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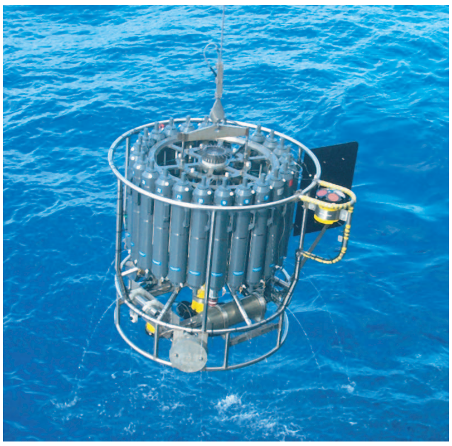
International Max Planck Research School
on Earth System Modelling

Irrigation and global change – new applications for integrated global land use modeling

Timm Sauer



Berichte zur Erdsystemforschung 102/2011

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Acknowledgements

You actually hold in your hand the doctoral thesis by Timm Sauer, who is in dual role with the composer of these acknowledgements. The thesis is titled “Irrigation and global change – new applications for integrated global land use modeling”. I got in touch with the idea of writing it due to an advertisement of a PhD position at the Research Unit Sustainability and Global Change (Forschungsstelle Nachhaltige Umweltentwicklung / FNU) at Hamburg University. Under the supervision of Prof. Richard S. J. Tol the topic evolved from the initial plan “to extend an existing global agricultural land use model by integrating some formerly neglected but yet important issues”. As I was interested to deal with a subject related to water resources, the idea of integrating concerns of irrigation came up, which seemed likely as it (a) is directly related to agricultural crop production, and (b) had not been explicitly integrated in the model so far.

In the following time, the simple implementation of “irrigate or not” became more differentiated by considering a diverse set of irrigation factors. An irrigation module was developed, which integrates crop and site-specific irrigation methods into a global economic partial equilibrium model for the land use sectors.

In retrospect, this subject was on one hand very interesting and challenging, on the other hand it held quite some potential to attract public criticism and personal frustration, because several aspects of agricultural land use and water resources simply could not be accounted for that detailed, as university studies taught to be adequate, due to the large-scale configuration of the model. Nevertheless it remained undoubted to me (and to the other people involved) that this kind of analysis is not only interesting but also very important. In my opinion it “had to be done”, to make an essential contribution to what is commonly referred to as “integrated assessment”. Finally, the studies included in this thesis may provide new insights into the interdisciplinary trade-offs between determinants of global land use change, and broaden the scientific basis for further explorations of the complexity of anthropogenic land use concerns.

The completion of my thesis would not have been possible in this form without the help and support by many people whom I want to thank very much and sincerely at this point:

At first I want to thank my family for supporting me wherever they could during the years of my PhD and beyond. Furthermore, I owe a lot of thanks to Prof. Richard S. J. Tol and Dr. Uwe A. Schneider for their mentoring and their great helpfulness and understanding not only in scientific problems, and to the International Max Planck Research School on Earth System Modelling (IMPRS-ESM) for the helpful educative and organisational support. With regard to the IMPRS-ESM, I particularly want to thank Dr. Antje Weitz and Cornelia Kampmann for their highly appreciated dedication to almost any kind of PhD students´ concerns, and Prof. Martin Claussen for giving valuable advice as the chair of my advisory panel.

The compilation of Part II of the thesis was made possible thanks to contributions made by Petr Havlík, Georg Kindermann, and Michael Obersteiner from the forestry program at the IIASA institute in Laxenburg (Austria) and by Erwin Schmid from the Institute of Sustainable Economic Development at the BOKU uiversity in Vienna. I want to thank all of them for the smooth and friendly cooperation, and especially Petr for his really great efforts to make it all work.

Besides the support due to scientific and technical assistance, I benefited a lot from the (honestly!) cordial working atmosphere at the FNU. Thus: Thanks a lot to all the colleagues I have met during my PhD and will hopefully continue seeing in the future. In particular the company and the frequent dialog with the ones who started their dissertation about the same time as I did (Alvaro, Dritan, Ivie, Kerstin, Nikolinka) was very encouraging for me during those years and made a lot of things easier. (Even though Kerstin, as the closest neighbour – and being a well-educated person – sometimes simply had no other choice than to accept my company anyway…) Not to forget, a big thank-you and an even bigger hug to Markéta for the pushing (it succeeded!).

Overall, this thesis would not have been possible without financial support. The research leading to the presented results has received funding from the European Community's Sixth and Seventh Framework Programme (FP6/FP7) (Global Change and Ecosystems, grant agreement n° GOCE-037063), ENSEMBLES (n° GOCE-CT-2003-505539) (www.ensembles-eu.org), Global Earth Observation – Benefit Estimation: Now, Next and Emerging (GEO-BENE) (www.geo-bene.eu), European Non-Food Agriculture (ENFA, n° SSPE-CT-2005-006581) (www.fnu.zmaw.de), Integrated Sink Enhancement Assessment project (INSEA) (www.insea.eu.info), Climate Change – Terrestrial Adaptation and Mitigation in Europe (CC-TAME, n° 212535) (www.cctame.eu), Bio Energy Europe (BEE project funded by the European Commission, FP7 grant agreement n° 213417) (http://www.eu-bee.com), and the Integrated Climate System Analysis and Prediction cluster of excellence (CliSAP) (www.clisap.de). It was further supported by the International Max Planck Research School on Earth System Modelling (www.earthsystemschool.mpg.de).

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Abbreviations

A2	“A2” development scenario/narrative storyline by SRES
AdMosa	Adaption Mosaic (development scenario/narrative storyline by MA)
AFR	Sub-Saharan Africa
AgEBB	Agricultural Electronic Bulletin Board, Missouri
AM	Adaption Mosaic (development scenario/narrative storyline by MA)
a.o.	among others
AQUASTAT	FAO´s Information System on Water and Agriculture
arcmin	arc-minutes
B1	“B1” development scenario/narrative storyline by SRES
CPA	Planned Asia with China
CWU	Consumptive water use
CWU/Q90	Consumption-to-Q90 ratio
e.g.	exempli gratia = for example
EIA	Energy Information Administration
EPIC	Environmental Policy Integrated Climate model
et al.	et alii = and others
EEU	Central and East Europe without Former Soviet Union
FAO	Food and Agriculture Organization of the United Nations
FAOSTAT	FAO Statistical Databases & Data-sets
FASOM	Forest and Agricultural Sector Optimization Model
FNU	Forschungsstelle Nachhaltige Umweltentwicklung = Research Unit Sustainability and Global Change
FSU	Former Soviet Union
GAMS	General Algebraic Modeling System
GAMS IDE	GAMS Integrated Development Environment (text editor / graphical interface)
Gcal	gigacalories = 1E+09 food calories
GDP	Gross domestic product
GFASOM	Global Forest and Agricultural Sector Optimization Model
GGI	Greenhouse Gas Initiative
GHG	Greenhouse gases

GLOBIOM	Global Biomass Optimization Model
GlobOr	Global Orchestration (development scenario/narrative storyline by MA)
GO	Global Orchestration (development scenario/narrative storyline by MA)
ha	hectare
HRU	Homogeneous Response Unit
ICID	International Commission on Irrigation and Drainage
i.e.	id est = this means
IFPRI	International Food and Policy Research Institute
IIASA	International Institute for Applied Systems Analysis
IMF	International Monetary Fund
IMPRS–ESM	International Max Planck Research School on Earth System Modelling
IPCC	Intergovernmental Panel on Climate Change
ISI	Institute for Scientific Information
kcal	large calories
km^3	cubic kilometers
LAM	Latin America and Caribbean
m^3	cubic meters
MA	Millennium Ecosystem Assessment
MEA	Middle East and North Africa
mill	million
MPI–M	Max Planck Institute for Meteorology
NAM	North America
Non-Ag	Non-agricultural
OECD	Organisation for Economic Co-operation and Development
O&M	Operation & Maintenance
OrdStr	Order from Strength (development scenario/narrative storyline by MA)
OS	Order from Strength (development scenario/narrative storyline by MA)
PAO	Pacific OECD-countries
PAS	Other Pacific Asia
PEM	partial equilibrium model
Q90	measure of the monthly river discharge that occurs under dry conditions (monthly discharge is higher than the Q90 value 90% of the time)
SAS	South Asia
SimU	Simulation Unit

SRES	Special Report on Emissions Scenarios (published by IPCC)
SU	Soviet Union
UNDP	United Nations Development Programme
UNSD	United Nations Statistics Division
USDA-NRCS	U.S. Department of Agriculture, Natural Resources Conservation Service
vs.	versus
WAE	Water application efficiency
WEU	Western Europe
;-)	so-called emoticon that expresses serious irony, very popular these times

Für meine Mutter Elli Louise Sauer

Preface

The doctoral thesis at hand consists of four parts, which have been considered for publication in scientific journals, or as FNU working-papers respectively. These four parts are complementary and consistently linked within the dissertation as regards form and content.

The first part ("Exploring irrigation literature – a framework to assess agricultural water use") deals with the categorization of irrigation issues to facilitate the finding and implementation of research schemes. An overview on different aspects, scales, and aggregation levels of irrigation and related sciences is given. Based on this, a classification system for irrigation-related literature is established to improve the identification of specific problems and interdependencies among the broad field of irrigation science, and thus to facilitate integrated research approaches as well as literature surveys in general. The second part of the thesis ("Effects and sensitivity of irrigation parameters: the problem of implementation") qualitatively describes interdependencies between different determinants of irrigation water use. The focus is put on factors that could not be considered in the quantitative model analyses but nevertheless are of great importance to understand underlying mechanisms of irrigation decision making. Problems of their implementation into a global modeling framework are discussed. For selected variables the regional sensitivities toward impacts of "global change", as well as regional potentials for sustainable irrigated agriculture are assessed. Following these virtually basic works, the next study ("Agriculture and resource availability in a changing world: the role of irrigation") portrays the newly developed irrigation module and its integration into the GLOBIOM modeling framework. First simulation runs are carried out to obtain deeper insight into the role of irrigation and irrigation management options for global land use change. Finally, the fourth part of the thesis ("The value of irrigation in a global context") presents findings on the actual value of irrigation for "societal welfare" that are based on new simulations for an extended range of scenarios. The full citations of these four parts with regard to publication status at current stage are as follows:

Part I:

Sauer, T. (2009), Exploring irrigation literature – a framework to assess agricultural water use, *FNU working-paper, FNU-183*.

Part II:

Sauer, T. (2010), Effects and sensitivity of irrigation parameters: the problem of implementation, *considered for publication as FNU working-paper*.

Part III:

Sauer, T., P. Havlík, U. A. Schneider, E. Schmid, G. Kindermann, and M. Obersteiner (2010), Agriculture and resource availability in a changing world: the role of irrigation, *Water Resources Research, 46, W06503*, doi:10.1029/2009WR007729.

Part IV:

Sauer, T. et al. (2010), The value of irrigation in a global context, *to be submitted for peer-reviewed journal publication*.

The results and conclusions from these works are scientifically relevant in their depiction of large-scale developments of land use change and resource problems, with a focus on potentials to improve global water use efficiency. They are of highly interdisciplinary and integrative character, and they do not claim for giving exact numbers to precisely describe clearly definable processes.

Additionally, two further papers have been submitted to scientific journals, to which I contributed as a co-author. These papers are not integrated into the main part of the thesis but they are attached in the appendix. Apart from these co-authored papers (see citations below) the appendix includes an overview on the GLOBIOM model items and equations as used in the simulations, in terms of a formal description (Appendix–1).

Firstly submitted co-authored paper (Appendix–2):

Havlík, P., U. A. Schneider, E. Schmid, H. Boettcher, S. Fritz, R. Skalský, K. Aoki, S. de Cara, G. Kindermann, F. Kraxner, S. Leduc, I. McCallum, A. Mosnier, T. Sauer, and M. Obersteiner (2010), Global land-use implications of first and second generation biofuel targets, *Energy Policy (in press)*, doi:10.1016/j.enpol.2010.03.030.

Secondly submitted co-authored paper (Appendix–3):

Schneider U. A., P. Havlík, E. Schmid, M. Obersteiner, T. Sauer, R. Skalský, and S. Fritz (2010), Impacts of population growth, economic development, and technical change on global food production and consumption, *submitted to Agricultural Systems*.

Please note that this thesis represents an objective study. The results and conclusions given are neither what I expected nor what I "desired" to come out at all. In this context I should conclude that science makes sense ;-)

Summary

Fertile land and freshwater constitute two of the most fundamental resources for food production. These resources are affected by environmental, political, economic, and technical developments. Regional impacts may transmit to the world through increased trade. Irrigation is a necessary tool to achieve the aim of global food security. As the major water user and due to its importance for agricultural management it has far reaching implications on both, environmental and economic concerns. Accordingly the science of irrigation is a highly complex and interdisciplinary field of research that comprises numerous interlinked factors on various scales.

In the first part of this thesis an overview on the different facets of irrigation issues is presented. Major scientific categories are designated and further ranked by their "level of integration". A classification system for irrigation related literature is established to recognize the special role of irrigation science, to facilitate literature surveys and the formulation of research questions, and eventually to promote integrated investigations. Finally, the state-of-the-art of existing studies by topic and method is highlighted.

The successive chapter presents a qualitative assessment of interactions between irrigation factors and further determinants of global change. Problems of scale and the non-linearity of functional relationships are discussed. An assessment of parameter sensitivities and regional exposures toward land use change is conducted, and regions are accordingly grouped in terms of different "sensitivity classes".

These first two chapters both focus the complex linkages among irrigation factors, and the interdisciplinary, multi-level character of irrigation science. Consequently the purpose and expedience of using integrated assessment models becomes emphasized.

Against this background knowledge on interdisciplinary linkages, resulting questions of global importance, and the range of scientific approaches to assess irrigated agriculture, two studies using a global forest and agricultural sector model are conducted.

In the first simulation-based study the model is used to quantify the impacts of increased demand for food due to population growth and economic development on potential land and water use until 2030. The investigative focus is particularly put on producer adaptation regarding crop and irrigation choice, agricultural market adjustments, and changes in the values of land and water. In the context of resource sustainability and food security, this study accounts for the spatial and operational heterogeneity of irrigation management to globally

assess agricultural land and water use. The results indicate that agricultural responses to population and economic growth include considerable increases in irrigated area and water use but reductions in the average water intensity. Different irrigation systems are preferred under different exogenous biophysical and socioeconomic conditions. Negligence of these adaptations would bias the burden of development on land and water scarcity. Without technical progress, substantial price adjustments for land, water, and food would be required to equilibrate supply and demand.

The second study more concretely deals with the valuation of irrigation as regards its impact on socioeconomic welfare at a whole, considering the targets of achieving food security, economic growth, and ecological sustainability. Future changes in the value of water and irrigated cropland are analyzed under different scenarios of global change and water management, and discussed in the context of welfare effects. The overall aim is to derive agricultural policies and appropriate measures for a well-balanced global development of economic and ecological concerns.

Findings include that globalization rather enhances irrigation land and water use, and also has a stabilizing effect on food prices, whereas trends decentralization lower the stability of food prices and resource use balance and even lead to substantially increasing resource demands on the long term. The influence of irrigation decision-making "itself" on regional economic concerns, food prices, and food security is generally higher under globally decentralized structures than under globalization scenarios. However, the notion or definition of the value of irrigation varies by the viewer´s perspective, i.e. whether one emphasizes the input efficiency per produced unit of food, or its availability (or scarcity) in quantitative terms. The assessment of different irrigation-scenario impacts indicates that policy interventions, in terms of environmental, economic, and institutional-based regulations, can be effective means to support targets of socioeconomic stability, ecological sustainability, and food security. Restrictions to irrigation are likely to trigger a more efficient use of resources. Additionally, the adoption of improved management strategies other than irrigation to enhance crop yields is triggered as well. Simulation results imply that an unrestricted expansion in terms of a free choice of e.g., shifts between crop types and irrigation managements does not enhance improvements of resource use efficiency in a "self-regulating" manner at all. Potentials of "global sustainability" are projected to be greatest under scenarios of globalization, but the underlying causes may also be, e.g. due to discrepancies between rich and poor countries. Consequently we assume that a resulting high global sustainability does not necessarily mean high regional sustainability. In contrast, scenarios with an explicit focus on environmental policies are predicted to be successful only on short to mid term in terms of efficient irrigation water use, but on the long-term initial sustainability and welfare effects appear to be of unstable nature.

The global character of the model and of the conducted investigations naturally involves abstractions, aggregations, and simplifications. Thus, deficits with regard to data availability, temporal resolutions, and in particular spatial scales of our present analysis always have to be considered when evaluating the results. But though it seems utopian to derive “best practices” or “safe policies” from such global modeling efforts, it is worthwhile to use these available tools for an estimation of global trends, and make a reasonable contribution to the scientific basis for policy making.

PART I

Exploring irrigation literature –

a framework to assess agricultural water use

I / 1. Introduction

Agricultural crop production is essential to human existence [Tilman et al., 2002]. Decisions of crop production are shaped by physio-geographic conditions, and motivated by socioeconomic drivers. Land-use changes in turn affect the natural environment, and also determine the economic revenue of land-intensive productions, thus completing a vital feedback loop of interactions between human society and natural environment [Lambin et al., 2003]. Furthermore, drivers and impacts appear on different spatial, temporal, and thematic scales [Lotze-Campen et al., 2005]. Population growth increases pressure on natural resources to meet rising food demands. At the same time, climate change may add further pressure on agricultural systems [Lobell et al., 2008; Ramankutty et al., 2002].

Against this background, irrigation is used to enhance crop yields or to enable the cultivation of specific crops in a certain biophysical surrounding, respectively. Future agricultural water management will be determined by increasing water scarcity, competition for water, and growing concerns about the environmental impacts [Van Hofwegen, 2006]. To account for the interdisciplinary feedbacks in the context of both food and environmental security, great emphasis has to be put on the resilience, adaptability and sustainability of agro-environmental systems [Dolman et al., 2003].

All those aspects emphasize the need for integrated assessments. However, the manifold linkages inhibit an adequate analysis within one single study or model. It seems inevitable to consult exogenous information to gain integrated insights into the complexity of the subject.

This paper provides a conceptual framework to classify literature on water resources and irrigation in order to improve structuring of scientific approaches to irrigation related questions, and to facilitate the evaluation of existing studies. The classification concept is followed by a quantitative overview on the state-of-the-art of accordant publications.

I / 2. The peculiarity of irrigation science

Irrigated agriculture takes a particular important position with regard to water use for three reasons: First, it constitutes an essential link between biosphere and anthroposphere [Heistermann et al., 2006]; second, it represents one of the most basic tools of agricultural management to ensure food supply; and third, irrigation is the major water user as regards sectoral demands [Falkenmark and Lannerstad, 2005].

Irrigation embodies interdisciplinarity on a high level. On one hand it greatly extends and intensifies the "common concerns" of (rainfed) agriculture into the fields of geographic and environmental sciences, on the other hand it reaches far into issues of disciplines such as resource economics, engineering sciences, and eventually to what is consolidated as applied sciences. Concerns of applied science in turn may further include numerous interrelations on different scales.

The state-of-the-art in irrigation research encompasses a broad range of scientific literature, dealing with manifold aspects. Publications are related to different issues, like e.g. water availability, irrigation efficiency, water pricing, water delivery and application technologies, or sustainable management, and may apply different approaches as regards content and method. Furthermore, the appearance and relevance of drivers and feedbacks may substantially vary among local to global investigations.

I / 3. Why classify irrigation literature?

The common process of defining a new research topic usually starts with the formulation of one or several central research questions. Next, one has to identify criteria, factors, and parameters that are assumed to describe the relevant interrelations and processes, which functionally determine the chosen subject-matter of research.

To efficiently support targeted research it is helpful to distinguish thematic categories of science that deal explicitly with the processes and factors in question. In case of research questions that are of complex character as to require integrated approaches, it is further a challenge to reveal particular linkages between such categories, which could be regarded as "constitutional", i.e. linkages that will arise inevitably at a certain depth of exploration into the respective subject.

The establishment and revelation of such categories and linkages facilitates (a) the conception of research ideas among the scientific context for a better understanding of causalities and interrelations, (b) to formulate priorities with respect to innovative research questions and emphasized topics, and (c) to improve and accelerate personal surveys and evaluation of existing literature.

I / 4. Classification of literature dedicated to irrigation issues

I / 4.1 Classification by content

As pointed out in the foregoing chapters, it seems reasonable to find a consistent system to classify irrigation related literature in order to facilitate scientific research. In this paper, the development of such a classification system is presented. The framework consists of four “integration levels” that are structured hierarchically based on their degree of integration and specification, respectively. Each level comprises several “major categories of irrigation research topics” (Figure 1).

Level 1 represents least integrative but most specified subjects whereas level 4 includes labels that stand for highest integration of sub-topics and thus represent rather generalized terms. This means, low levels represent more or less precisely definable categories that can be treated separately as discrete research fields and thus may be investigated independently from other categories of any level. However, they may as well be analyzed in an interdependent context with other categories. High levels, in contrast, represent ambiguous labels that are not clearly defined but integrate a varying number of different research fields (or sub-categories), potentially in inter- or transdisciplinary manner. Accordingly, studies dealing with lower level topics can be assumed to provide a greater degree of detail (on their particular “delimited research field”) than studies of higher level topics.

The different integration levels are thematically linked in a vertical way: Highly integrative categories integrate issues of less integrative, i.e. lower ranked categories, e.g. studies of the category “Water management” (level 4) may emphasize “Water use efficiency” (level 3), which in turn integrates issues of “Water demand” as well as “Green and blue water assessment” (both level 2) that are further determined by, a.o. local “Basin hydrology” (level

1). The “horizontally arranged” topics of one and the same level are also likely to be linked among each other, in terms of interactions or thematic overlaps.

VERTICAL HIERARCHICAL STRUCTURE: LEVEL OF INTEGRATION	*HORIZONTAL STRUCTURE: (INTERACTING) ISSUES ON THE SAME LEVEL OF INTEGRATION*				
4	Water management	Water policy	Water resource assessment		
3	Water use efficiency and water productivity	Water use and livelihoods (socio-economic and cultural issues, incl. access to water, tradition and know-how, poverty alleviation)	Environmental impacts	Water supply and availability	Water demand by sectors
2	Land use potentials and options	Green and blue water assessment	Virtual water	Irrigation (and drainage) scheduling and design	Farm micro-economics (costs and benefits of irrigation options)
1	Basin hydrology	Crop sciences, plant-physiology	Agricultural and resource economics		

Figure 1: Classification of irrigation literature by content

I / 4.2 Distinction by approach and method

Besides differences in content and thematic emphasis, further criteria to classify studies can be found in terms of approach and methodological technique. Existing analyses may be distinguished regarding

a) The flow of information: top-down and bottom-up systems;

b) The dominating analysis technique: engineering and economic approaches;

c) The system dynamics: comparative static, recursive dynamic, and fully dynamic designs;

d) The spatial scope: farm level, watershed, national, multi-national, and global representations;

e) The sectoral scope: agricultural, multi-sector, full economy, and coupled economic and environmental models. The agricultural-sector scope can be further refined in terms of integrated, geography or economy-focused [see Heistermann et al., 2006].

