft, A.L. 2006. The Complex Dynamics of Transboundary Water Management. IHDP Newsletter, 1/2006, 23–24.

Rockström, J., Folke, C., Gordon, L., Hatibu, N, Jewitt, G., Penning de Vries, F., Rwehumbiza, F., Sally, H., Savenije, H., & Schulze, R. 2004. A watershed approach to upgrade rainfed agriculture in water scarce regions through Water System Innovations: an integrated research initiative on water for food and rural livelihoods in balance with ecosystem functions. Physics and Chemistry of the Earth, 29, 1109–1118.

Ronneberger, K.E. 2006. The global agricultural land use model KLUM – A coupling tool for integrated assessment. Reports on Earth System Science, 26. Max Planck Institute for Meteorology / IMPRS-ESM.

Ronneberger, K., Tol, R.S.J., & Schneider, U.A. 2005. KLUM: A simple model of global agricultural land use as a coupling tool of economy and vegetation. FNU Working paper 65. Hamburg University and Centre for Marine and Atmospheric Science, Hamburg, Germany.

Ronneberger, K., Berrittella, M., Bosello, F., & Tol, R.S.J. 2006a. KLUM@GTAP: Introducing biophysical aspects of land use decisions into a general equilibrium model: A coupling experiment.

Ronneberger, K., Criscuolo, L., Knorr, W., & Tol, R.S.J. 2006b. Integrating dynamic land use decisions into a dynamic global vegetation model to assess the impacts of a changing climate. A feasibility study for Europe with KLUM@LPJ.

Rosegrant, M.W., Cai, X., & Cline, S.A. 2002a. World Water and Food: Dealing with Scarcity. Washington, D.C., USA: International Food Policy Research Institute.

Rosegrant, M.W., Meijer, S., & Cline, S. 2002b. International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT): Model Description. International Food Policy Research Institute, Washington, DC.

Rounsevell, M.D.A., Berry, P.M., & Harrison, P.A. 2006. Future environmental change impacts on rural land use and biodiversity: a synthesis of the ACCELERATES project. Environmental Science & Policy, 9, 93–100.

Swanson, T., & Xepapadeas, A. 2003. Editorial Introduction. Environmental and Resource Economics, 26, 1–4.

Van Hofwegen, P. 2006. Task Force on Financing Water For All, Report 1: Enhancing access to finance for local governments - Financing water for agriculture. Chaired by Angel GURRIA. World Water Council.

Von Westarp, S., Chieng, S., & Schreier, H. 2004. A comparison between low-cost drip irrigation, conventional drip irrigation, and hand watering in Nepal. Agricultural Water Management, 64, 143–160.

Wallace, J.S. 2000. Increasing agricultural water use efficiency to meet future food production. Agriculture, Ecosystems and Environment, 82, 105–119.

Yuan, T., Fengmin, L., & Puhai, L. 2003. Economic analysis of rainwater harvesting and irrigation methods, with an example from China. Agricultural Water Management, 60, 217–226.