I / 5. The state-of-the-art in irrigation science: a quantitative overview

The output density of publications on irrigation related subjects has increased rapidly over the last decades (see Figure 2), conditioned by scientific and technological developments and accompanied by rising environmental and societal challenges. Accordingly, the number of publishing researchers has grown, too. So has the number of "publications per researcher" due to a growing number of journals, and organisational and technological improvements in the processes of submitting, reviewing, and publishing.

From all publications of the past 100 years directly related to irrigation, 50% were published within the last 20 years (i.e. since the beginning of the 1990´s), and even 30% in the recent 10 years alone. Before the 1970´s, only 10% of today´s cumulated lot came to press. As mentioned at the start of this chapter, this impressive development may be easily explained with "modern world problems" like increasing scarcity of adequate resources, population pressure, and changing climatic conditions, in conjunction with ever-increasing technical potentials. This huge amount of information in turn needs to be at least coarsely classified in order to be born by the potential user.

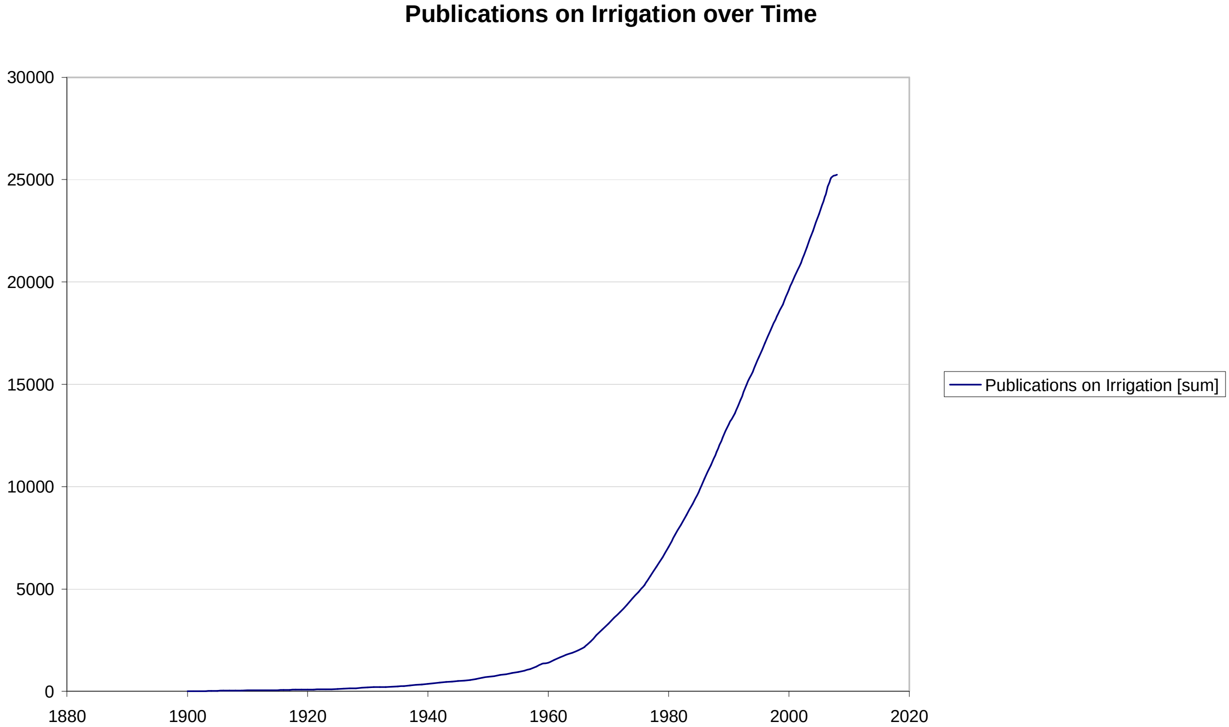

Figure 2: Development of published irrigation research (papers per year) in the past 100 years [source: ISI]

The state-of-the-art in irrigation literature is highlighted quantitatively by means of various criteria (e.g. topic, approach, spatial scale). The figures are based on surveys conducted online at “ISI Web of Knowledge” (Institute for Scientific Information) in April 2008. For statistics on “topics” and “spatial scale” certain combinations of key words were searched for in the ISI topic-section. Regional-scope information is obtained by searching for studies that have the term of “irrigation” explicitly included in their title.

Altogether, more than 85,000 publications related to the topic of irrigation can be found. The largest part of the studies (37%) deals with plant-based analyses focusing physiological processes of relevance for irrigation projects, in conjunction with specific methods applied. Another 18% are of similar methodological nature but emphasize technological or technical approaches on water productivity. More "extended" studies on irrigation water management, including policy aspects, represent the second largest group of about 27%. Essays on farm scale scheduling and cost-benefit analyses make up 9%. Remarkably, only 1% of all publications explicitly describe land and water-use modeling techniques. Finally, other topics than those already mentioned (e.g. evaluations of specific irrigation systems, water resource assessments, and macro-economic valuation) are grouped together. This group reaches a magnitude of 8% (Figure 3).

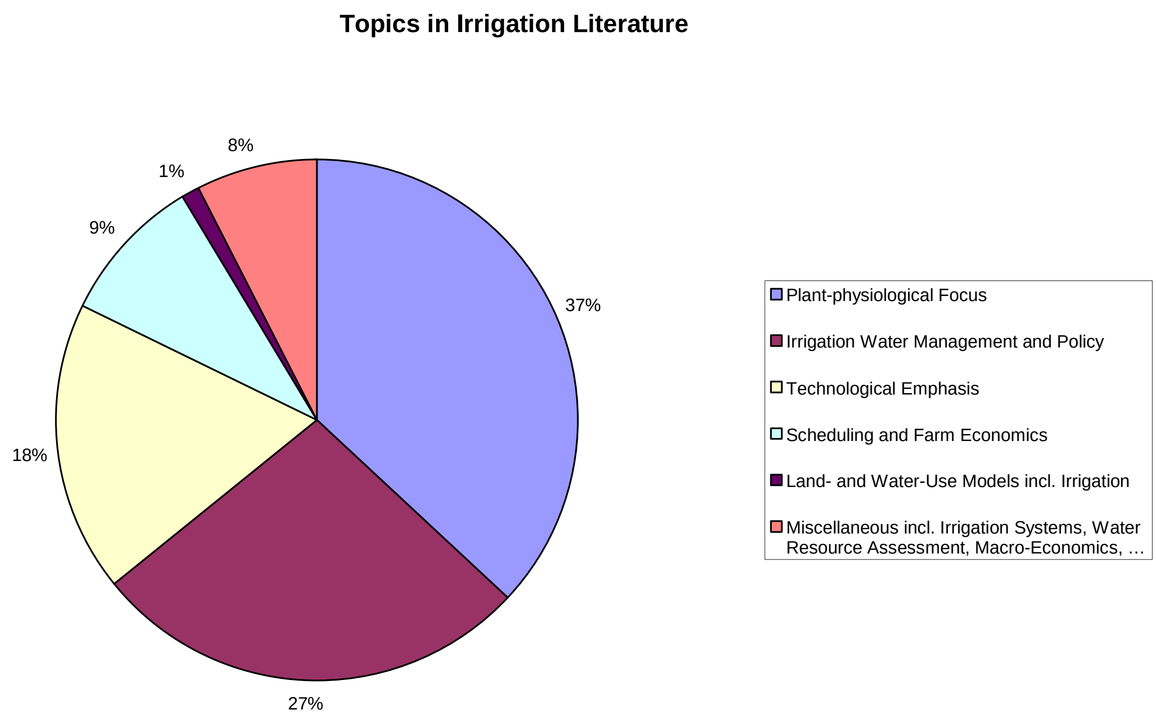

Figure 3: Proportions of studies by topic of total irrigation publications [source: ISI]

Almost half of all publications are dedicated to farm level or small scale investigations. An also relatively high fraction of 41% is captured by basin scale assessments. About 11% of the studies operate on larger scales, but only 1% is explicitly labelled as global scale analyses (see Figure 4).

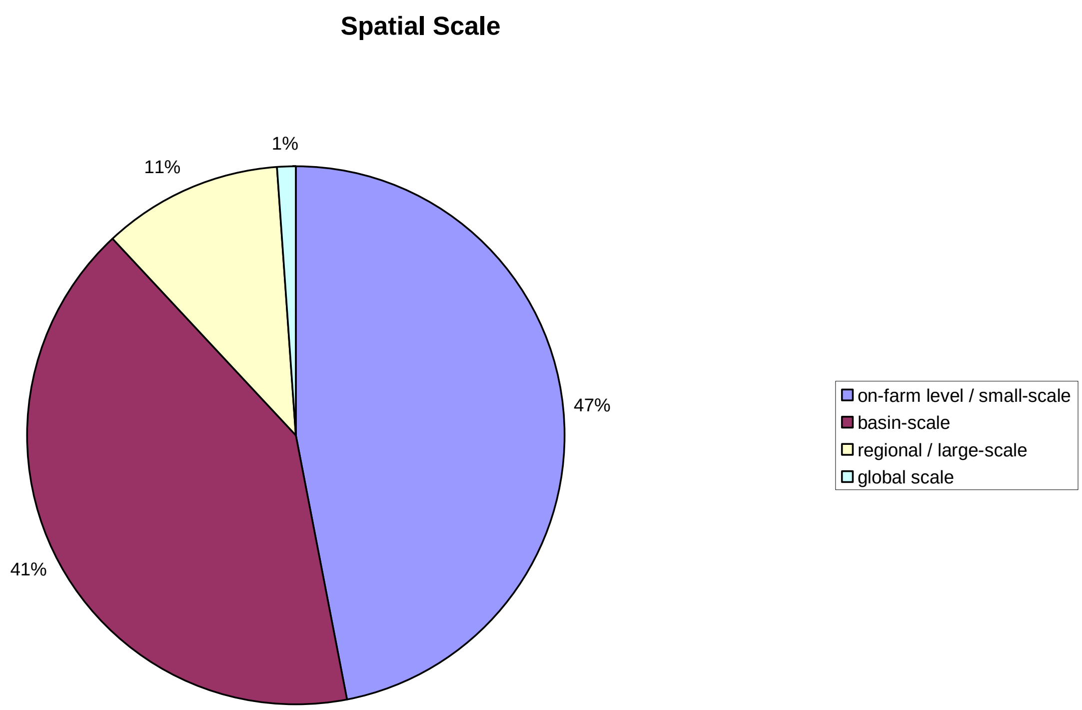

Figure 4: Proportions of studies by their spatial scale of total irrigation publications [source: ISI]

Figure 5 shows the number of regionally focused irrigation studies for selected countries or regions. Most research has been done in the United States, followed by India. Another important region is the Mediterranean area. Furthermore, Australia and Sub-Saharan Africa are often subjects of investigation, followed by China and Russia, both with an upward trend regarding research activities.

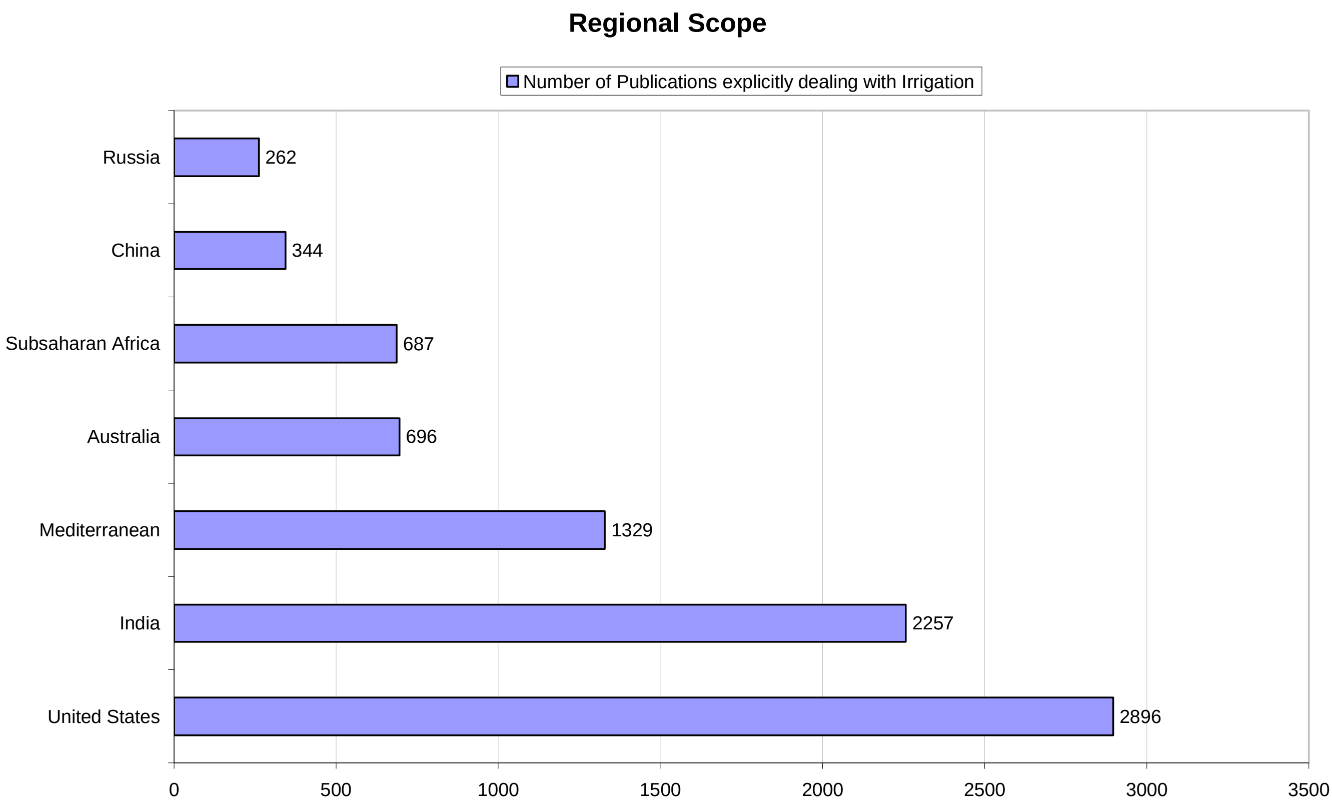

Figure 5: Regional hot-spots of irrigation research [source: ISI]

Looking at the modelling approach, 71% are geographically focused, 24% place emphasis on socioeconomic issues, and 5% adopt an integrated approach (see Figure 6).

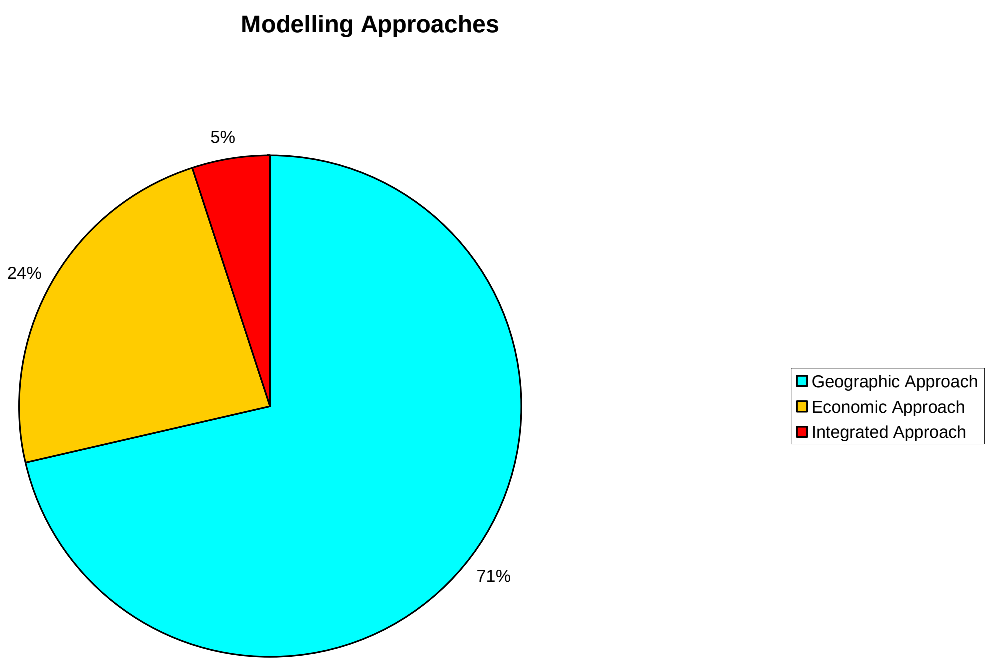

Figure 6: Distribution of approaches in land and water-use models accounting for irrigation [source: ISI]

I / 6. Conclusions

Irrigation science is a highly interdisciplinary and differentiated field of research. Because it is an immediate interface between the natural and the socioeconomic sciences manifold interdependencies with sub-disciplines on various scales consequently led to a great amount of studies, which may substantially differ between each other though being collectively labeled as "irrigation research".

There are two major arguments for the formation of a classification system for irrigation literature: Firstly, it points out the diversity and complexity of irrigation science and reveals pathways for an integrated assessment of agriculture, water use, and ecological concerns. Secondly, it is a helpful tool to promote and guide innovative research in terms of focused and efficient approaches. A classified overview on irrigation issues and how they are treated in literature can be helpful to obtain insights on relevant matters and linkages, to systematically sort information, and to eventually support targeted research on irrigation related questions.

Nevertheless it should be borne in mind that seamless transitions between the proposed categories may appear. Classification systems like the one proposed in this paper should be understood as useful tools for goal-oriented evaluation but not as "hard-criteria" instruments to derive solutions to specific problems.

A look at the existing literature shows that most irrigation related analyses are carried out on small spatial scales, which is on one hand reasonable with regard to consideration and projection of system complexity and inherent multifunctionality. But on the other hand the embedding large-scale relations and mechanisms which are of significant importance for the dynamics of the earth system and the omnipresent term of "global change" are neglected.

The challenge will be to integrate micro and macro-scale cognition, even though under the burden of further simplification and abstraction. Because of the problems mentioned, only relatively few integrated large-scale approaches exist so far. To account for small-scale processes and determinants within large-scale frameworks as claimed within "global integrated assessments" requires the consideration of knowledge and approaches from yet more or less separately treated compartments of irrigation research. Against the background of the discussions on growing resource scarcity, the overall objectives of achieving new insights on global interdependencies between water resources, biodiversity, socioeconomy, and food security, and of depicting future pathways of sustainable development are challenges that inevitably also require the support of what can be referred to as "irrigation science". The proposed classification system with its integrative structure is meant to support the systematic exploration of such “modern day problems” in an interdisciplinary context.

PART II

Effects and sensitivity of irrigation parameters: the problem of implementation

II / 1. Introduction

There are several aspects that argue for an integration of irrigation decision factors traditionally applied to farm and basin scale analyses into global assessments of agricultural water use. Motivation and aims of this have been discussed by Sauer et al. [2010] and are also addressed in the subsequent chapters of this thesis.

Changes of such irrigation factors may quantitatively influence the output variables of integrated modeling efforts. The problem, or rather the challenge is (1) to determine a reliable and consistent range of values for these biophysical, economic, and technical parameters, (2) to transform these values to our large-scale model resolution, (3) to explore the parameters by means of a sensitivity analysis, and finally (4) to validate and discuss their general reproducibility within a global PEM.

The model presentation in Parts III and IV of this thesis deals with the integration of irrigation issues into a global land use model. However, not all parameters related to irrigation decision making could be considered, not at last due to problems of scale in the implementation of these concerns.

According to our statement above, we think that these other factors should at least be discussed qualitatively or respectively, in a hypothetical quantitative manner to not neglect their potential role in farmers´ irrigation choice.

II / 2. Irrigation parameters and impact factors

The model applies a range of irrigation-related parameters (Table 1). These biophysical, economic, and technical parameters are used to simulate land use changes in conjunction with overall socioeconomic and biophysical background settings (“impact factors”, see Table 2).

Table 1 - Irrigation parameters
Combined slope and soil conditions
Water supply and prices
Land supply and prices
Water application efficiency
Irrigation investment costs
Labor demand for O&M
Labor costs
Energy prices

Table 1: Irrigation parameters

The “impact factors” (Table 2) represent biophysical, agroclimatic, socioeconomic, and technical background settings, and indicate specific trends and relationships among the irrigation parameters. In turn, they may vary depending on the particular scenario storyline.

Table 2 - Factors that impact the value of irrigation parameters
Climate change: precipitation and temperature (water availability)
Population growth: sanitation and food-related water demand
Economic development: Income, food and lifestyle change-related water demand, other sectoral water demand
Water stress
Literacy level
Labor markets
Technical progress
Irrigation potential as a combined result of water availability, soil conditions, technology, and infrastructural development

Table 2: Factors that impact the value of irrigation parameters

In the following we discuss how the irrigation parameters may be affected by changes in the superordinate impact factors.

II / 3. Interrelations between determinants of irrigation

We generally assume that variations in climatic conditions (subsequently referred to as “climate changes”) may alter total water availability as well as its spatiotemporal distribution. Furthermore, population growth and economic development may alter sectoral demands for freshwater. In general, potential rates of increase or decrease in parameter values depend on their particular regional exposure with regard to circumstantial conditions that may favour or disfavour the developments in question.

The assumed relationships between model irrigation parameters (Table 1) and impact factors (Table 2) are discussed in the following hypotheses and illustrated in Figure 1.

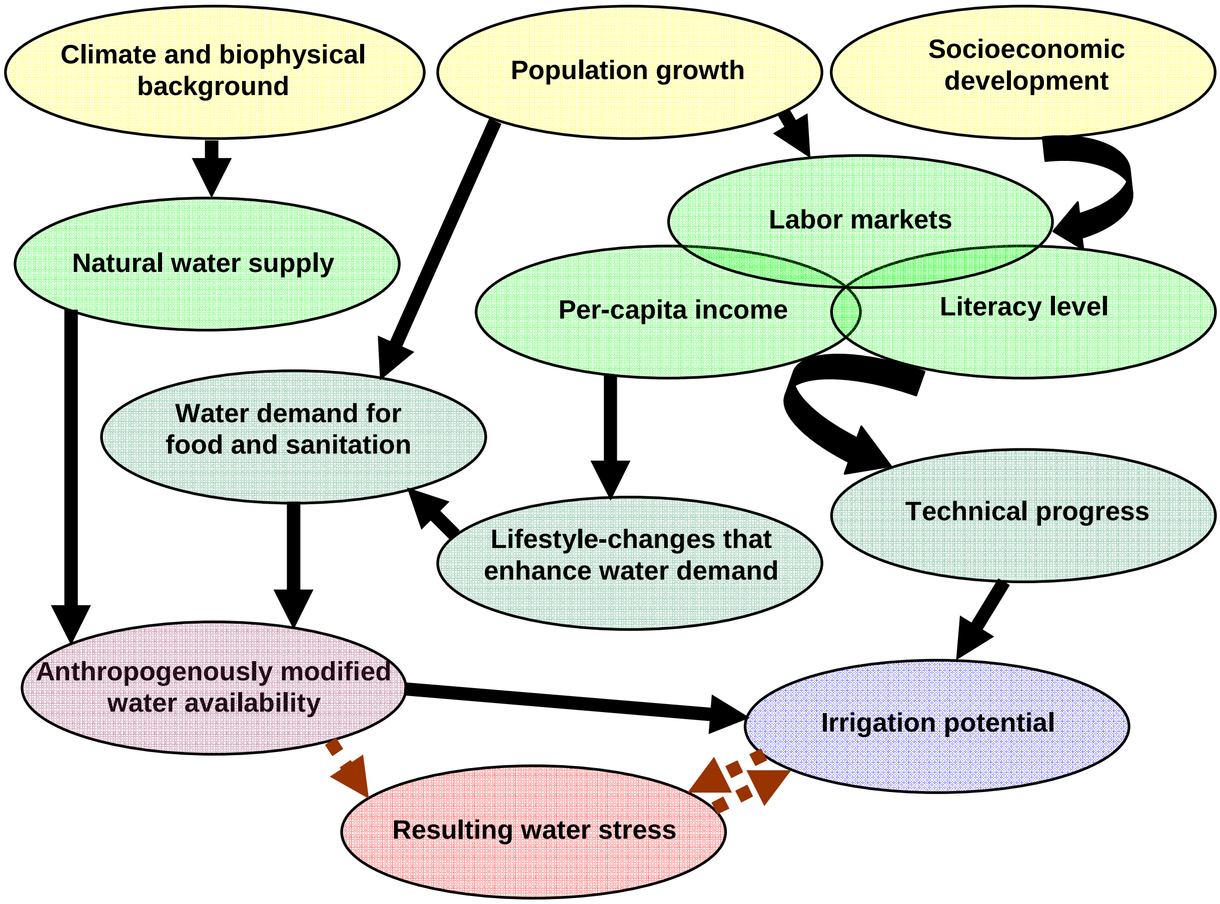

Figure 1: Linkages between “impact factors” and selected irrigation parameters

II / 3.1 Water supply and water price

The parameter “water supply”, its elasticity and supply function, and the derived water price are affected by base-year and future water stress (water supply-to-demand ratios and future changes in terms of growth rates). Physical water scarcity and growing water demands decrease water availability for agriculture and trigger policy interventions in terms of water pricing.

A high ratio of future water withdrawal-to-availability more strongly decreases water supply than a lower ratio. Accordingly, high future ratios increase water prices (and indirectly investment cost). For our ranking of regional sensitivities to water stress (see Figure 4) we consider a.o. the indicator of projected CWU/Q90 ratios given by Alcamo et al. [2003], which implicitly focuses hot spots of withdrawals for agriculture and irrigation.

II / 3.2 Land supply and land price

Supply of land suitable for agriculture is primary a function of climate and soil conditions [Ramankutty et al., 2002] in conjunction with the sectoral demands for land resources, and potential degradation of land quality over time. The price of land is based on its supply function and the assumed elasticity of land supply.

The rate of land degradation (and of resource degradation in general) may be determined by using a base-year ranking of “irrigation potential” (see Figure 3) for indicator.

II / 3.3 Externalities

External costs and risks to sustainability in terms of resource degradation are a complex function of climatic conditions and soil quality limits that restrict cultivation [Ramankutty et al., 2002] on one hand, and factors that directly or indirectly influence the biophysical environment on the other hand. Direct impacts may be due to agricultural management practises, including different forms of irrigation, which in turn are affected by economic development, income, and literacy, but also by the regional distribution of labor force [Bruinsma, 2003].

II / 3.4 Capital investment costs

Irrigation costs in general, including considerations on the price of water itself are affected by base-year and future water stress. These can be expressed by water demand-to-supply ratios, and future changes in terms of estimated growth rates.

In GLOBIOM, capital costs of irrigation are represented by rather coarse estimates. Real world complexity of economic relationships is considered abstractedly in the following assumptions: Capital costs are affected by base-year rankings of economic development, income, and literacy (see Figure 2) as well as by the overall irrigation development potential. Low economic development and income levels increase relative investment cost. A low level of literacy increases the relative costs with respect to the share of maintenance. Low potentials of irrigation expansion and development also increase the relative investment costs. We further assume that a high irrigation development potential leads to a price increase for irrigation inputs because of increased demands, but nevertheless decreases total investment costs in relative terms due to functional relationships between economics and resource availability aspects that underlie the development potential. Furthermore, on short term humid climate may increase relative investment cost due to less developed “irrigation markets”. On the other hand, aridity may also increases relative investment cost due to commonly higher problems of poverty in arid regions.

II / 3.5 Labor demand and labor costs

The expenses for labor as required for irrigation operation and maintenance (O&M) are affected by the base-year rankings of economic development, income, and literacy: Low economic development, income, and literacy levels decrease labor costs. In addition there is an impact due to changes in labor force [Bruinsma, 2003].

II / 3.6 Technological progress and water application efficiency

Technological progress is affected by base-year and future water stress, which we assume to enhance policy interventions to promote research. Water stress is expressed by demand-to-supply ratios and their future changes.

The potential rates of technological development are also affected by the regional base-year rankings of economic development, income, and literacy.

Water application efficiency (WAE) is closely related to technological progress and thus affected by regional base-year rankings of economic development, income, and literacy as well as by base-year and future water stress (due to technological progress and water stress itself). We also assume water efficiency to be related to the potentials of irrigation expansion and development.

Water stress and a low irrigation development potential increase WAE due to growing pressure on resources, whereby the rate of increase depends on baseline income and literacy levels.

Low income tends to decrease WAE potentials because of relatively low economic motivation concerning tasks of maintenance, in conjunction with only short to mid term agricultural planning due to specific problems due to low-income-situations. Low base-year literacy level lowers WAE potentials because of relatively low technological standard, whereas higher literacy has a positive effect because of assumedly higher technological standard. Economic development levels and technological standard are likely to be interrelated in an analogue manner.

In addition, we assume that humid climate favours an increase in WAE, whereas aridity lowers WAE potentials.

II / 4. Regional exposure and sensitivity of irrigation parameters toward "global change"

We collected and assessed qualitative and quantitative information to derive potential changes of indicators with relevance for irrigation developments. As data availability on "global change" to describe the future development of sensitive irrigation-related model parameters is rather scarce in terms of quantified projections, we mainly estimated regional rankings and relative differences as obtained from literature survey. Relative differences are estimated using a rule-based approach on the combined effects of the "impact factors" and with respect to each region´s individual exposure toward potential changes of these factors. We thus provide ratios that represent the relative differences between the model regions concerning the projected increase or decrease of parameter values.

We assume that one region's exposure toward changes in irrigation practises and policies is related to its current levels of certain socioeconomic indicators. Accordingly we group the regions by their current (baseline) levels of literacy and income, by their current state of economic development, and by their average evapotranspiration rates [FAO / IIASA, 2000; IMF, 2007; UNSD, 2009; World Bank, 2006]. Depending on the particular irrigation parameter in question this information can be used individually or in combined form to derive future trends (see Figures 2 and 3). Tables presenting an overview on the model regions, including their abbreviations, can be found in chapters III / 3.1 and IV / 4.

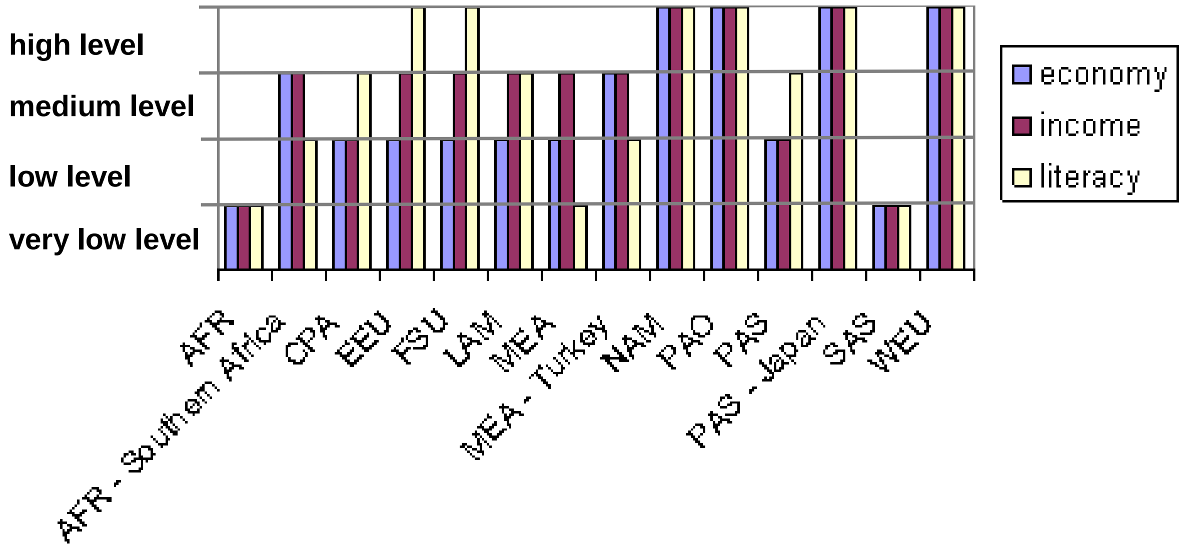

Figure 2: Socioeconomic grouping of world regions

Regarding the combined influence of these indicators one finds that the current conditions to allow a positive prognosis for the triggering of technological progress are worst for Sub-Saharan Africa (AFR). In a ranking from lowest to higher development potentials AFR is followed by South Asia and India (SAS), Middle East and North Africa (MEA), Central and South America (LAM), and Southeast Asia (PAS). China, Turkey, Brazil, Mexico, and Eastern Europe overall show a transitional status between the formerly mentioned regions and those with good conditions with respect to high-standardized and efficient exercise of irrigation (Japan and South Korea, North America, Australia, rest of Europe).

Information on irrigation potentials with regard to availability and suitability of land resources, but also considering the regional capacities for expanding irrigation infrastructures could be obtained from FAO / IIASA [2000]. The regional ranking of irrigation potential is partly different from that of the other impact factors due to its biophysical context. It may be higher for regions with a formerly lower level of irrigation, be it due to lack of financial resources, lack of professional experience, or even lack of former necessity to irrigate, such as in Europe, AFR, and South America. In turn it is lower for rather traditional regions of irrigated agriculture such as Asia and North America (NAM) because their capacities of irrigation expansion are somewhat exhausted (Figure 3).

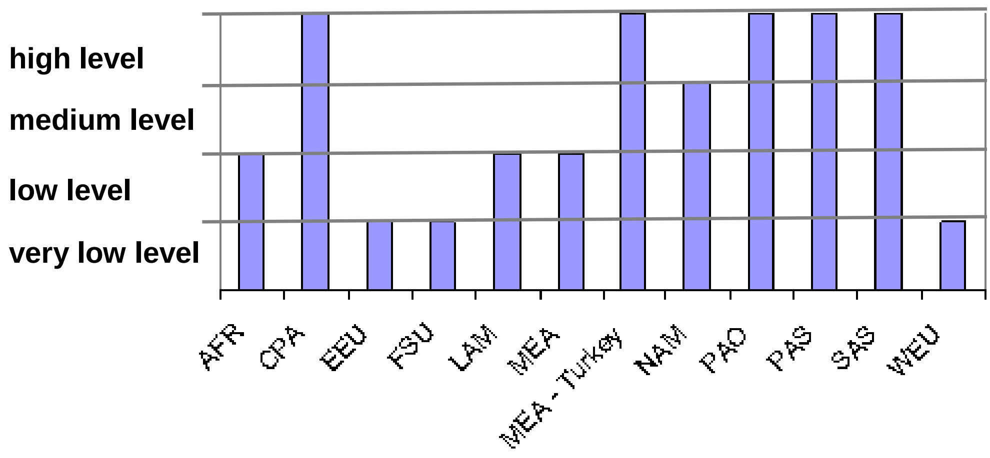

Figure 3: Irrigation potential by world region

We assume potential water stress to be the main factor to drive changes among the determining parameters of future irrigation decisions. Based on projections for the 2020s by Alcamo et al. [2003] we establish a regional ranking that depicts the relative water stress between regions considering climate changes, natural water availability, socioeconomic development, and sectoral water demands under the A2 scenario [see IPCC, 2000]. In addition to the coarse-resolution water stress projections by Alcamo et al. [2003] we also use their information on changes of solely natural water availability, and on water withdrawals, to further weight the data with respect to the specific relevance of these indicators for irrigation decisions. The resulting ranking is presented in Figure 4. The given numbers reflect the projected regional susceptibility to experience water stress in percentage of the region, which is expected to experience the highest water stress (Middle East and North Africa/MEA).

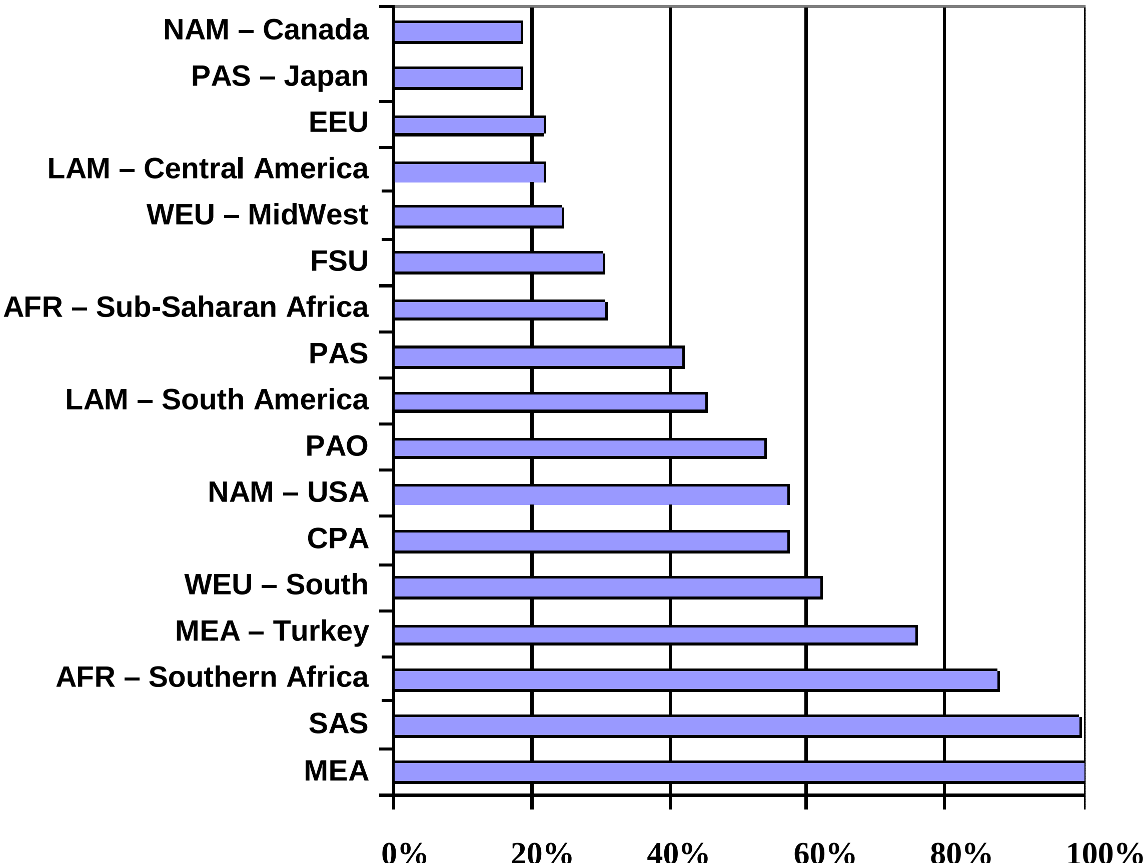

Figure 4: Regional sensitivities to experience water stress

It should be noted that these numbers are related to the A2 IPCC emission scenario, and do not reflect natural water availability, but instead are based on demand and supply ratios, which in turn are based on various development indicators including regional socioeconomic information. Besides MEA we expect SAS and – to a slightly lesser extent – South Africa to experience highest increases in water stress that may affect irrigation parameters. Turkey and Mexico also show a high susceptibility to water stress of approx 75% compared to MEA. Southern Europe, Australia, USA, South America (except Brazil) as well as China and Southeast Asia (except Japan) are expected to experience a water stress level between 60-40% of that from MEA. AFR, Brazil, and the Former Soviet Union (FSU) show a value of about 30% intensity of the highest ranking, whereas the rest of the world is between 15-25%.

Please keep in mind that any future development of parameter values is subject to particular scenario assumptions on the political, socioeconomic, and environmental background. The estimates given in this chapter refer to the SRES storyline of the A2 scenario.

PART III

Agriculture and resource availability in a changing world: the role of irrigation

III / 1. Introduction

Global population is projected to grow by about 65 % within the next 50 years. At the same time, average per capita income is expected to rise [Wallace, 2000]. Together, these two developments imply a substantial increase in demand for water and food – not only because of more people, but also because of trends toward more water-intense lifestyles and diets. Water resources are an important economic driver in many regions because they may constrain food production, energy generation, and activities in other economic sectors. The complex interdependencies between water resources and food production have been referred to in recent studies as an evolving global food crisis [Hightower and Pierce, 2008; Lundqvist et al., 2008].

The future supply of food and water faces several challenges. First, technical progress in agriculture may be subject to decreasing rates because of biophysical limits [Beadle and Long, 1985; Bugbee and Salisbury, 1988]. Second, future land expansion may be restricted because of physical limits and conflicting demands. Furthermore, the productivity of existing cropland may decline because of soil degradation and expansion of other sectors on fertile agricultural land [Foley et al., 2005; Ramankutty et al., 2002]. Third, environmental and human health regulations may constrain agricultural management and put limits to intensification [Rockstroem et al., 2004; Tilman et al., 2001; Van Hofwegen, 2006]. Fourth, continued growth in domestic and industrial sector water consumption will decrease the available water volume for agriculture [Bouwer, 2000; Rosegrant et al., 2002]. Fifth, climate change is likely to change the productivity of agricultural systems. These impacts will differ across locations and involve both improvements and deteriorations [Lobell et al., 2008; Milly et al., 2008; Ramankutty et al., 2002]. While the above mentioned challenges may differ locally, their net impact is likely to affect all countries as agricultural commodities are internationally traded.

The global dimension of agricultural water use is evident from the fact that agriculture accounts for more than 70 % of anthropogenic water withdrawals. Furthermore, about 20 % of total arable cropland is under irrigation, producing about 40 % of the global harvest [Bruinsma, 2003]. With continuing population growth and limited potential to increase suitable cropland, irrigation becomes an increasingly important tool to ensure sufficient global supply of food in the future [Wichelns and Oster, 2006].

Increasing levels of irrigation will raise the cost of water and in some regions this may have severe consequences. As water scarcity increases, inefficient allocation of water causes higher costs to society. Missing property rights and inadequate water pricing are major causes of such inefficiencies. Preventing these externalities from growing out of proportion is therefore in societies' best interest. However, national and international policymakers need scientific guidance to adequately regulate water use. In particular, appropriate assessments of agricultural water use need to consider a) the heterogeneity of natural and farming conditions, b) international commodity markets especially for agricultural products, c) agricultural and land use related environmental policies, and d) synergies and trade-offs between different land use related externalities [Cowie et al., 2007; Khan et al., 2008].

In this study, we investigate global interactions between agricultural production and the availability of land and water resources, focusing on irrigation as the major tool and determinant to affect both agricultural productivity and environmental resources. A first attempt to integrate crop and site-specific irrigation methods into a global partial equilibrium model (PEM) for the land use sectors is presented, in which we quantitatively analyze how irrigation decisions respond to different development scenarios.

III / 2. Background

Investigations dealing with the amount, distribution, and availability of agricultural water are often unique regarding method, scope, and scale. A brief review of global assessments of the distribution and variability of water supply is given by Oki and Kanae [2006]. More integrated approaches investigate interactions between economic development, water demand, and potential water stress by linking hydrological projections of climate change impacts on freshwater availability with population growth or socio-economic development scenarios among the broader context of global change [Alcamo et al., 2003; Arnell, 1999 and 2004;

Simonovic, 2002; Voeroesmarty et al., 2000]. Other studies put a more detailed emphasis on the manifold impacts of land and water use changes on the natural environment [Foley et al., 2005; Hussain, 2007; Tilman et al., 2001]. Finally, there are some comprehensive assessments, which integrate global change scenarios with supply and demand of water. These assessments depict trends and limits of future water resource development in a global all-sector context [Bouwman et al., 2006; Molden, 2007; Rosegrant et al., 2002]. The common objective across studies is to provide reasonable projections of future water use and to assess potential for achieving sustainable food security.

The estimates of land and water required for irrigation may differ, subject to the particular research methods and the underlying scenario assumptions. Furthermore, future demand for cropland and irrigation water also depends on changes in obtainable yield and water use efficiency, and thus may be significantly affected by technological progress and water management. With regard to agricultural water management, future improvements are likely to be related to efficiency gains in the use of green water [Liu et al., 2009; Rijsberman, 2006; Rockstroem et al., 2009].

Most existing empirical studies that explicitly predict or simulate the adoption of agricultural irrigation practices stay at farm or basin scales. A few global assessments of irrigation distribution and impacts exist but mainly within disciplinary boundaries, i.e. within physical geography or economics. These studies, however, do not account for site-specific differences between alternative irrigation systems and usually reduce and simplify decisions to a choice between rainfed and irrigated agriculture. Global integrated land use models accounting for multi-sectoral competition and limitations of land and water resources are rare [Heistermann et al., 2006].

Our analysis aims to assess future pathways of global land use and their sustainability, based on scenarios of population and economic development and their impact on demand for food and other agricultural and forest commodities. We want to quantify the complex feedbacks that occur across different scales between irrigation decisions, technologies, agricultural markets, and resources.

To achieve this, crop and site-specific irrigation methods are integrated into a global economic partial equilibrium model (PEM) for the land use sectors. Irrigation concerns are depicted by biophysically constrained and economically motivated choices between alternative irrigation systems, each representing individual technical, environmental, and economic characteristics.

The model enables an integrated assessment of global agricultural land and water use, and of the interrelations with irrigation management that takes place on smaller scales, accounting for resource economics, commodity markets, and international trade. Analyses explicitly consider regional capacities of irrigation system applicability, performance, and distribution based on respective geographic constraints and crop requirements. The model output shows the impacts of political, technical, environmental, and market developments on agricultural management decisions and their effects on scarcity of land and water, agricultural commodity supply and prices, and environmental externalities. These externalities include greenhouse gas emissions, soil sediment losses, and nitrogen leaching.

The primary objective of this study is to gain insights about global interactions among economic development, resource scarcity, and irrigation decisions. We consider the diverse set of agricultural water use options within a global economic partial equilibrium model analysis. The depiction of different irrigation methods is relevant to integrated global irrigation assessments because of major differences in suitability and cost. Previous global studies have neglected system differences. Due to data limitations, our approach applies several simple assumptions. Model results thus have to be interpreted with care.

III / 3. Materials and methods

This section is structured as follows. We portray the model and basic components of the irrigation module, followed by a more detailed description of the determinants of irrigation choice. For each of these elements we describe the methods used to derive parameter values, and the assumptions made on how the depicted elements are constituted and interlinked. Finally, we briefly explain the computation of total irrigation costs.

III / 3.1 Global forest, agriculture and biomass sector model – GLOBIOM

We apply a mathematical programming-based global recursive dynamic partial equilibrium model integrating the agricultural, bioenergy, and forestry sectors – GLOBIOM (Global Biomass Optimization Model). The agricultural and forest market equilibrium is computed by choosing land use and processing activities to maximize the sum of producer and consumer surplus subject to resource, technological, and policy constraints, as described by McCarl and Spreen [1980]. The market equilibrium reveals commodity and factor prices, levels of domestic production and consumption, export and import quantities, resource usage, and environmental impacts for 28 world regions, which are here for ease of presentation further aggregated to 11 regions (Table 1). A detailed description of GLOBIOM including an algebraic model description giving information on the contained parameters, variables, and equations can be found in Havlík et al. [2009]. In what follows, we only briefly present the aspects most relevant for this article.

Table 1 - Study world regions (incl. abbreviations)
North America (NAM)
Western Europe (WEU)
Pacific OECD (PAO)
Central and East Europe w/o Former Soviet Union (EEU)
Former Soviet Union (FSU)
Planned Asia with China (CPA)
South Asia (SAS)
Other Pacific Asia (PAS)
Middle East and North Africa (MEA)
Latin America and Caribbean (LAM)
Sub-Saharan Africa (AFR)

Table 1: Study world regions

GLOBIOM is a bottom-up model with a detailed representation of the supply side based on the spatially explicit description of land resource endowments through a system of Simulation Units (SimU). A Simulation Unit is the spatial aggregate of 5 arc-minutes pixels, which are homogenous with respect to weather, soil, topographical, and land cover characteristics, and which are within the same 30 arc-minutes pixel and within the same country boundaries [Skalský et al., 2008]. In total, we define more than 200.000 SimUs covering the globe. Their size varies between approximately 10x10 km and 50x50 km. Crop, forest, and energy biomass production technologies are specified as fixed input-output ratios calculated for each relevant SimU. The flexible model structure enables to aggregate the SimU specific parameters over one or more dimensions of homogeneity to reduce the size of the final program to solve. For the application in this article, we aggregated the SimUs over the 30 arc-minutes grid dimension.

Crop production accounts for 18 of the globally most important crops (Table 2). The average yield level for each crop in each country is taken from FAOSTAT [FAO, 2007a]. For

17 crops, fertilization and irrigation management specific yields are simulated with the bio-physical process model EPIC (Environmental Policy / Integrated Climate) [Williams, 1995] at the level of SimUs. (Oil palm is not simulated with EPIC. Only country level parameters based on FAOSTAT are used.) These 17 crops together represent about 75 % of the 2007 harvested area as reported by FAO [2007a]. Four management systems are considered (irrigated, high input - rainfed, low input - rainfed, and subsistence management systems) corresponding to the International Food and Policy Research Institute (IFPRI) crop distribution data classification [You and Wood, 2006].

Table 2 - Model crops
Barley
Cassava
Chickpeas
Cotton
Dry beans
Groundnuts
Maize
Millet
Oil palm fruits
Potatoes
Rapeseed
Rice
Sorghum
Soybeans
Sugar cane
Sunflower seed
Sweet potatoes
Wheat

Table 2: Model crops

III / 3.2 Irrigation module

We compute irrigation water consumption at the field (SimU) level, which accounts for the beneficial water use by the crops, and the application efficiency of the particular irrigation system. We do not compute gross water use in terms of actual water withdrawals from surface waters or groundwater. Thus we do not consider the efficiency of water delivery from source to field, which would account for return flows and water potentially available for re-use.

The model portrays four major types of irrigation systems: surface systems including basin and furrow irrigation, localized drip, and sprinkler irrigation. The suitability of these systems depends on various factors, which influence crop suitability, water demand, energy requirement, labor intensity, and overall cost, and thus affect motivation-based decision making that aims at individual as well as societal welfare maximization. The interdisciplinary range of factors that determine irrigation decisions in our model is shown in Table 3.

Table 3 - Biophysical, technical, and economic determinants of irrigation choice		
Biophysical factors	Technical factors	Economic factors
Crop characteristics (water tolerance, rainfed and irrigated yields, irrigation demand) Soil infiltration rate Slope inclination Length of growing period Water resource availability	Water application efficiency Operation time per irrigation event Level of pressurization (energy and labor requirement) Coverage per irrigation system unit	Crop market prices Investment capital cost Energy prices Labor cost Land and water prices (resource economics)

Table 3: Biophysical, technical, and economic determinants of irrigation choice

For each irrigation method we evaluate bio-physical and technical suitability to exclude inappropriate system applications. Among the bio-physical determinants of irrigation system choice, the model enables us to take directly into account the slope, soil, and crop types. For the purpose of this study, we further disaggregated the first slope class considered in the basic SimU delineation (0-3 degrees) into 5 sub-classes (Table 4). The new slope classes were defined with respect to threshold values that determine the applicability of the different irrigation methods [Brouwer et al., 1988]. In combination with the soil type (Table 4), the slope class determines the suitability to apply a particular irrigation system as well as the appropriate choice of flow rate, which is a parameter to compute operation costs. However, the slope class representation in our model does not enable to account for elements like terraces. Since in some regions such elements make up a non-negligible fraction of the total cropland and hence create incompatibilities between the slope maps and crop distribution maps, we adjusted the suitable area for surface irrigation methods with respect to these areas.

Table 4 - Classifications for slope inclination and soil texture	
Slope classes definition (intervals) (slope inclination in units of degree)	Soil classes definition
0 - 0.35	sandy
0.35 - 1	loamy
1 - 1.6	clay
1.6 - 2.25	stony
2.25 - 3	peat
3 - 6	
6 - 10	
10 - 15	
15 - 30	
30 - 50	
> 50	

Table 4: Classifications for slope inclination and soil texture

Not all crop types may be irrigated by all irrigation systems [Brouwer et al., 1988]. Besides the restrictions due to slope and soil type, the suitability of a particular irrigation method is determined by the crop-specific tolerance toward moisture, the characteristic planting and harvesting techniques, the specific physical habit of the crop, and its economic market value (i.e., low market value crops are excluded from being irrigated by high-cost drip irrigation). For all irrigation system constraints related to crop and soil type see Table 5.

Table 5 - Irrigation system suitability by soil and crop type			
	sandy soil	loamy soil	clay soil
Barley	F / S	B / F / S	F / S
Cassava			
Chickpeas	F / D / S	B / F / D / S	F / D / S
Cotton	F / D / S	F / D / S	F / D / S
Dry beans	F / D / S	F / D / S	F / D / S
Groundnuts	F / D / S	F / D / S	F / D / S
Maize	F	F	F
Millet	F / S	B / F / S	F / S
Oil palm fruits	*F / D*	*F / D*	*F / D*
Potatoes	F / S	F / S	F / S
Rapeseed	F / S	F / S	F / S
Rice	B / F	B / F	B / F
Sorghum	F / S	B / F / S	F / S
Soybeans	F / D / S	B / F / D / S	F / D / S
Sugar cane	F / S	B / F / S	F / S
Sunflower seed	F / D	F / D	F / D
Sweet potatoes	F / S	F / S	F / S
Wheat	F / S	B / F / S	F / S

Abbreviations
B: basin irrigation, F: furrow irrigation, D: drip irrigation, S: sprinkler irrigation

Table 5: Irrigation system suitability by soil and crop type

Unlike for land resources, irrigation water availability is not defined at SimU level yet. In the model, irrigation water use is currently constrained through an artificial supply function, representing the relative water scarcity through its increasing marginal cost. The upper limit on irrigation water availability is computed by considering the sustainably exploitable internal renewable water amount, and water demands from other sectors (domestic, industry, livestock, submitted environmental flow) [FAO Land and Water Development division, 2008; Rosegrant et al., 2002].

Consumptive irrigation water requirements by irrigation system are calculated under consideration of system-specific field application efficiencies in addition to the beneficial-use crop irrigation demands. The application efficiency varies by region and is determined by considering regional climatic factors [FAO / IIASA, 2000] and indicators of socio-demographic development [UNDP, 2000] (Table 6).

Table 6 - Water application efficiency by irrigation system and region				
World region	Water application efficiency by irrigation system (%)*			
	Basin	Furrow	Drip	Sprinkler
North America	53	48	93	85
Western Europe	55	50	93	86
Pacific OECD	38	33	86	71
Central and East Europe	55	50	93	86
Former Soviet Union	55	50	93	86
Planned Asia with China	45	40	89	79
South Asia	35	30	84	68
Other Pacific Asia	40	35	88	75
Middle East and North Africa	25	20	80	60
Latin America and Caribbean	40	35	88	75
Sub-Saharan Africa	30	25	82	64

*Estimates based on information by Clemmens and Molden [2007], FAO/IIASA [2000], and UNDP [2000]

Table 6: Water application efficiency by irrigation system and region

The model chooses the extent of a particular irrigation system considering irrigation cost per spatial unit for all appropriate combinations of regional geographic background, crop type, and irrigation system. Specific irrigation system characteristics are portrayed in Table 7.

Table 7 - Specific characteristics of different irrigation systems				
	Basin	Furrow	Drip	Sprinkler
Functional type	Gravity	Gravity	Pressurized	Pressurized
Irrigation system category	Surface irrigation	Surface irrigation	Localized irrigation	Sprinkler irrigation
Capital cost	low	low	high	medium
Energy demand for operation	none	none	low	high
Maintenance and labor intensity	low	high	medium	medium

Table 7: Specific characteristics of the different irrigation systems

III / 3.3 Parameterization: Energy requirement

Energy use is computed as a function of irrigated area, water amount, pressure requirement, and total irrigation time [Buchanan and Cross, 2002].

On-farm irrigation scheduling is affected by geographic and technical properties (Table 3). We use a simplified but consistent approach to represent these interdependencies through a generalized irrigation scheduling. In this context, the application depth per irrigation event is an important parameter to calculate cost-effective energy demand. A stepwise approach to determine application depth is used, based on the simplifying assumption of fixed operation times per irrigation event (Table 8).

Table 8 - Assumed fixed operation times per irrigation event by irrigation method

Irrigation method	Estimated number of operation hours per irrigation event*
Basin irrigation	48
Furrow irrigation	48
Drip irrigation	48
Sprinkler irrigation	60

*Estimated guide values by Buchanan and Cross [2002]

Table 8: Assumed fixed operation times per irrigation event

The irrigation schedules assume constant application depths during the entire growing season. Information on soil infiltration rate, suitable slope, the acceptable range of flow rate by soil type at optimal slope, and corresponding size of irrigated area are taken from Brouwer et al. [1988].

In a first step we calculate maximum number of events with respect to length of growing period [Fischer et al., 2002] and common application frequencies [Brouwer et al., 1988; Buchanan and Cross, 2002]. Using the total irrigation water demand over the complete vegetation period, we determine application depth per event by region, crop, and method.

Second, we calculate the maximum application depth by soil type with respect to recommended flow rates and particular soil infiltration rates, at slopes that are reported to be most suitable for the particular irrigation method [Brouwer et al., 1988].

To account for slope effects on surface irrigation performance, we modify the application depths for basin irrigation, using ratios of recommended to minimum flow rate as multiplier while assuming proportionality of irrigation depth and flow rate. Then we derive slope-related basin-size coefficients, which depict the maximum basin area by slope class in percent of the basin area at optimum slope when flow rate remains constant (Table 9). For this, we assume quadratic basins and a linear relationship between slope and basin size. These slope coefficients were applied to previous soil-indexed optimal-slope application depths.

Table 9 – Basin irrigation: Coefficients for the adjustment of application depth to higher slopes (accounting for relationships between slope inclination, soil-dependent flow rates, and maximum basin area)

Slope class (intervals in units of degree)	Basin-slope coefficient
0 - 0.35	0.875
0.35 - 1	0.092
1 - 1.6	0.013
1.6 - 2.25	0.006
> 2.25	not convenient for basin irrigation

Table 9: Basin irrigation: Coefficients for the adjustment of application depth to higher slopes (accounting for relationships between slope inclination, soil-dependent flow rates, and maximum basin area)

Regarding furrow irrigation, we consider soil and slope influences on maximal furrow length and their implications for acceptable flow rate according to numbers given by Brouwer et al. [1988]. We translate furrow lengths to area per furrow and determine application depth per furrow (by region, crop, soil type, and slope) for maximal area, under consideration of operation time:

$$AD_{slope,\,soil} = OT * FR\,max_{slope} \,/\, A\,max_{slope,\,soil}$$

$AD_{slope,\,soil}$: Application depth per irrigation event for furrow irrigation by slope class and soil type, in mm.

OT: Operation time per irrigation event for furrow irrigation, in sec.

$FR\,max_{slope}$: Maximum flow rate per furrow by slope class, in l/sec.

$A\,max_{slope,\,soil}$: Maximum area per furrow by slope class and soil type, in m².

After modifying the surface application depths we re-calculate the number of annual irrigation events based on total water requirements and determine the application depth per event.

Energy use for irrigation is determined by underlying pressure requirements. Total pressure requirement is the sum of sprayer pressure (for non-surface systems) and static head pressure to bridge elevation differences. Information on sprayer pressure and static head pressure calculation was obtained from Buchanan and Cross [2002] and USDA-NRCS [2007].

III / 3.4 Parameterization: Labor requirement

Labor requirement is the number of irrigation events times the estimated work hours per event as taken from Turner and Anderson [1980; cited in Buchanan and Cross, 2002] (Table 10).

Table 10 - Estimated work hours per acre and irrigation event	
Irrigation method	Estimates of labor required* (hours per acre per event)
Basin irrigation	0.5
Furrow irrigation	0.7
Drip irrigation	0.07
Sprinkler irrigation	0.1

*Based on guide values given by Buchanan and Cross [2002]

Table 10: Estimated work hours per acre and irrigation event

To depict variations in labor intensity by crop type, we use crop-specific cost data [AgEBB, 2006; Paul, 1997] to calculate a labor multiplier (Table 11).

Table 11 - Labor multiplier by crop type and irrigation method				
Crop type	Crop labor multiplier by irrigation method*			
	Basin	Furrow	Drip	Sprinkler
Rice	2.3	2.3	–	–
Vegetables (all)	1	1.5	1	1
All other crops	1	1	1	1

*Estimates based on information by AgEBB [2006], and Paul [1997]

Table 11: Labor multiplier by crop type and irrigation method

III / 3.5 Irrigation cost

We apply an economic optimization approach dealing with trade-offs between competing land use types. Within the optimization procedure, trade-offs in terms of cost-benefit comparisons are dealt with from a sectoral perspective, and on behalf of maximized welfare across the modeled sectors. In the agricultural sector, farmers are the prior agents of decision making, which are also assumed to act driven by economic motivation. However, for the optimization the surplus of the agricultural sector as a whole is relevant. From such a macroeconomic (national) accounting point of view we consider total expenditures for irrigation, and we neglect public cost recovery and subsidies for irrigation facilities or water delivery to farmers for reasons of simplification. This is done with respect to the global scale and the relative coarse temporal, spatial, and sectoral resolution of our PEM.

Irrigation costs include capital costs and costs for operation and maintenance (O&M). Operation costs are composed of pressure-related energy costs in terms of energy prices by source [EIA, 2006; Metschies, 2005], and labor costs in terms of average agricultural wages per hour [IMF, 2007; World Bank, 2006]. For a schematic overview on the determination of total irrigation costs see Figure 1.

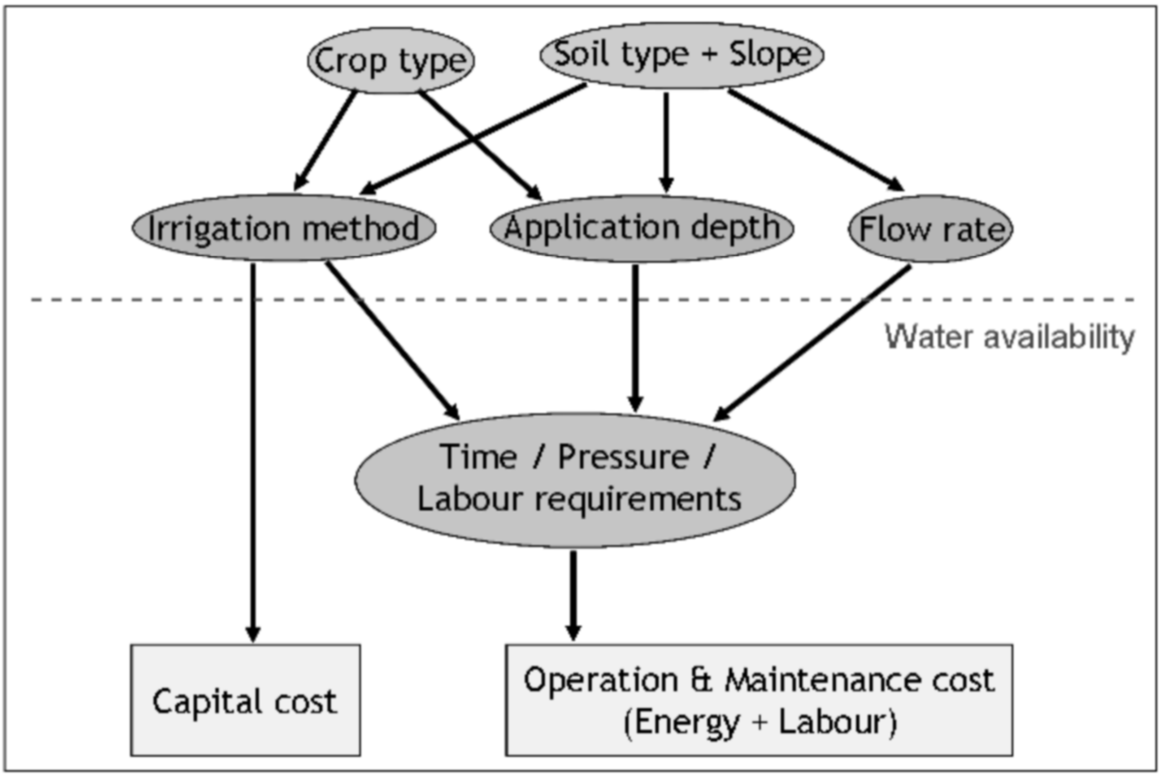

Figure 1: Scheme for determining total irrigation costs

Non-labor capital and maintenance costs differ between systems but are assumed to be globally identical despite the fact that they may substantially differ between regions [Rosegrant et al., 2002]. Using average discounted annual capital costs per spatial unit for sprinklers [Reinbott, 2005] and additional information on technical and economic comparisons of sprinkler, drip, and surface irrigation systems [Phocaides, 2000], we determine cost ratios to derive average capital cost per year for each irrigation method. Maintenance cost was set to 5 % of capital cost for non-surface and furrow irrigation, and to 3 % for basin irrigation [Paul, 1997; Phocaides, 2000].

III / 4. Scenario description

Population growth and economic development affect the agricultural sector on the commodity markets through increased demand for food, and indirectly also through increased demand for wood. Economic development additionally affects food demand qualitatively via shifts in consumption patterns and increasing demand for water-intense commodities. For the simulation of future food demand, we use regional projections of per capita food intake levels differentiated in animal and crop calories from Alexandratos et al. [2006], and the regional population projections from the IIASA GGI B2 baseline scenario [IIASA, 2008]. In regions with increasing rates of economic development, expected dietary shifts are represented by a growing fraction of livestock products among the daily calorie intake.

Population and economic growth will put supplementary pressure on land and water availability through increased demand for these resources in other sectors, especially residential/domestic and industry sectors. The additional pressure on water availability for irrigation is calculated by reducing the basic water availability for agriculture by projected increases in livestock, domestic, and industry water consumption. These increases are calculated proportional to population and imposed on basic water consumption levels in these sectors as reported by FAO Land and Water Development Division [2008]. For the calculation of the additional pressure on land availability from the residential sector, we assume that residential land growth takes the form of urban expansion. We use the population density data from Demographia [2006] and assume that residential expansion eliminates cropland.

We present results for two scenarios – “No pressure from domestic and industry sectors” and “Pressure from domestic and industry sectors”. The former scenario ignores the additional land and water demand from non-agricultural sectors but considers commodity market effects. For both scenarios, we implement projections on the development of bioenergy and biofuels according to the POLES simulation results corresponding to an updated version of Russ et al. [2007].

The base year distribution of irrigation systems is calibrated to closely reproduce system distribution as derived from FAOSTAT, AQUASTAT, and ICID databases [FAO 2000, 2004, and 2007b; FAO Land and Water Development Division, 2008; ICID, 2008] (Table 12).

Table 12 - Baseline irrigation system distribution by region

World region	Assumed fraction of irrigation methods on total irrigated area (%)*		
	Basin and Furrow	Drip	Sprinkler
North America	47.48	6.59	45.93
Western Europe	33.97	17.95	48.08
Pacific OECD	79.71	5.04	15.25
Central and East Europe	38.50	2.62	58.88
Former Soviet Union	58.30	0.05	41.65
Planned Asia with China	97.00	1.00	2.00
South Asia	95.64	0.20	4.16
Other Pacific Asia	100	0	0
Middle East and North Africa	87.60	1.40	11.00
Latin America and Caribbean	86.66	2.50	10.84
Sub-Saharan Africa	69.51	4.73	25.76

*Estimates based on information by FAO [2000-2008], and ICID [2008]

Table 12: Baseline irrigation system distribution by region

III / 5. Results

This section summarizes the simulated trends of irrigated area, system distribution, and water use at global level. Subsequently, we discuss projected developments with regard to drivers and mechanisms of agricultural decisions.

Rising demands for food lead to increasing crop, land, and water prices. Irrigation water use in the model is constrained through a price sensitive supply function. This marginal cost function passes through the observed/estimated price quantity pair of irrigation water. The curvature of the supply function is defined by employing a constant price elasticity. The water price is not an observed market price but rather a calibrated estimate of all costs of getting the water. Thus, it depicts the internal value of water rather than the real price of irrigation water, which actually does not exist in many regions. Technological progress affecting productivity is not considered in the model runs. The resulting global water price indexes are presented in Figure 2.

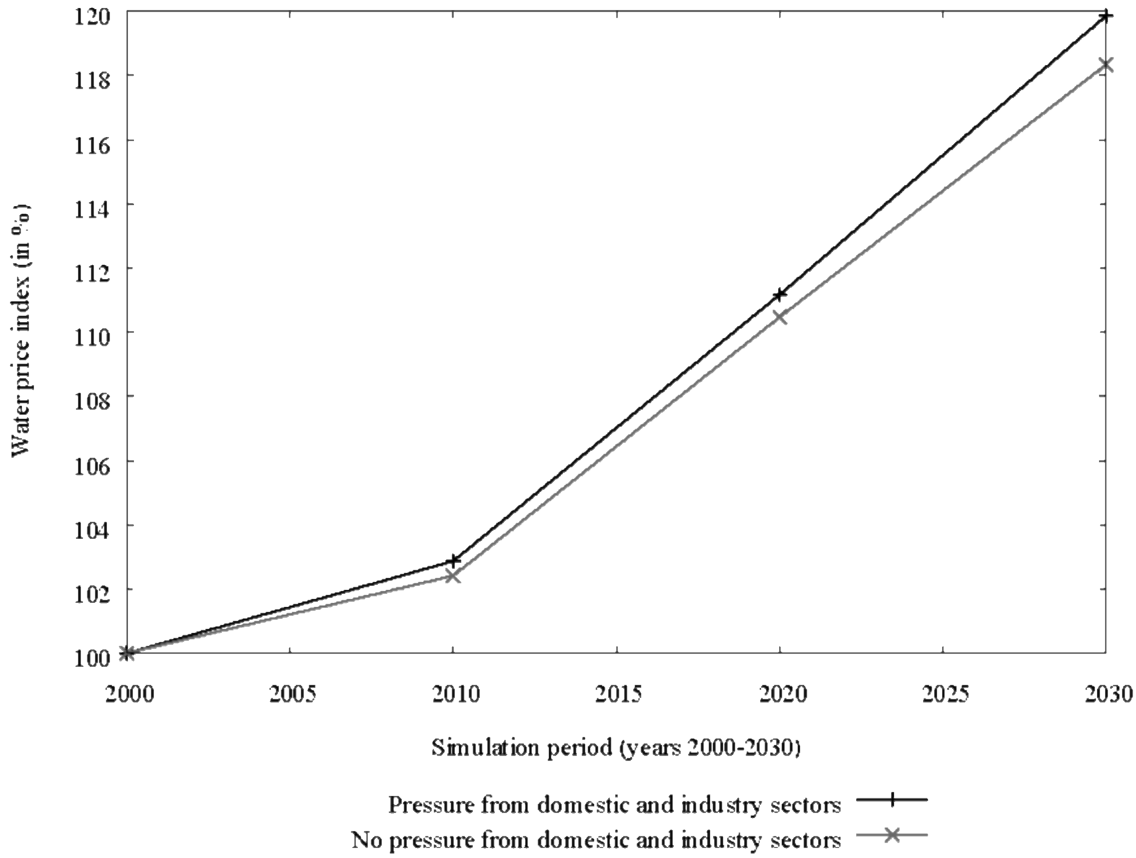

Figure 2: Results: Water price index

Irrigation water requirements strongly depend on bio-physical conditions, crop type, and water use efficiencies. As explained in chapter 3.2, we depict consumptive irrigation water use at field level rather than gross irrigation water withdrawals that include water losses between source and field.

The simulation results on global irrigation water use project a moderate increase in the first decade of the simulation period. The increase in total water use is relatively high during the second decade but declines thereafter (Figure 3). Note that the water endowment constraints implemented for each model region were not binding in the examined scenarios.

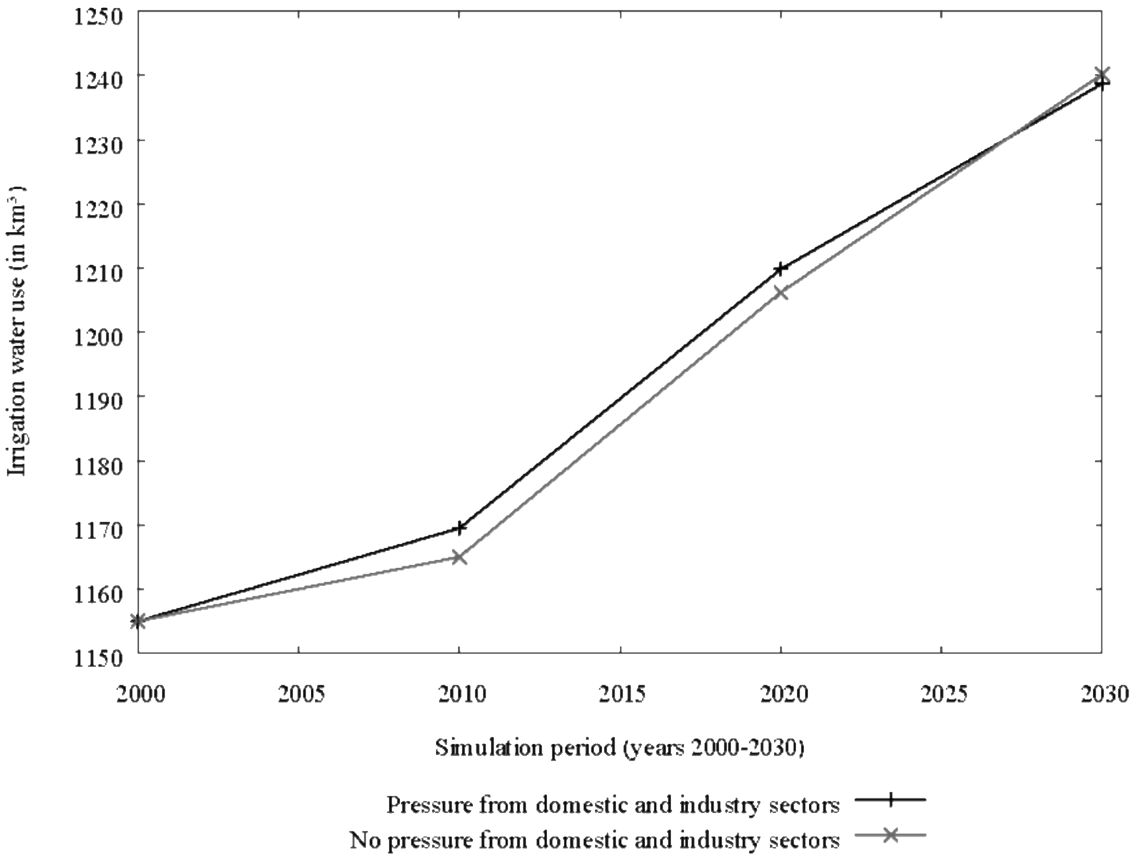

Figure 3: Results: Global irrigation water use

Changes in the water volume for irrigation can be decomposed into changes in water consumptions per hectare and changes in the area under irrigation. Our simulations project the highest absolute increase in irrigated area to occur in South Asia (SAS). Highest relative increases of irrigation area expansion are found for the former Soviet Union (FSU), Central and East Europe (EEU), North America (NAM), and Latin America and the Caribbean (LAM). In Sub-Saharan Africa (AFR), a considerable expansion of irrigated area starts with a delay if seen in relation to population growth. The global trend of irrigated land expansion is depicted in Figure 4.

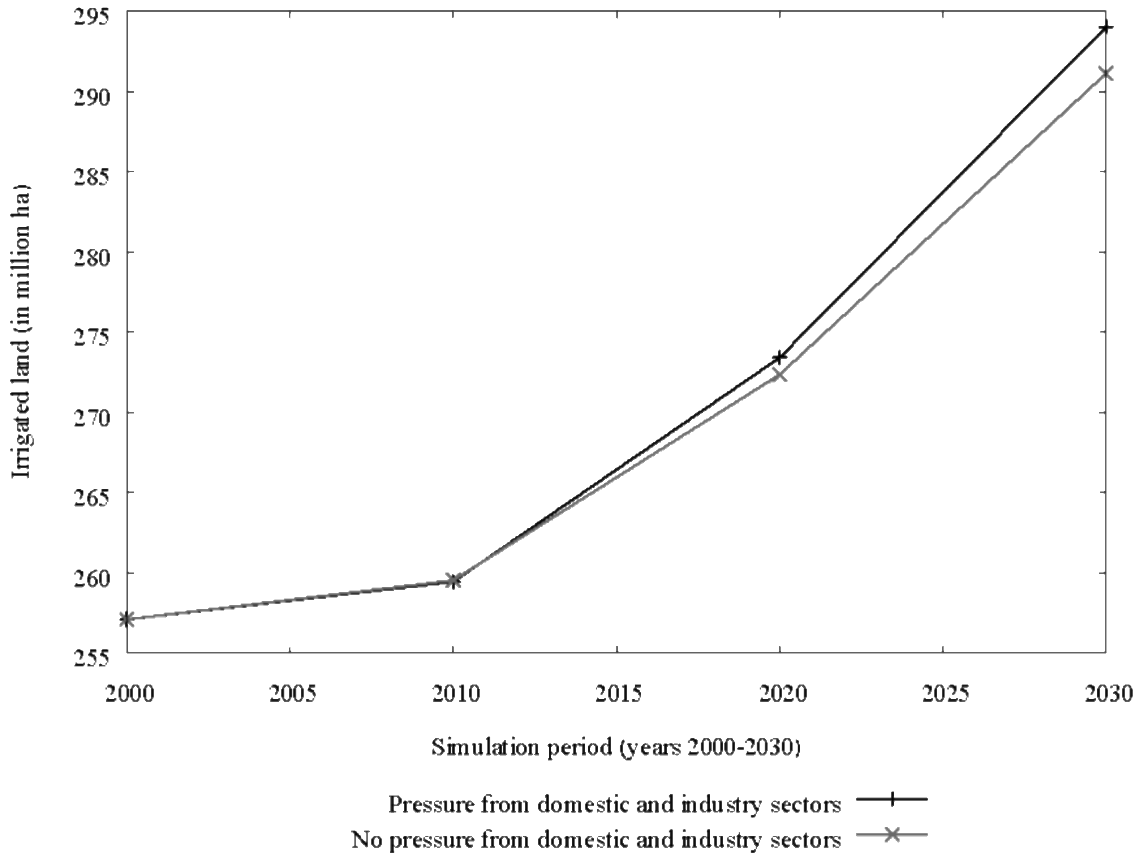

Figure 4: Results: Global irrigated land

Global water use intensity more or less remains constant in the first ten years of the simulation period, later it decreases at growing rates (see Figure 5). Whereas water intensity remains constant in CPA and LAM, it substantially decreases in Africa and – to a lesser extent – in SAS, despite high rates of population growth and high increases of per-capita calorie intake. Globally, a general trend of combined expansion and extensification of irrigated agriculture can be identified.

Shifts in regional irrigation management toward improved water use efficiency are triggered in correspondence with increasing rates of population growth, with respect to our population scenarios. Before that, efficiency improvement is progressing at comparably low rates.

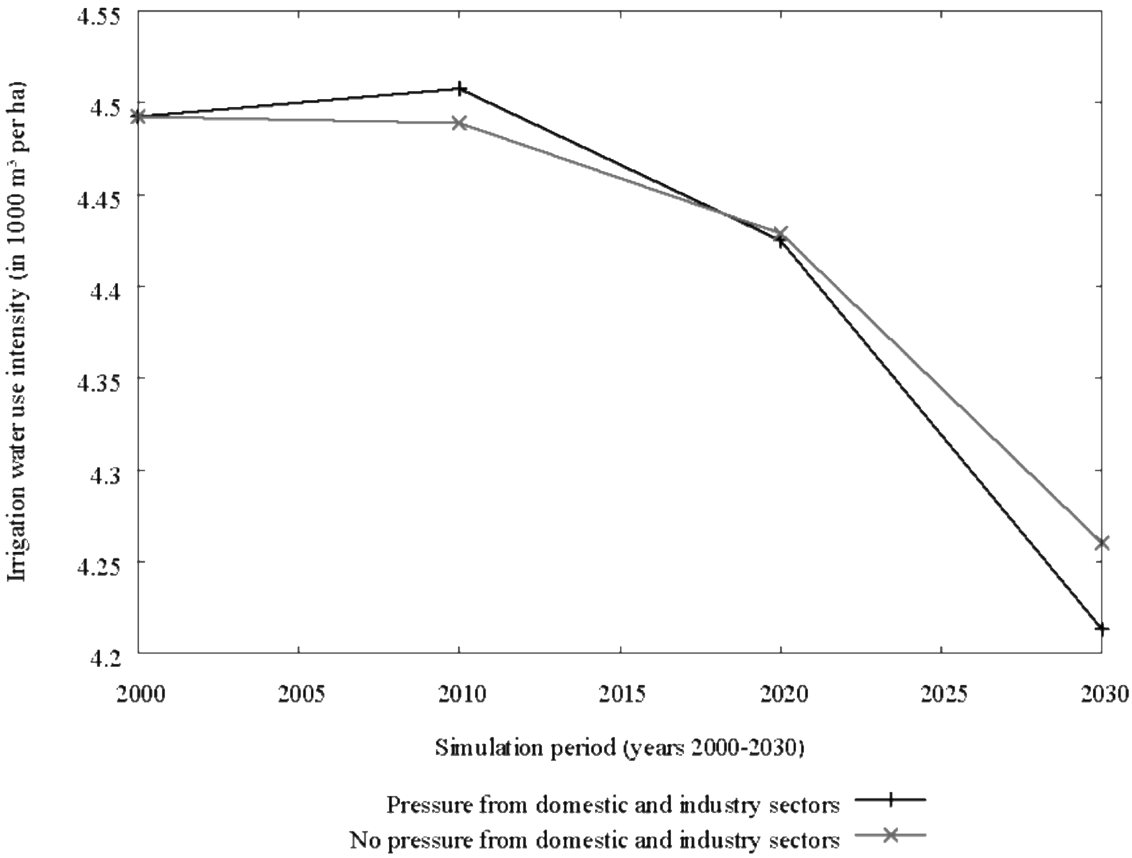

Figure 5: Results: Global agricultural water use intensity

We will face a general trend of irrigated area expansion to sufficiently meet changing food demands. Additional water pressure simultaneously triggers an extensification of management practices in terms of decreasing water use intensity, and consequently approves water-efficient irrigation methods or crop types with lower irrigation demands.

Food demand-induced incentives for irrigation expansion may lead to more water-efficient irrigation methods. A growing trend toward an application of more costly but also more water-efficient methods can be detected (see Figure 6 for global trends).

On global scale, a progressive substitution of surface methods by sprinkler systems appears first, before eventually also the share of micro-irrigation methods such as drip irrigation significantly starts to grow. In developed regions such changes appear earlier and more gradual than in less developed regions. However, technological standards and cost recovery for investment and O&M may also play a role to affect such developments.

According to these results, shifts to more efficient management of water use seem an inevitable consequence of growing populations and economic development. The depicted option of changing the irrigation technique is one of many and implies the importance of putting integrated concepts on today's agenda to ensure a timely mitigation of tommorow's resource problems.

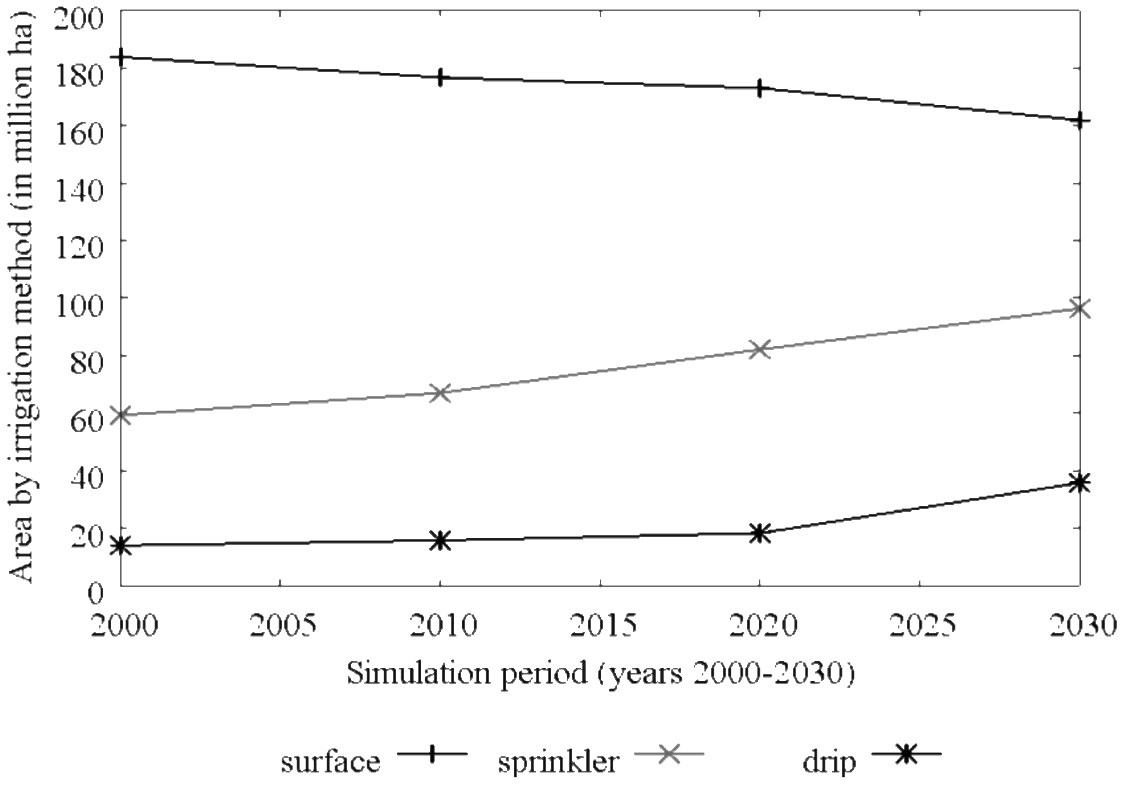

Figure 6: Results: Irrigation methods (global)

III / 6. Discussion

Global projections of agricultural land and water use are rare. Comparisons between projections have to be interpreted with caution because of differences in scenario assumptions, analysis scope and resolution, and modeling approach [Heistermann et al., 2006]. In general, existing studies may be distinguished regarding the dominating analysis technique in bottom-up and top-down studies, regarding the system dynamics in static, recursive dynamic, and fully dynamic specifications, and regarding the resolution and scope with respect to space and economic sectors. Furthermore, projections of changes in crop area and water demand are influenced by specific assumptions on population, economic, and policy development and their associated impacts to agricultural commodity demand and relevant resource endowments, climate change and its effect on agricultural productivity, and technical progress rates including crop yield improvements.

To place this study in perspective, we compare our irrigation water projections with previous global assessments by Doell and Siebert [2002], Molden [2007], Postel [1998], Rosegrant et al. [2002], and Seckler et al. [1998] (Table 13). If only values of water withdrawals are given, we approximate consumption data using average ratios from studies that provide values on both items.

However, crop coverage in our analysis is restricted to the crops shown in Table 2. To evaluate our baseline and simulation results this always must be considered.

For a more detailed review of global water resource assessments and modeling approaches we refer to the works by Simonovic [2002], and Wallace and Gregory [2002].

Table 13 - Comparison of irrigation water use projections

	Doell and Siebert [2002]	Rosegrant et al. [2002]	Postel [1998]	Seckler et al. [1998]	Molden [2007]	Sauer et al. *(restr. crop cov.)*
Projection period	2000	1995-2025	1995-2025	1990-2025	1995-2050	2000-2030
Base year: Area actually irrigated [Mha]	250	-	249.5	245.07	339.66	257
Base year: Irrigation consumptive water [km³]	1287	1435.5	900	1272 [a]	1426	1155
End of projection period: Area actually irrigated [Mha]	-	-	-	392.11	394	293
End of projection period: Irrigation consumptive water [km³]	-	1196–1745 [b]	2950	1910–2639 [a,b]	2039 [a,*]	1236

[a]Available data refers to withdrawal (not consumption): Estimated ratio of Consumption/Withdrawal = 0.54 for base year, and 0.69 for end of projection period respectively

[b]Range of data for different scenario simulations

[*]Available data refers to total agricultural water use:
Assumed livestock fraction of 27 km³ [Doell and Siebert, 2002] was subtracted to obtain irrigation amount

Table 13: Comparison of irrigation water use projections

Our base year irrigated area is 257 million hectares (Mha). This estimate is in line with data on actual irrigated areas for the period of 1995-2000 covering a range from 210 to 340 Mha [FAO, 2007b; Gardner, 1998; Gleick, 2000; Molden, 2007; Rosegrant et al., 2002; Siebert and Doell, 2007].

Comparing consistent information on total water withdrawals for irrigation, consumptive irrigation water use, and beneficial crop irrigation water use, as given by Doell and Siebert [2002] and Rosegrant et al. [2002], we find that on average about 25 % of the globally withdrawn water for irrigation is actually taken up by the crops, 56 % is not consumed and available for subsequent use, and 19 % is unproductively lost.

Existing estimates of global consumptive irrigation water use vary between 900 km³ [Postel, 1998] and about 1700 km³ [Shiklomanov, 2000] per year for the period of 1995-2002. Other reference values to be mentioned are 1287 km³ [Doell and Siebert, 2002] and 1435.5 km³ [Rosegrant et al., 2002]. In contrast, total withdrawal for irrigation is estimated to be in the range of 2000-3000 km³ per year worldwide [Siebert and Doell, 2007]. Overall, these values are of comparable magnitude with our consumptive irrigation amount of about 1155 km³ for the represented crops in 2000.

Table 13 compares average global values across all crops and irrigation methods (see remarks on the restricted crop coverage of our analysis). Differences in base-year numbers may not only be due to different assumptions and techniques in the estimation of irrigation area and corresponding irrigation water requirements, but also due to different reference periods or dissenting definitions of irrigation itself (with respect to surface irrigation using rainwater). Future projections are further subject to the model-endogenous process of crop allocation, which in our analysis considers international agricultural market interactions.

The comparisons show that the relative increase of irrigation water use is highest at Postel [1998] with about 227 % and lowest at our study (7 %), and at Rosegrant et al. [2002] respectively (ranging from a decrease of 17 % to an increase of 22 % depending on the scenario). Importantly, with regard to average global water use intensity, Seckler et al. [1998] and Molden [2007] project an intensification of irrigation practises whereas our results indicate an extensification.

The different projections discussed are likely caused by different assumptions on water productivity, trends of resource degradation, and water use efficiencies underlying the projection of consumptive water use.

Our food demand and resource projections for 2030 suggest that an expansion of irrigated area by 14 % and an increase in consumptive irrigation water by 7 % are likely required when considering irrigation method based efficiency shifts.

Rijsberman [2006] cites several studies projecting required increases in total cropland (rainfed and irrigated) of 29 % to 34 % to meet the food demands in 2025. As already mentioned, existing trajectories of consumptive irrigation water use until 2025 under business-as-usual scenarios vary between increases of 22 % and 227 % [Postel, 1998; Rosegrant et al., 2002; Siebert and Doell, 2007]. However, more optimistic scenario assumptions on productivity growth and water use efficiency may lead to completely different projections. For example assuming an average yield increase of 40 % by 2025 relative to 2000 for the main crop types, Rosegrant et al. [2002] project a much smaller increase in crop area. These investigations result in a total combined increase of only about 10 % for both irrigated and rainfed land with a simultaneous increase in irrigation water amount of only 4 % to meet world food demand in 2025.

In this assessment we regard population growth and economic development as the most important primary drivers of global land use change and water use.

Population growth leads to an increased demand for food in general, with an expected increase in total agricultural water use. Besides, population growth is connected to increasing pressures on land and water resources from the residential and domestic sectors in terms of land demands for settlement and water demands for drinking and sanitation. In simplified relative terms this means that more food has to be produced on less land – a goal that implies an increasing share of irrigated farming – as well as less water is available for agriculture, which implies the need for improved water use efficiency. Real options are more diverse and include the expansion on marginal lands as well as trade-offs between the different land use sectors.

Consequently, one major research question is whether an intensification or extensification of land use practices is appropriate to mitigate problems of resource scarcity. We approach this question by focusing on the role of alternative irrigation methods and the related potentials to achieve sustainable food security. The quantitative results are presented in the foregoing paragraphs. However, a deeper look at the underlying relations by further decomposing the term of irrigation water use seems adequate for policy support, as well as with respect to the scientific contribution of the study.

Economic growth is assumed to enhance per-capita income. Higher per-capita income increases the demand for water due to changes in lifestyle and diets. Concerning agriculture, the demand for more water-intense commodities like, e.g. livestock products is assumed to increase. These tendencies consequently put additional pressure on water resources and - in conjunction with population-based developments - underline the need for improvements of water use efficiency. But increased per-capita income also enables higher investments in agricultural water management and irrigation systems. Concluding, a rise in per-capita income may have significant effects on a) the net total and agricultural water demands, as well as on

b) the gross irrigation water demand. Our study predicts an increase in the absolute net water demand, but also an improvement in the efficiency of irrigation water use.

Thus, per-capita income can be regarded as the major driver of changes in the chosen irrigation method as it drives both, the incentive for water efficiency improvements due to increased water demands, and the feasibility of necessary monetary investments in advanced systems or in research that enhances technological progress. The latter point, however, is only of theoretical nature as in our model there is no link between economic indicators and irrigation investments.

Important key factors to guide these developments are respective policies that explicitly consider water pricing. The need to treat water as an economic good becomes more obvious with growing economic competition for adequate water resources and rising problems of water scarcity. However, the agricultural share on total economic production and labor force in industrialized countries is expected to decrease [Lotze-Campen et al., 2005] despite the growing absolute demand for agricultural commodities and an expected increasing global share of irrigation on total water use. Explanations for such a declining economic importance of the agricultural sector may be found in other preferences and priorities among the lifestyle changes that accompany economic welfare. In turn, this promotes a more efficient allocation of agricultural input resources such as land and water in several respects, as the competition for these resources is not only exacerbated but also shifted for the benefit of the more viable economic sectors.

III / 7. Conclusions

Our study integrates alternative irrigation systems into a global agricultural and forest model (GLOBIOM) to estimate regional adaptations in agricultural water use for different development scenarios. The new model combines the heterogeneity of irrigation systems and natural resources with micro and macro-economic drivers. The innovation of integrating explicit irrigation systems in their particular biophysical, economic, and technical context into a global partial equilibrium model of the agricultural and forestry sectors improves large scale land use change assessments. The model evaluates interdependencies between socio-economic development and policies as well as land use related externalities, resource availability, and food supply. The analysis shows that agricultural responses to population and economic growth include considerable increases in irrigated area and agricultural water use, but reductions in the average water use per irrigated hectare.

Furthermore, we show that irrigation is a complex decision beyond the binary decision of adopting irrigation or not. Different irrigation systems are preferred under different exogenous conditions including bio-physical and socio-economic factors. Negligence of these adaptations would bias the burden of development on land and water scarcity.

Without technical progress in agriculture, a population and income level as predicted under GGI B2 scenario for 2030 would require substantial price adjustments in land and water use to equilibrate the food supply and demand. Our projections suggest that an expansion of irrigated area by 14 %, and of consumptive irrigation water use by 7 % are likely to be needed when considering irrigation method based efficiency shifts.

To accurately estimate land and water scarcity the likely adaptation of farmers to different irrigation methods needs to be quantified. In particular, we excluded from this analysis institutional and other barriers to an adoption of more advanced irrigation technologies. Furthermore, this work needs to be complemented by more detailed hydrological studies on the physical availability of green and blue water at much finer than regional scale.

This study also underlines the need for integrated approaches to assess the role of water resources and irrigation in the context of future food security and overall socio-economic welfare. The inclusion of technical and economic aspects of irrigation choice can provide new insights into the interdisciplinary trade-offs between determinants of global land use change. To conclude, let us state that the present article represents only the very beginning of our analysis and the model is being continuously improved so that new, more accurate results can be presented soon.

PART IV
The value of irrigation in a global context

IV / 1. Introduction

Water is an important factor for many economic sectors, and it is essential for the food and biomass production. Water also represents a physically limited resource subject to risks of chemical contamination. While economic motives may be the most important drivers of anthropogenic land use decisions, biophysical constraints need to be considered in terms of environmental sustainability if one wants to account for stability of desired welfare effects. Consequently, the valuation of natural resources seems to be an evident need also from a socioeconomic point of view.

Here, we investigate the value of irrigation water for agriculture in the context of global economic development, population growth, technical progress, and food security. This valuation is based on simulations with a global partial equilibrium model (PEM) for the land use sectors. We use the model GLOBIOM (Global Biomass Optimization Model) [Havlík et al., 2010], which explicitly considers different irrigation options and their specific biophysical, microeconomic, and technical determinants [Sauer et al., 2010].

We implement and assess different development and irrigation adaptation scenarios to gain meaningful insights on the value of irrigation and agricultural water in the future. Particularly, we explore scenario changes in the value of water and irrigated cropland, and their linkage to producer and consumer surplus. We also discuss potential impacts as caused by changes of further irrigation factors. The value of water is analyzed with regard to its influence on the optimized welfare for both, producers and consumers. This analysis includes the consideration of sectoral trade-offs concerning resource demands (land and water), like e.g. the possibility to increase production by means of deforestation. Further we investigate the role of water to meet increasing food demands, the resulting costs to farmers, and the potential surplus value due to irrigation restrictions and/or irrigation system changes.

IV / 2. Background and objectives

In this study we focus on the value of irrigation to achieve primary aims of food security and socioeconomic welfare optimization. We investigate irrigation in both its roles, as an economic production factor and a factor that affects the sustainability of anthropogenic resource use. We do this under consideration of underlying food demand, and on a global scale. Furthermore we discuss policy instruments to enhance water use efficiency.

We choose a global PEM to depict interactions among economic development, resource scarcity, and irrigation decisions. There are at least three arguments for a global scale analysis. Firstly, the evidently global dimension of agricultural water use due to its share of more than 70% of anthropogenic water withdrawals, and a share of 40% of the global harvest contributed from irrigated croplands [Muralidharan and Knapp, 2009]. Secondly, the fact that even local changes or impacts of land use may affect all countries due to international trading of agricultural commodities [Sauer et al., 2010]. Thirdly, water scarcity is a problem of global concern, which not only affects the agricultural sector. Policy actions and regulations are often based on international agreements, and may eventually be implemented on large scales from national to regional levels. In this context, we nevertheless want to remark that river-basin scale approaches pose the essential "next step" for a successful implementation of integrated water management concepts.

Interrelations between growing sectoral competition for resources, biophysical limits, and technical progress are likely to affect future agricultural water use and food production. [Beadle and Long, 1985; Bouwer, 2000; Bugbee and Salisbury, 1988]. Economic development may additionally affect food demand qualitatively and quantitatively via shifts in consumption patterns and increasing demand for water-intense commodities [Sauer et al., 2010]. With continuing population growth and limited potential to increase suitable cropland, irrigation becomes an increasingly important tool to ensure sufficient global supply of food in the future [Wichelns and Oster, 2006].

Management-induced yield-increases enhance agricultural productivity, but intensive agriculture in turn already has and further will cause degradation and depletion of cropland and water resources [Foley et al., 2005; Ramankutty et al., 2002; Tilman et al., 2001]. In addition, the productivity of agricultural systems may also be impacted by climatic changes. These impacts will differ across locations and involve both improvements and deteriorations [Lobell et al., 2008; Milly et al., 2008].

To meet the changing food demands of growing populations, the necessity of improving or at least maintaining agricultural productivity thus implies the need to increase water use efficiency. Overall, a general trend of irrigated area expansion to sufficiently meet changing food demands can be expected. The trend of irrigating formerly rainfed cropland supposedly gets accelerated by additional land pressure from the residential sectors, but simultaneously an extensification of management practises is triggered in terms of a decrease in average water use intensity [Sauer et al., 2010]. However, from an integrated point of view such efficiency gains should be strived after not only within the "irrigation sector" but also by considering water allocations among the different sectors [Johansson et al., 2002].

Improved policies are one basic mean to promote sustainable water management. It is necessary to provide incentives that enhance water use efficiency, and this also should include considerations of alternative irrigation techniques [Calzadilla et al., 2010]. A particular challenge is to quantify the feedbacks between irrigation decisions, technologies, agricultural markets, and resources, as they occur across different scales.

Sauer et al. [2010] point out that irrigation is a complex decision beyond the binary decision of adopting irrigation or not: Different irrigation systems are preferred under different exogenous conditions including biophysical and socioeconomic factors. With respect to this, there is a need to account for alternative irrigation options within integrated assessments of land use, as the negligence of adaptations to particular exogenous conditions would "bias the burden of development on land and water scarcity". Consequently, the likely adaptation of farmers to different irrigation methods needs to be quantified to accurately estimate land and water scarcity.

As mentioned before, water is on one hand an essential input for many economic sectors including food and biomass production, but on the other hand a resource of limited availability. Evidently the assessment of water resources and water use, and consequently their valuation, is of great importance from both points of view: the socioeconomic and the ecological. Because of these relations we want to investigate the value of water more specifically with regard to its roles within (a) agricultural food-crop production, and (b) the aspired gain of socioeconomic welfare. The research questions behind the conduction of our model analyses are dealing with the actual contribution of irrigation water to the achievement of "optimal welfare". Against the background of potential conflicts and/or trade-offs between social, economic, and ecological interests, we aim to reveal pathways and supportive policy approaches to meet these different goals by means of integrated solutions, and under different socioeconomic, political, and technological environments. We regard the target of a well-balanced global development of economic and ecological concerns to be one basic condition for a sustainable functioning of the earth system in the long-term.

In the context of global change, we apply a global PEM for an exploration of agricultural land and water value, and to assess the welfare effects of irrigation decisions. Using a PEM enables the consistent linking of the motivation-based approach of economic optimization on the producer side, with the underlying socioeconomically justified food demands, and the constraints imposed by the biophysical environment. Common overall aims that actually embed these linkages are the striving for sustainable global food security, and for the stability of economic and ecological structures.

IV / 3. Irrigation as an economic decision and the implications for policy

IV / 3.1 Cost recovery and sustainability

Discussing the "value of irrigation" may embody different methodological aspects and distinct definitions, whose ambiguities are expressed in terms such as "quantitative (monetary) vs. qualitative assessment", "internal vs. external effects", or "direct vs. opportunity cost". Mostly, the centric question under discussion is the one of "economy vs. ecology".

Economic aspects often are presented in explicit monetary terms, whereas ecological concerns may be treated more abstractedly in the context of "sustainability". However, both are mostly accounted for in terms of "costs", or respectively are considered within evaluations of "profitability" that in turn is determined by revenue and cost items.

Past and recent (economic) assessments of irrigation mainly apply approaches of a monetary quantification of "irrigation cost". As such approaches appear to be the most explicit form of "applied irrigation valuation" within existing studies, and thus pose the framing background of "real-world policies", we want to review their basic conclusions in the following to provide insight at which considerations actually guide irrigated agriculture in practice.

According to Easter and Liu [2005] total irrigation costs can be divided into three main categories of direct project costs, environmental costs, and marginal user costs:

(1) Direct costs include the fixed investment costs for all infrastructures related to water delivery and irrigation, as well as the variable costs for all kinds of operation and maintenance (O&M).

(2) Environmental costs are external costs for the environmental impacts of irrigation due to any degradation or depletion of resources, which may be directly or indirectly charged on the irrigator by means of policy regulations.

(3) Marginal user cost is "the present value of future sacrifices implied by current resource use" [Howe, 1979, cited in Easter and Liu, 2005] and accounts for increasing future costs of water supply resulting from the assumption that more accessible and thus less expensive water resources are used up first.

An important question with respect to the role of irrigation costs is whether, or respectively what amount, decision-making farmers themselves have to pay. The subject of "cost recovery" more and more becomes centre in discussions on water resources management. Lessons learned from negative implications of public funding and subsidy policies in the past, especially within the irrigation sector, is prompting new strategies for a more sustainable handling of water as a scarce economic production factor.

In the past, a common underpricing of water along the widespread subsidization of irrigation water services, the payment of price bonuses to agricultural commodities in excess to their market value, and the resulting promotion of profit-enhancing irrigated agriculture have led to an excessive development of water consumption [Iglesias and Blanco, 2008; Massarutto, 2003]. Accordingly, one may derive that the "pushing of irrigation, as costs were sustained by public costs" [Massarutto, 2003] consequently made a substantial contribution to the commonly acknowledged problems of resource degradation arising from irrigation in many regions worldwide, such as salinization and soil fertility loss, groundwater degradation, or water logging.

Despite the special role of agriculture for food security, Massarutto [2003] argues that "irrigation" is an economic input in sectoral production, and the demand for irrigation originates from general market forces. Thus it seems questionable why it should be offered at subsidized price.

To mitigate future water problems, market-based instruments that involve the principle of having the water users pay for water and for sharing water infrastructures, or for the pollution of water resources respectively, appear to gain rising acceptance. Approaches on sectoral cost recovery of water services have to consider potential social, environmental, and economic consequences, which in turn depend on local to regional biophysical and socioeconomic conditions. Based on these, policy activities of water pricing have to be designed region-specifically, and should be carefully assessed by newly developed economic management tools [Iglesias and Blanco, 2008].

The establishment of institutional frameworks seems worthwhile to promote appropriate combination of incentive-based and regulatory approaches. Water pricing is a reasonable mean to achieve financial sustainability of water supply systems. Furthermore it may play an important role in technology adoption, and indirectly affects fertilizer use. However, its effectiveness in prohibiting diffuse water pollution and as a "demand management measure" remains unclear, same as the circumstances that favour the success of water markets [Iglesias and Blanco, 2008].

IV / 3.2 How to enhance irrigation water use efficiency?

As stated above, we do an investigation of "irrigation in both its roles, as an economic production factor and a factor that affects the sustainability of anthropogenic resource use". When reminding that on one hand land and in particular water resources are naturally limited in their availability, and that on the other hand the anthropogenic demand for these resources will most likely increase in the future, the general claim for improvements of water use efficiency is evident. Consequently, "water use efficiency" commonly is a basic concern in any assessment of irrigation or water resource management. Different definitions and distinctions of this term can be found, depending on subject, scale, and target of the particular essay.

Apparently, the importance of water use efficiency and its overt cognition grows with the occurrence of water stress. Water scarcity is subject to hydroclimatic conditions and sectoral water demands. Anthropogenic water demand in turn is influenced by a variety of factors, including the economic costs and benefits of alternative land use options. With regard to irrigation water use one may distinguish between the efficiency of on-field water application, and the delivery of water from source to field. Food demand-induced needs for irrigation expansion may be met a.o. by using irrigation techniques with higher application efficiencies. Sauer et al. [2010] found that agricultural production will likely shift to more water saving irrigation practices over time, i.e. a widespread shift to more expensive but also more water-efficient irrigation techniques is finally triggered. Results also indicate that without technical progress in agriculture substantial price adjustments for land, water, and food to equilibrate predicted supply and demand are required.

Water pricing is commonly regarded as an adequate instrument to regulate and guide water use and irrigation investments in favour of sustainability and equity goals [Easter and Liu, 2005; Johansson et al., 2002]. Several authors appoint the establishment of a self-organized, decentralized "irrigation sector", that is responsive for charging and collecting water fees, to be an important basis to overcome past failures in the financial organisation of irrigation planning and management. Water should become treated as a multipurpose economic good, with "water consumption" as the appropriate measure for water accounting instead of "water supply". Collected fees are meant to cover the costs of an irrigation project (or of water services in general) to account for financial sustainability, without depending on continued government subsidies [Cornish and Perry, 2003; Easter and Liu, 2005; Perry, 2001].

The main underlying reasons for levying water charges are (1) to fund O&M, (2) to encourage productive and conservative use of water, and (3) to recover infrastructure investment costs, which mainly have been publicly funded so far [Perry, 2001]. Such "irrigation charging" on one hand aims to generate financial resources to eventually achieve financial sustainability through cost recovery of annual O&M, and (at least in parts) of capital investment and depreciation costs. On the other hand it may be used as an instrument of demand management by reducing water demands, or improving water productivity through volume-based charges, or respectively by reallocating the water to higher value uses [Cornish and Perry, 2003]. More information on the legal, regulatory, operational, and economic requirements for effective water demand management and water-saving policies are given by Perry [2001].

A variety of different water pricing approaches exists among which three major methods can be identified in terms of area-based pricing, volumetric pricing, and market equilibrium pricing [Easter and Liu, 2005]. For each of these primary labels different methodological approaches or combinations of charging methods may arise. As explained in more detail by Easter and Liu [2005] and Johansson et al. [2002], the application of a particular pricing method may depend on the social, physical, institutional, and political circumstances, which in turn can appear on different temporal and spatial scales. Besides political, institutional, and legal settings this also comprehends factors and criteria like the primary purpose of the water charging (e.g., "sectoral cost-accounting" or "water resource accounting"), the potential crop range to choose from, water supply-to-demand ratios, the actual irrigation system, technological standards, water delivery options and costs, land values, the annual time horizon for irrigation, farm income, or the installation costs for meter measures.

Because of the explicit large-scale character of our study we use a very basic resource-accounting approach of volumetric water pricing with dynamic price elasticity to account for rising marginal costs (see Figure 1 in chapter 4.2.1), due to the assumption that more easily accessible and thus less expensive water resources are used up first [compare Howe, 1979, cited in Easter and Liu, 2005].

IV / 4. Model specification

This study uses the global, recursive dynamic, and partial equilibrium model GLOBIOM (Global Biomass Optimization Model). GLOBIOM simulates land use activities in the agricultural, bioenergy, and forestry sectors and their interactions with international commodity markets. Commodity production explicitly depicts three land use types: cropland, managed forest, and areas for short rotation tree plantations. The spatial and crop resolutions account for the globally most important crops and in 28 international regions, which are aggregated to 11 world regions within our analyses (Table 1).

Table 1 - Study model resolution: Crops and world regions

Crops	World regions
Barley	North America (NAM)
Cassava	Western Europe (WEU)
Chickpeas	Pacific OECD (PAO)
Cotton	Central and East Europe w/o former SU (EEU)
Dry beans	Former Soviet Union (FSU)
Groundnuts	Planned Asia with China (CPA)
Maize	South Asia (SAS)
Millet	Other Pacific Asia (PAS)
Oil palm fruits	Middle East and North Africa (MEA)
Potatoes	Latin America and Caribbean (LAM)
Rapeseed	Sub-Saharan Africa (AFR)
Rice	
Sorghum	
Soybeans	
Sugar cane	
Sunflower seed	
Sweet potatoes	
Wheat	

Table 1: Study model resolution: Crops and world regions

IV / 4.1 Model basics

The optimization model is written in GAMS and determines land use and processing activities to achieve a maximization of the sum of producer and consumer surplus. The choice of variables is subject to resource, technological, and policy constraints [Havlík et al., 2010]. Explicit demand functions with mostly constant elasticity and spatially explicit production functions for a set of individual production technologies are considered. In our analysis, prices and international trade flows are endogenously determined. As for the availability of resources, explicit supply functions are used only for water supply. The production technologies are specified as Leontief functions with implied fixed input – output ratios. However, the input – output ratios can change, as different mixes of technologies can be chosen to produce each product.

Spatial variation in weather, land quality, and management regimes, which affect agricultural and forest production and related environmental impacts are considered using geospatial data [Skalský et al., 2008]. The database contains information on topography, land cover, crop management, soil, and climatic parameters, on spatial resolutions of 5 and 30 arcmin as well as on country basis. Parameters that are assumed to be constant over time and thus unaffected by climate or land use change are classified and geographically clustered to delineate Homogeneous Response Units (HRU). The HRU layer depicts particular combinations of altitude, slope, and soil texture conditions (Table 2). With regard to the model´s spatial resolution there are up to 97 HRUs per region.

Table 2 – Slope and soil classes as applied in the model simulations

Slope classes definition (intervals) (slope inclination in units of degree)	Soil classes definition
0 - 0.35	sandy
0.35 - 1	loamy
1 - 1.6	clay
1.6 - 2.25	stony
2.25 - 3	peat
3 - 6	
6 - 10	
10 - 15	
15 - 30	
30 - 50	
> 50	

Table 2: Slope and soil classes as applied in the model simulations

In a next step, parameters that may change over time are integrated on the basis of Simulation Units (SimU), including information on climate, land cover, land use type, and irrigation. The SimUs are delineated by intersecting the global HRU layer with a 0.51x0.51 grid as well as with country boundaries. As explained in more detail by Havlík et al. [2010], for each SimU a number of land management options are simulated using the biophysical process model EPIC (Environmental Policy Integrated Climate Model) [Izaurralde et al., 2006; Williams, 1995]. The SimU level thus represents the geospatially explicit basic resolution for all further estimations of biophysically based effects with regard to land use and management options.

The HRU/SimU concept allows the consistent aggregation of these land-related characteristics (potentials and risks) for a chosen level of resolution to be subsequently used in our economic land use assessment. As shown in Appendix–1 each land related activity and all land resources are currently indexed by country, altitude, slope, and soil class.

IV / 4.2 Crop, livestock, and biofuel production

Crop commodities enter one of three demand channels: demand by the food industry, livestock production, and biofuel production [see also Havlík et al., 2010].

IV / 4.2.1 Food crops

We apply constant elasticity functions to model the demand for food crops. The parameterization is done according to FAOSTAT data on prices and production quantities [FAO, 2009], and by using own price elasticities as reported by Seale et al. [2003].

Average yield level by crop and country is taken from FAOSTAT [FAO, 2009]. Crop yield coefficients are simulated with EPIC considering different options of irrigation, fertilizer, and subsistence management systems corresponding to the International Food and Policy Research Institute (IFPRI) crop distribution data classification [You and Wood, 2006].

An irrigation module to account for global implications of multiple choices in irrigation decision making is applied, which is described in detail by Sauer et al. [2010]. This module considers biophysical, technical, and economic aspects and data of irrigated agriculture to be used in aggregated forms within our integrated global assessment of land use change processes.

The spatial distribution and specification of selected main determinants of irrigation choice are put into relation with requirements and characteristics of four basic irrigation methods. The suitability and costs for the application of a particular irrigation system in combination with the demand for particular crops can be evaluated against the actual biophysical and socioeconomic background.

The irrigation techniques included are basin, furrow, drip, and sprinkler irrigation. To assess the suitability and performance of each system at the particular regional biophysical and socioeconomic conditions we consider various factors concerning crop suitability, water demand, energy requirement, labor intensity, and overall cost. The model optimizes the extent of a particular irrigation system under consideration of irrigation cost per spatial unit for all appropriate combinations of regional geographic background, crop type, and irrigation system [Sauer et al., 2010].

The computation of consumptive irrigation water requirements by irrigation system account for beneficial-use crop irrigation demands and system-specific field application efficiencies, which in turn vary by region and are determined under consideration of regional climatic factors [FAO / IIASA, 2000] and indicators of socio-demographic development [UNDP, 2000] (Table 3).

Table 3 - Water application efficiency by irrigation system and region

World region	Water application efficiency by irrigation system (%)*			
	Basin	Furrow	Drip	Sprinkler
North America	53	48	93	85
Western Europe	55	50	93	86
Pacific OECD	38	33	86	71
Central and East Europe	55	50	93	86
Former Soviet Union	55	50	93	86
Planned Asia with China	45	40	89	79
South Asia	35	30	84	68
Other Pacific Asia	40	35	88	75
Middle East and North Africa	25	20	80	60
Latin America and Caribbean	40	35	88	75
Sub-Saharan Africa	30	25	82	64

*Estimates based on information by Clemmens and Molden [2007], FAO/IIASA [2000], and UNDP [2000]

Table 3: Water application efficiency by irrigation system and region

Regarding water availability we use selected observation data on renewable water resources and water demands from other sectors to define upper limits [FAO Land and Water Development division, 2008; Rosegrant et al., 2002], and eventually constrain irrigation water use through an artificial supply function, representing the relative water scarcity through its increasing marginal cost (Figure 1).

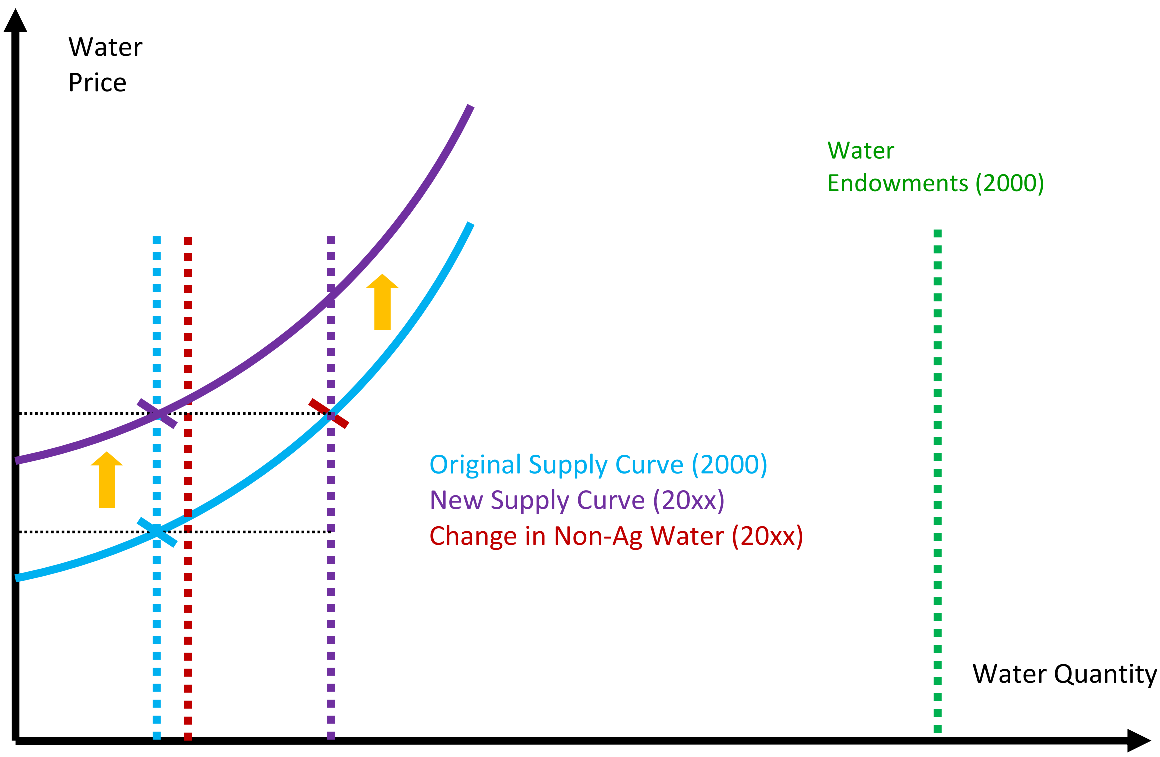

Figure 1: Computation of the water supply function

Given total endowments of exploitable renewable water resources (green dotted line in Figure 1), observed quantities of agricultural water use (light blue dotted line), and the according water supply curve (solid light blue line) for the reference year 2000 are used in combination with assumed changes in non-agricultural water use in the year 2030 (red dotted line, here generalized for “year 20xx”). To eventually obtain the increment in the shift of the water supply curve in year 20xx (violet solid line) we add agricultural water use in the reference year 2000 (light blue dotted line) to change in non-agricultural water use in year 20xx (red dotted line) to derive the curve represented in the dotted violet line. We then shift the water supply curve for year 20xx according to the implied price change by the additional amount of non-agricultural water. Mathematically, the supply shift is computed as a price shift, i.e. a shift of the price parameter value for an exogenous price-quantity pair (for more details see Schneider et al., 2010, as also included in Appendix-3 of this thesis).

IV / 4.2.2 Livestock, feed crops, and crop-based biofuels

Demand for livestock products, which are represented by aggregated regional livestock production in terms of the commodity “animal calories” as a bundle of livestock products, is represented through downward sloping demand curves.

The accordingly required amount of feed crops, and thus the livestock-related demand for cropland, is based on the FAOSTAT Supply Utilisation Accounts [FAO, 2009].

Crop based biofuel production considers first generation technologies for (a) ethanol from sugar cane and corn, and (b) biodiesel from rapeseed and soybeans.

IV / 4.3 Managed forests and Short Rotation Tree Plantations

Primary forest production in our model is based on traditional managed forests, and short rotation tree plantations respectively, and accounts for sawlogs, pulplogs, other industrial logs, traditional fuelwood, and biomass for energy. Subsequent processing of sawlogs, pulplogs, and biomass for energy is also included in the model. For more details on the underlying demand and production parameters (including harvesting costs) see Havlík et al. [2010].

IV / 4.4 Land use change as a result of competitive trade-offs between sectors

We allow for endogenous land use changes within a fixed amount of area assigned to the three main land cover classes mentioned above. The total area available for production remains constant over time, with land use type changes being consistently transferred from one to the next simulation period in terms of a recursive dynamic modeling.

In the land use allocation process general restrictions on conversion options within the different land cover types, as well as SimU-scaled suitability and productivity potentials are considered to exclude particularly inappropriate conversions.

By means of scenario analyses these general “conversion rules” and suitability restrictions enable us to assess the role of parameters such as the costs of land cover conversion. In this sense, restriction means a prohibitively high cost, e.g. because the land considered as free is already used for some other activities [Havlík et al., 2010].

To calibrate the model, cost parameters related to land use activities (SimU specific crop areas, regional primary forest products supply, regional animal calorie supply) are adjusted in a way that the marginal costs of these activities equals their marginal benefits in the reference baseline simulation.

IV / 5. Scenario settings

We explore the global value irrigation and its interrelations with land use change. In particular we put a focus on the influences of restricted resource availability and of socioeconomic development, within a global, large-scale modeling approach.

The underlying scenarios of our simulations consist of two dimensions, with regard to assumptions made on how parameters of the base model in general, and of the irrigation module in particular may change in the future.

The first dimension comprises overall development scenarios that portray changes and effects of direct drivers such as land cover change and energy use, and of indirect driving forces in terms of population, GDP, technical progress, and yield growth. We apply four different development scenarios, of which three are taken from the Millennium Ecosystem Assessment (MA) [for general information on the MA see Millennium Ecosystem Assessment, 2003] and one from the SRES scenarios of the Intergovernmental Panel on Climate Change (IPCC).

Notably, the MA scenarios also explicitly consider consequences for ecosystem services and human well-being. From MA, we apply data according to the “Global Orchestration”, “Order from Strength”, and “Adaption Mosaic” storylines [see IIASA, 2005], and from SRES the data of the B1 scenario. The IPCC scenarios have been described and discussed in many publications. For a compact insight we hereby refer to the IPCC Special Report Emission Scenarios [IPCC, 2000].

The second dimension implements the basic irrigation scenarios “No irrigation”, “Irrigation 2000”, and “Free irrigation” (also refered to as “Water can expand”). Future capacities of different irrigation components (potentially and actually irrigated area, distribution of particular irrigation systems, water availability) can be treated variously in terms of constant, restricted, or free development

The model enables us to combine these scenarios in various ways and implement them on different temporal scales with respect to the class-width of the time scale within our simulation horizon between the years 2000-2030.

IV / 5.1 Development scenarios

IV / 5.1.1 MA – Global Orchestration (GO)

The GO scenario portrays a strong trend of globalization with respect to global trade, economic liberalization, and an equitable access to goods and services. Economic expansion and technology advances are generally high and further supported by large investments in public health and education sectors. Supra-national institutions are assumed to deal with global environmental problems (e.g., climate change, fisheries) but only in terms of a reactive approach to ecosystem management. Underlying demographic changes include high migration whereas fertility and mortality levels are low in comparison to the other MA scenarios. Crop yield growth rates due to improvements in energy and water use efficiency are particularly high in developing countries.

Human well-being is regarded somehow decoupled from environmental ecology with the prior focus on economic development and related changes in lifestyle and food consumption patterns. The resulting land use changes (including the decline of forest) and “urban prioritization” cause ecological impacts (e.g., degradation and scarcity of natural resources, flood hazards) that affect relatively few people (especially in rural regions of poorer countries) but with a relatively high intensity. This in turn poses substantial challenges for ecosystem management [IIASA, 2005].

IV / 5.1.2 MA – Order from Strength (OS)

The OS scenario represents a highly regionalized and fragmented world as regards markets and sociopolitical issues. A strong regulation of trade and a low economic and informative connectivity among regions focuses on national security and self-sustenance but also slows down the pace of technological growth. However, “strategic businesses” such as oil and water sectors are mostly put under state control. With regard to global environmental issues, the regional emphasis inhibits global agreements and eventually triggers a degradation of global commons and growing global inequality. Due to degradation associated with agricultural intensification, and a low diffusion of more efficient technologies crop yield growth is low.

The emergence of “rich versus poor countries” favours a shifting of industries along this gradient in terms of a “selective globalization”. In turn, unsolved global environmental problem in conjunction with a restricted trade of e.g., crops lead to ecological degradation, and to food and water shortages in poor countries. Analogue to the GO scenario, the sustainability approach is a reactive one [IIASA, 2005].

IV / 5.1.3 MA – Adaption Mosaic (AM)

The main characteristic of the AM scenario is its accountancy for ecological issues. Policies and strategies concerning ecosystem management are considered on mainly local to regional scales, with respect to the rather complex nature of ecosystem functioning. Additionally, investments in human and social capital are assumed to further strengthen the awareness of the importance as well as the fragility of ecosystems. This rather decentralized scenario includes the existence of trade barriers, but a generally free transfer of information and knowledge, supporting technological progress. Among the regions different styles of governance exist with consequently different outcome that may be both, positive or negative. Changes to more sustainable (extensive) agricultural production practises slow down yield growth, especially in developed countries.

On one hand this “autonomy approach” represents a high flexibility and adaptability but on the other hand (environmental) problems of global scale are neglected. The recognition of these global issues eventually enhances the development of cooperative networks between the different governmental units to better manage global commons. These developments are guided by locational advantages such as a high connectivity potential due to river networks, which additionally means potential improvements of respective economic and social standards [IIASA, 2005].

IV / 5.1.4 SRES – B1

Characteristic for the B1 storyline are increasing trends of regionalization to globalization as regards interactions and the equity of socioeconomic standards. Population is assumed to globally peak in mid-century and to decline thereafter. The economic structures in B1 are rapidly changing to a “service and information economy” with an emphasis on sustainable technologies and a focus on global solutions. However, “additional climate initiatives” are not considered [IPCC, 2000].

IV / 5.2 Irrigation scenarios

In addition to the overall development-scenarios we apply different irrigation scenarios. Common to all scenarios is the use of average weather patterns for each homogenous response unit. Extreme weather events are not considered. The variance of weather variables affects the crop yields simulated with the EPIC model. However, these crop yields are passed as deterministic coefficients without probability distribution to GLOBIOM.

IV / 5.2.1 No irrigation

The “No irrigation” scenario simulates agricultural production without the option to irrigate.

IV / 5.2.2 Irrigation 2000

In the “Irrigation 2000” scenario, we constrain irrigated area and irrigation water amounts in a region to not exceed observed regional levels of the year 2000. The distribution of irrigation water to particular crops and systems may change though.

IV / 5.2.3 Free irrigation

“Free irrigation” (or: “Water can expand”) refers to a model setup, where the total irrigated area in a region can expand to formerly non-irrigated suitable land including arable land but also other land categories. The amount of irrigation water is restricted by regional freshwater endowments minus the projected water demands from non-agricultural sectors.

IV / 6. Results

Against the background of the combined scenarios we describe the simulation results for the variables food demand, food prices, total economic surplus, irrigation water use, irrigation and rainfed land use, and the declining availability of water for agriculture as a consequence of water demands of the forestry, bioenergy, and residential sectors. Further interpretations of the results with respect to the valuation of irrigation with regard to global food security and sustainability targets are given in the subsequent sections. In the following we first describe average global results as obtained from the combination of the two scenario dimensions of "Development scenarios" and "Irrigation scenarios".

The projected absolute magnitude of global food demand differs slightly by development scenario. Under all development scenarios, the relative impact of different irrigation scenarios is the same. We find that for "Irrigation 2000" and "Free irrigation" the amount of crop and livestock products is equally high, whereas for "No irrigation" total food production is little lower with a very decent shift in food demands from crop to livestock products.

In absolute terms, food demand is highest under GO, followed by B1, and lowest under OS. The dietary share of livestock products is highest under B1. For both, vegetarian and animal food products, the demands are rather high under B1 and GO, and relatively lower under AM and OS. As for the development over the time horizon of our study, results indicate average increases in crop consumption of 32% under GO, 27-28% under B1, 19-20% under AM, and 13-13,5% under OS (compare Figures 2 and 3). In general these increases are slightly higher for the "Free irrigation" sub-scenario in comparison to "Irrigation 2000" and "No irrigation". Independently of the irrigation scenario, the relative increases in livestock-products consumption are 11% under B1, 9,4% under GO, 4,2% under AM, and 2,1% under OS.

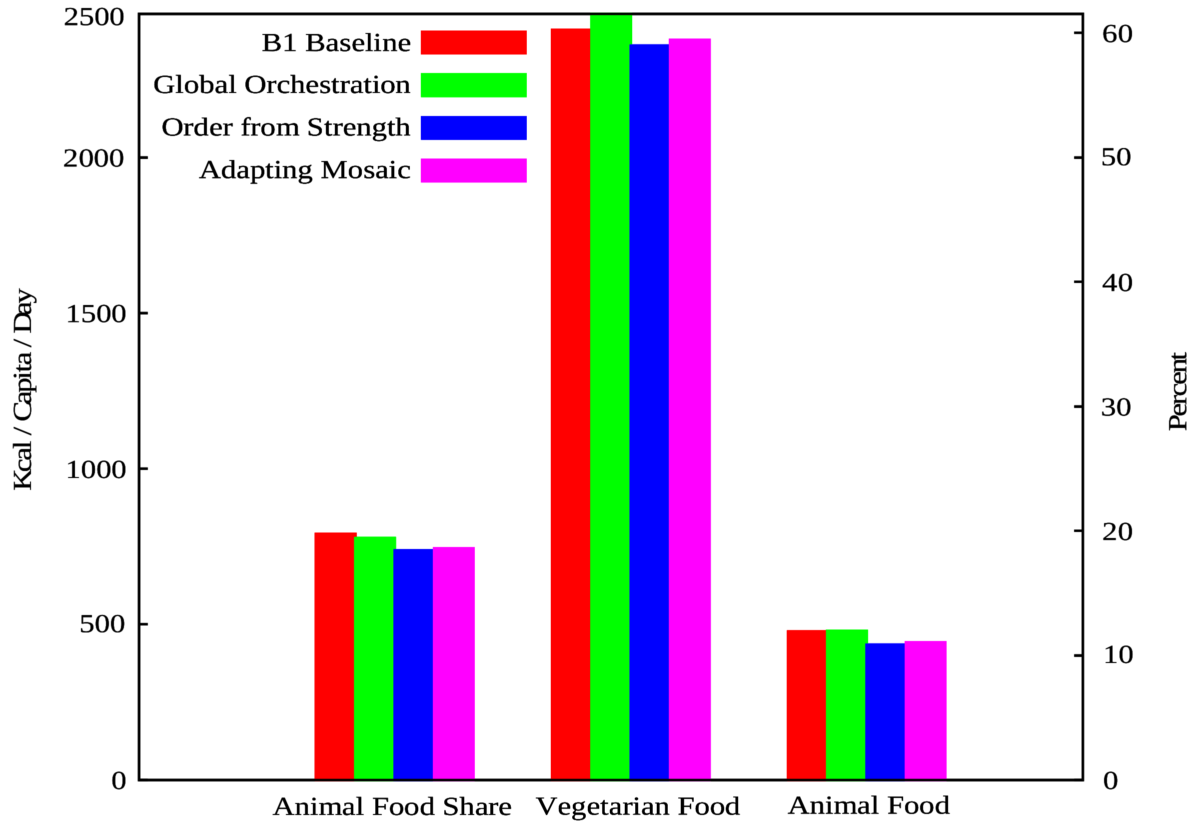

Figure 2: Global food consumption in 2010 under “Free irrigation”

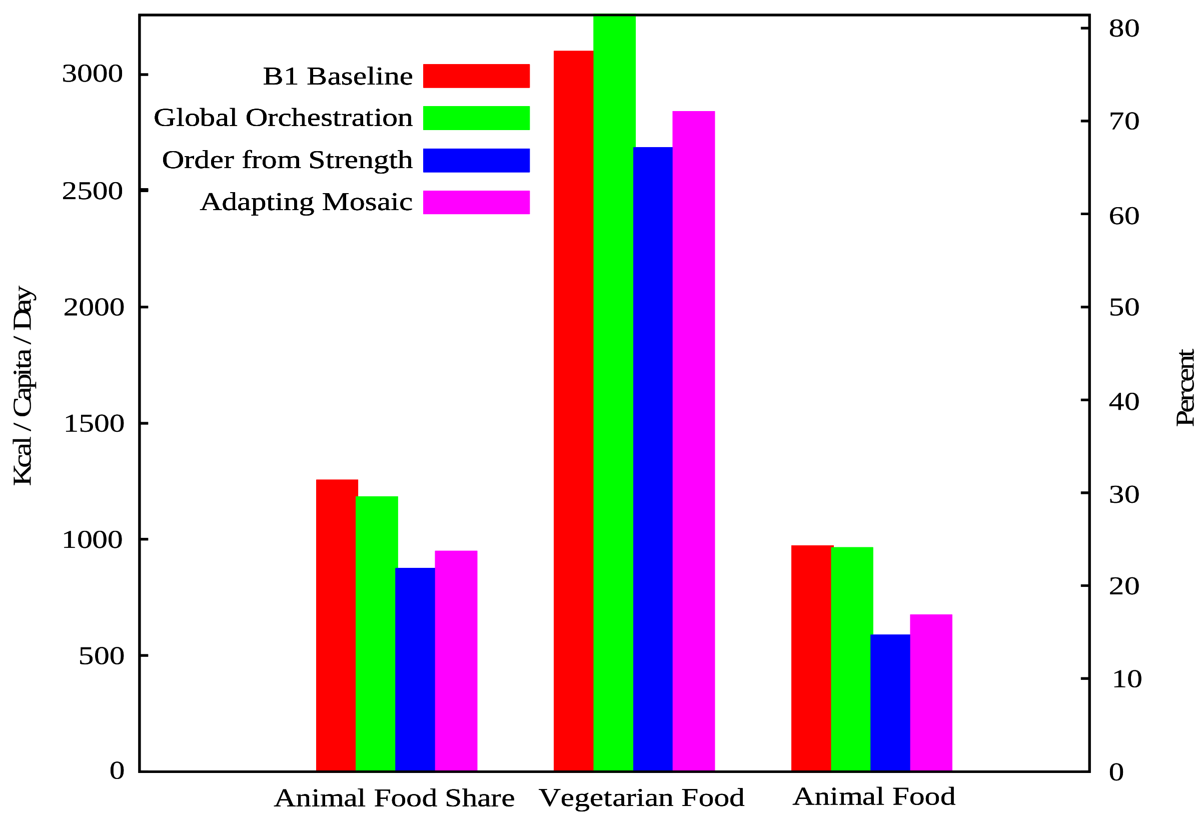

Figure 3: Global food consumption in 2030 under “Free irrigation”

Food prices, in the following dealt with as the global average over all crops and regions, generally decline between 2010 and 2020 for all scenario combinations. Under “No irrigation”, a strong increase of food prices between 2000 and 2010 is projected (Figure 4). We also detect his increase in parts under “Irrigation 2000” but in rather moderate form (in combination with B1, OS; almost stagnating under AM, and respectively a moderate decrease in combination with GO).

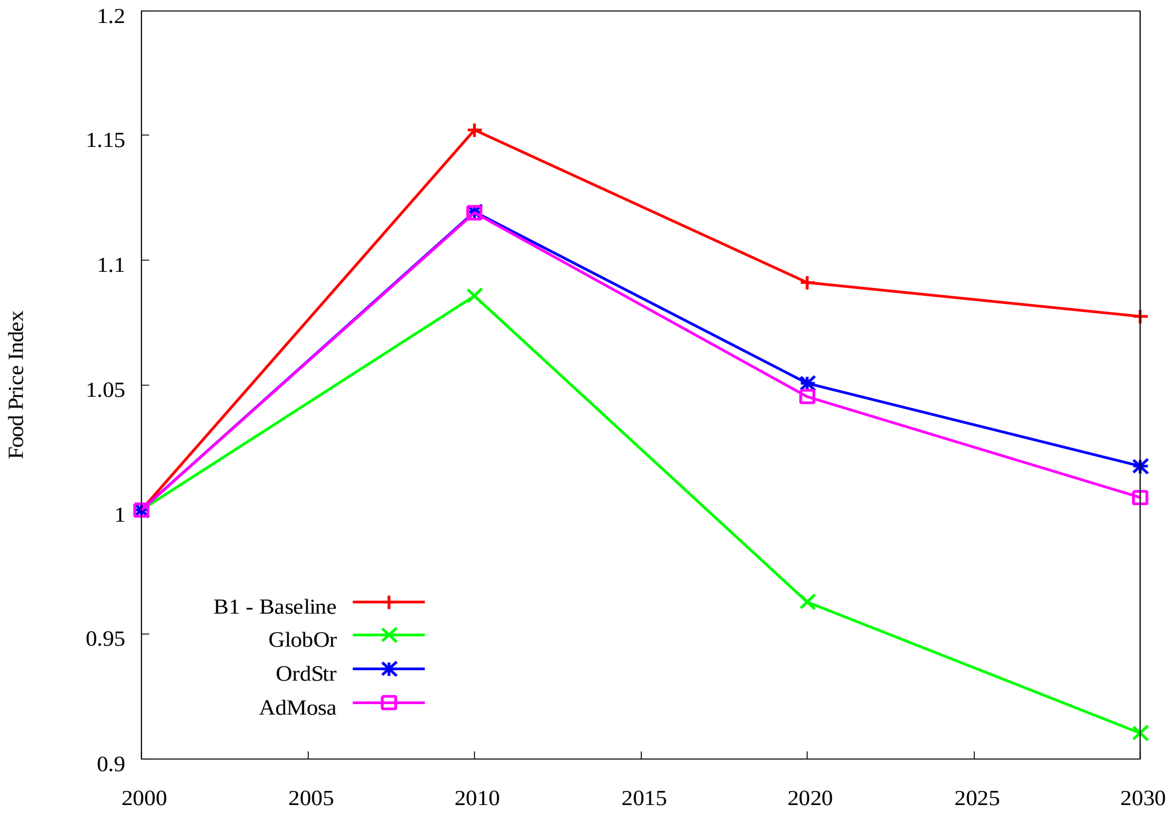

Figure 4: Predicted global food price developments until 2030 under “No irrigation”

Simulated food prices in 2030 (as related to the base year reference price) are highest under B1 and lowest under GO (followed by AM). Besides, the GO scenario is the only development scenario, under which an absolute decrease of food price until 2030 is modeled for all irrigation scenarios (i.e. the 2030 price is below the 2000 reference price for any combination of development and irrigation scenarios). Comparing the results for the different scenario combinations we find that the magnitude of variation in food price values between our irrigation scenarios is highest under OS and lowest under GO (compare Figures 4 and 5).

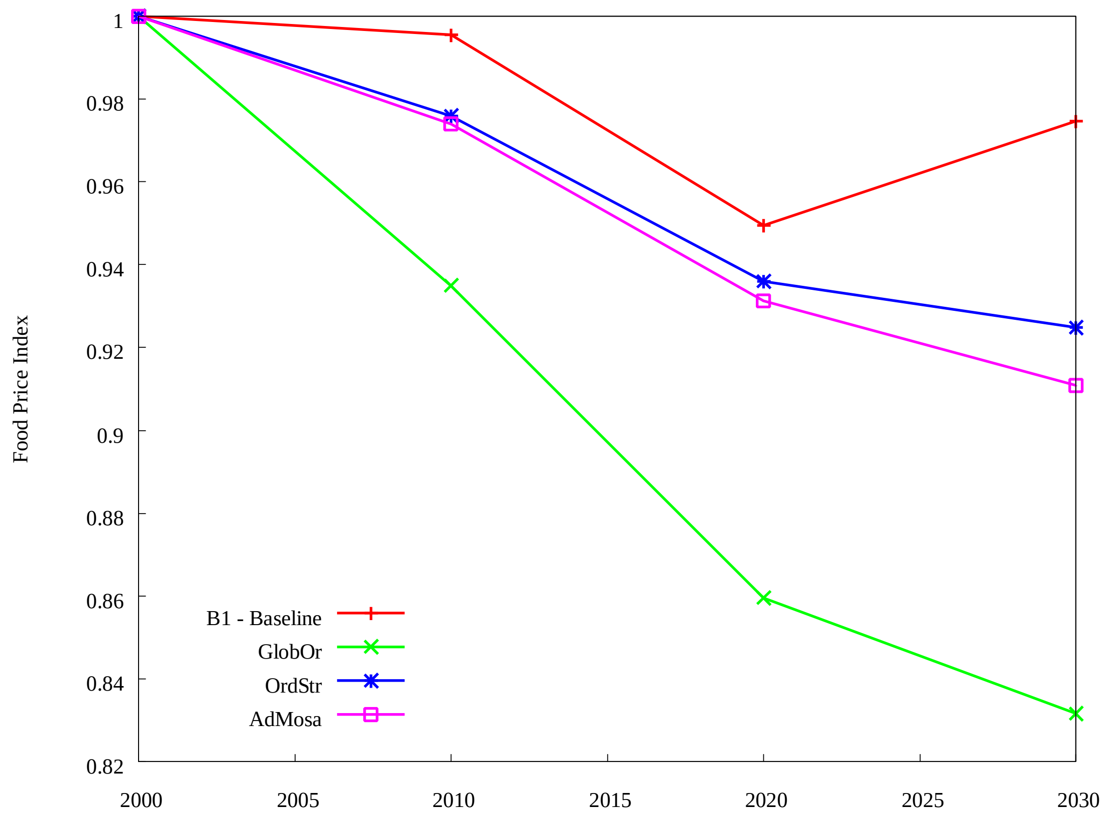

Figure 5: Predicted global food price developments until 2030 under “Free irrigation”

Water availability for irrigation in our model is also affected by the water demands of other sectors. Independently of the actual irrigation scenario we compute a steady increase in these other sectors´ demands. Increase rates are relatively higher between 2010 and 2020, and eventually slow down between 2020 and 2030 (Figure 6). Notably the increase in the first phase is lowest under GO.

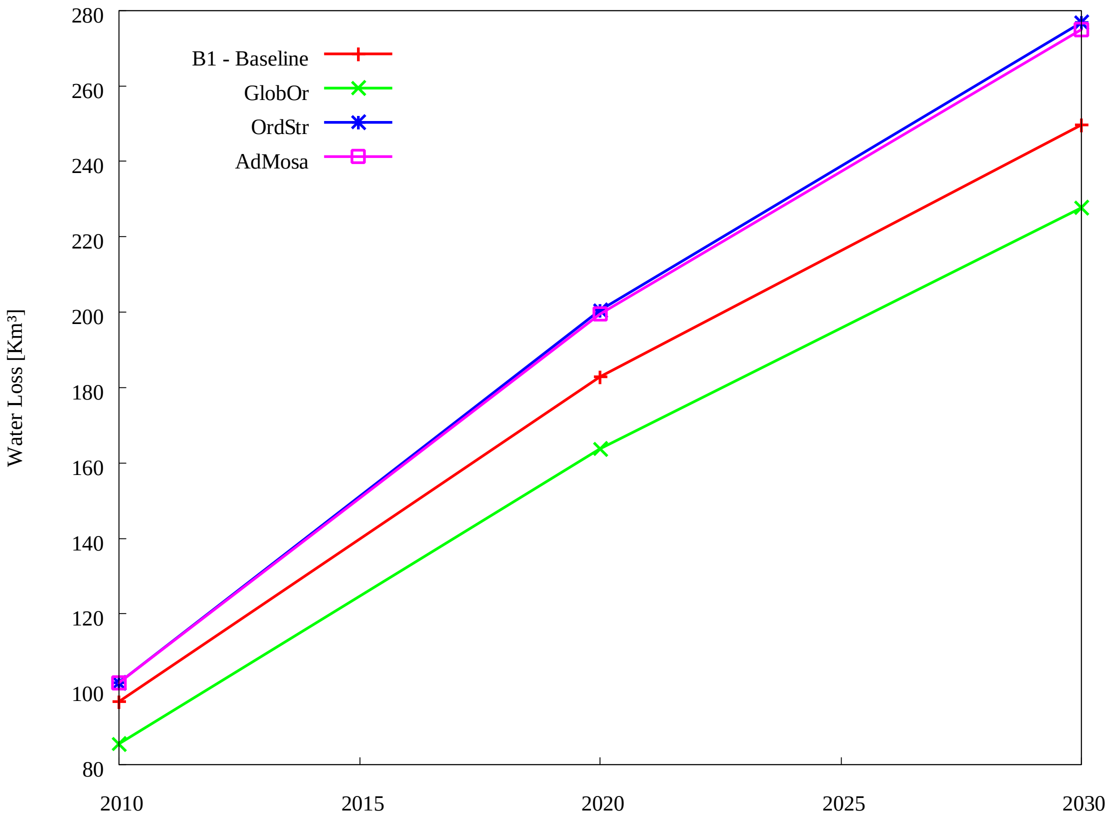

Figure 6: Predicted global decrease of irrigation water availability until 2030 under "Irrigation 2000"

To put demands for irrigation land in relation to total cropland we also take a look at simulation results on total agricultural land use including rainfed areas. Under all scenarios we find an expansion of cropland area at increasing rates. The absolute values predicted for 2030 are highest under B1 and lowest under OS for all irrigation scenarios (see Figures 7 and 8). In particular, the increase rate of cropland expansion is substantially higher under B1 compared to the other development scenarios. According to the irrigation-scenario settings, absolute numbers are highest under "No irrigation" and lowest under "Free irrigation". However, these differences are only rather small.

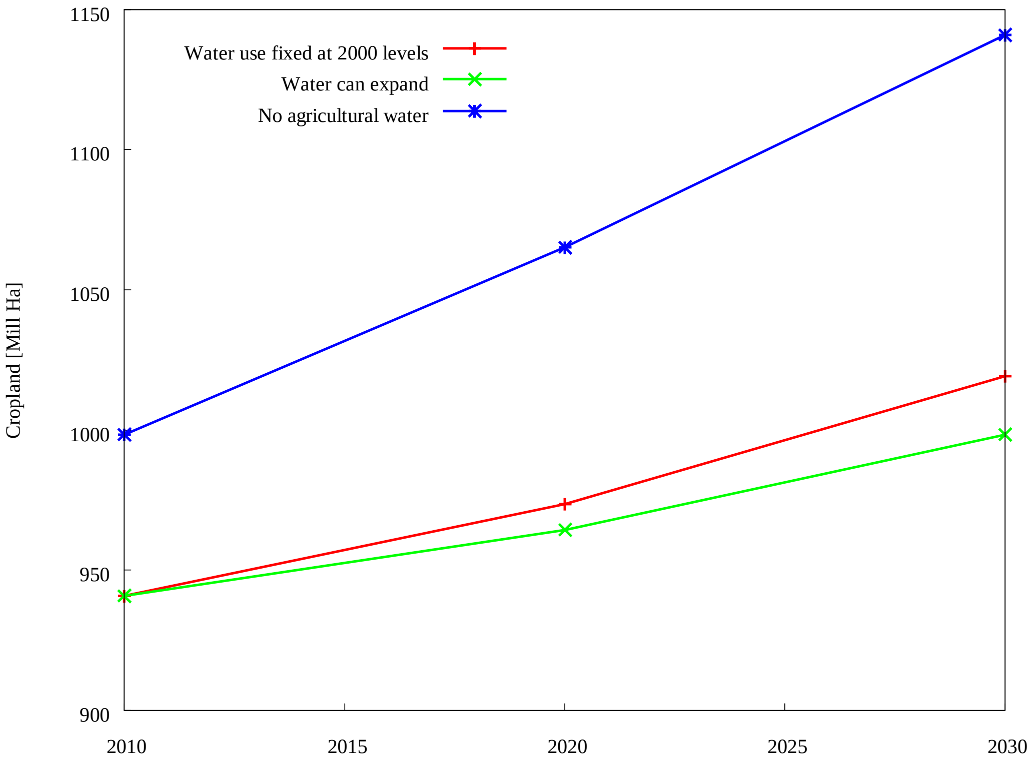

Figure 7: Development scenario B1: Predicted total global cropland area until 2030 under different irrigation scenarios

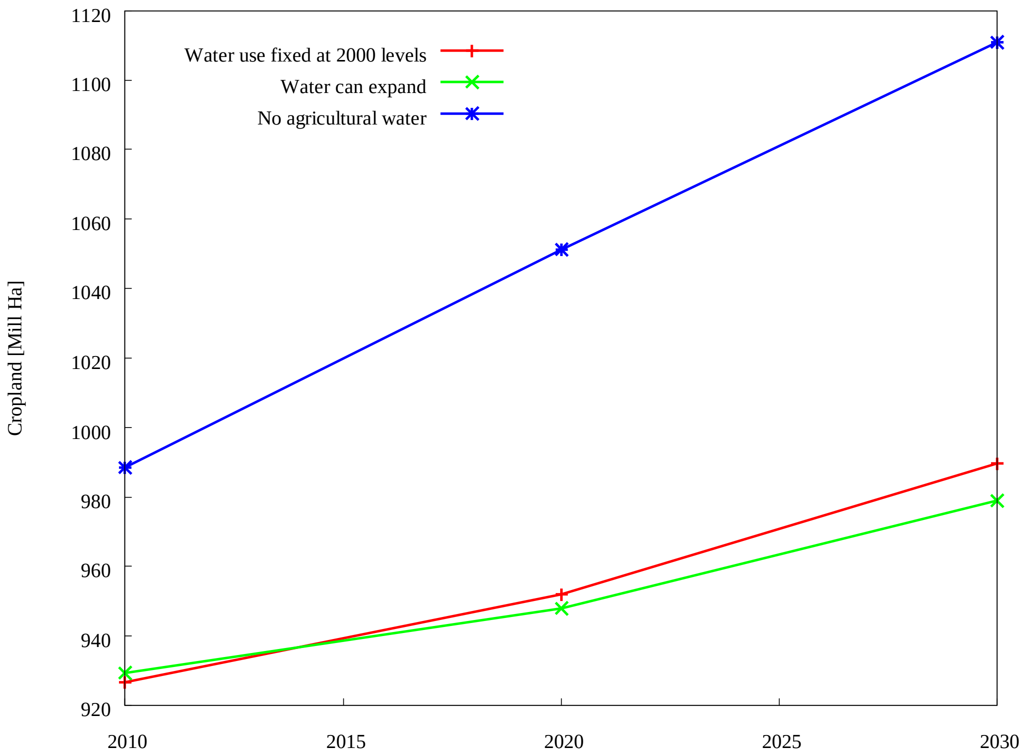

Figure 8: Development scenario OS: Predicted total global cropland area until 2030 under different irrigation scenarios

Total irrigation water use between 2000 and 2030 overall generally increases under “Free irrigation” conditions but, especially from 2000-2020, decreases under “Irrigation 2000” (Figures 9 and 10). Under all irrigation scenarios, the absolute global increase (or decrease, respectively) is highest under B1 and lowest under GO. Notably, under “Irrigation 2000” increase rates after 2020 are particularly high for AM and OS.

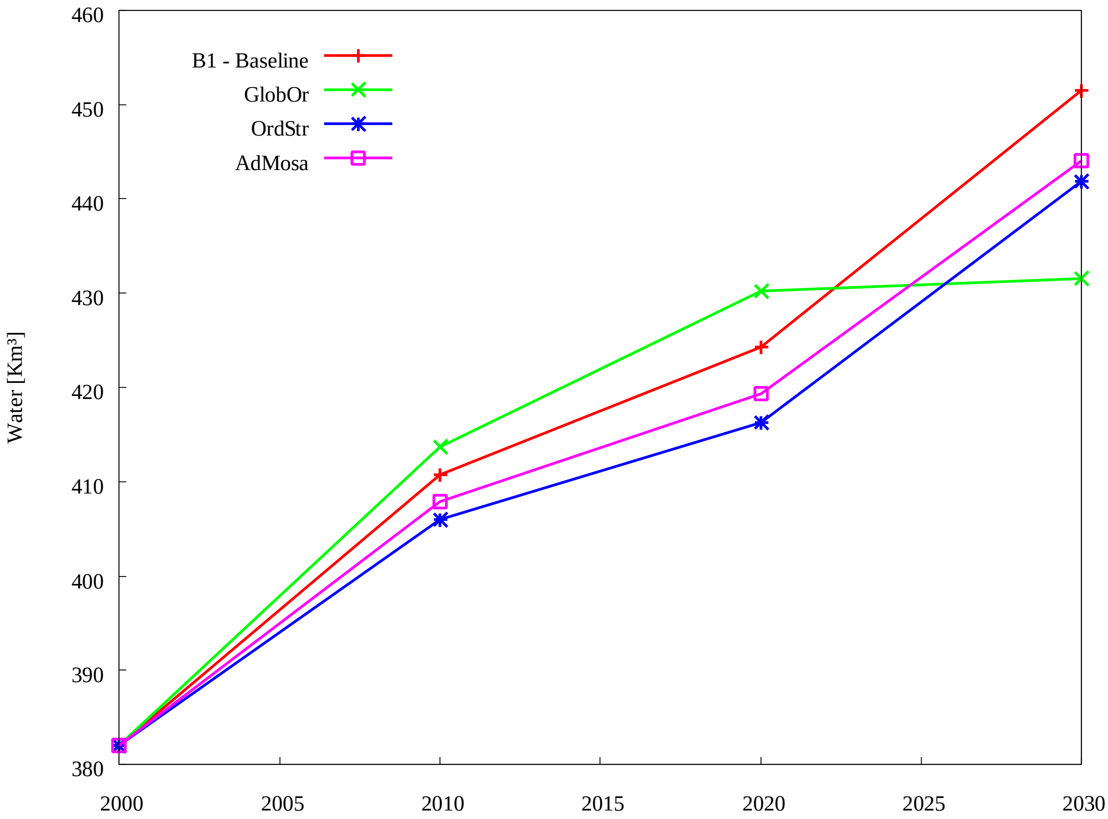

Figure 9: Predicted global irrigation water use until 2030 under “Free irrigation”

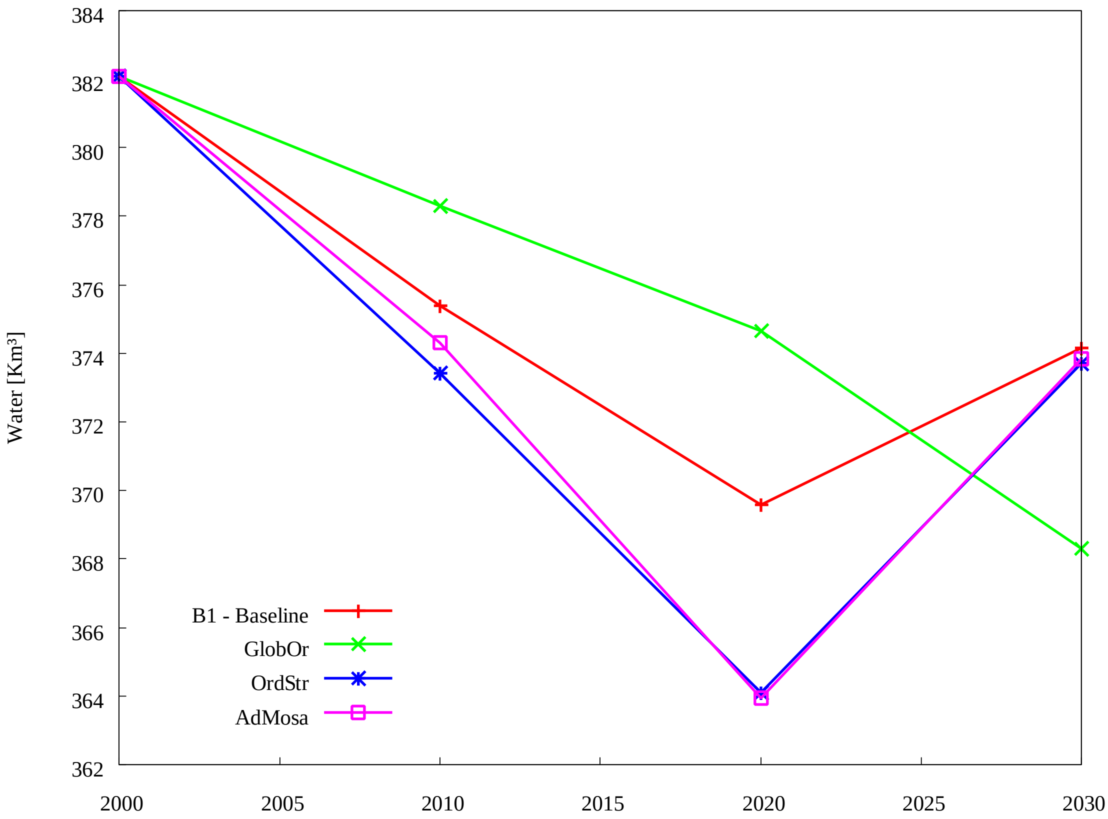

Figure 10: Predicted global irrigation water use until 2030 under “Irrigation 2000”

Very similar trends are detected for simulated irrigated area. Analogue to the water-use results the absolute numbers in 2030 are highest for the B1 development scenario and lowest for GO (see Figures 11 and 12). Under “Irrigation 2000” we find an overall decrease in global irrigated land area.

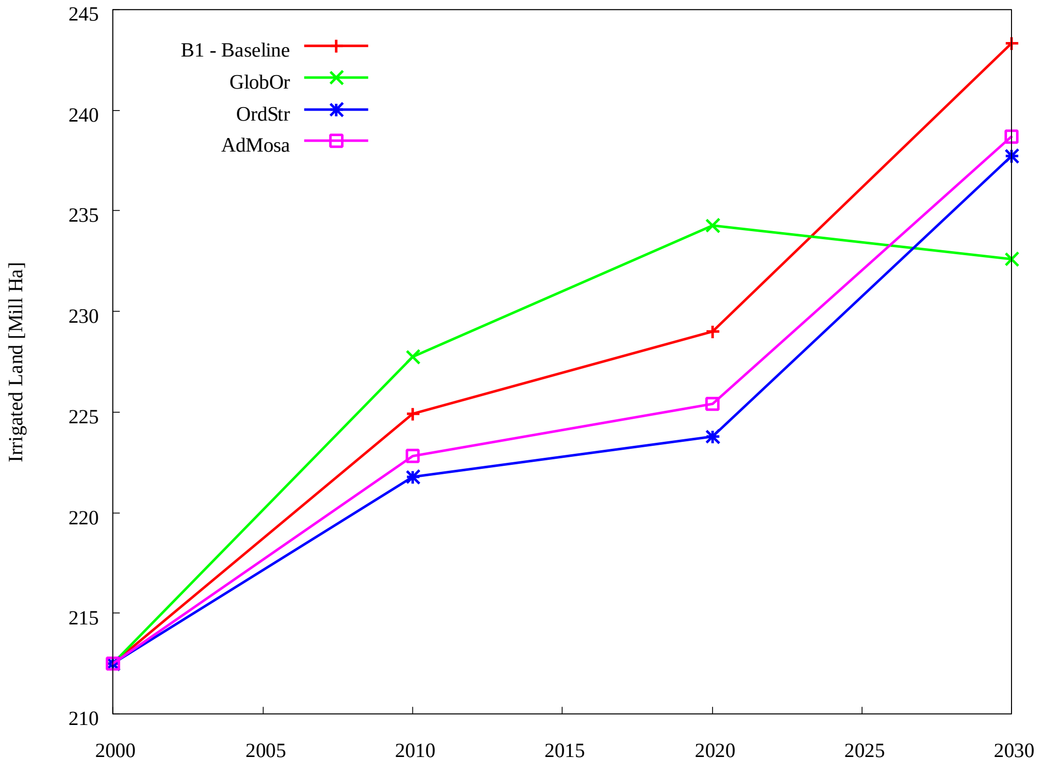

Figure 11: Predicted global irrigated area until 2030 under “Free irrigation”

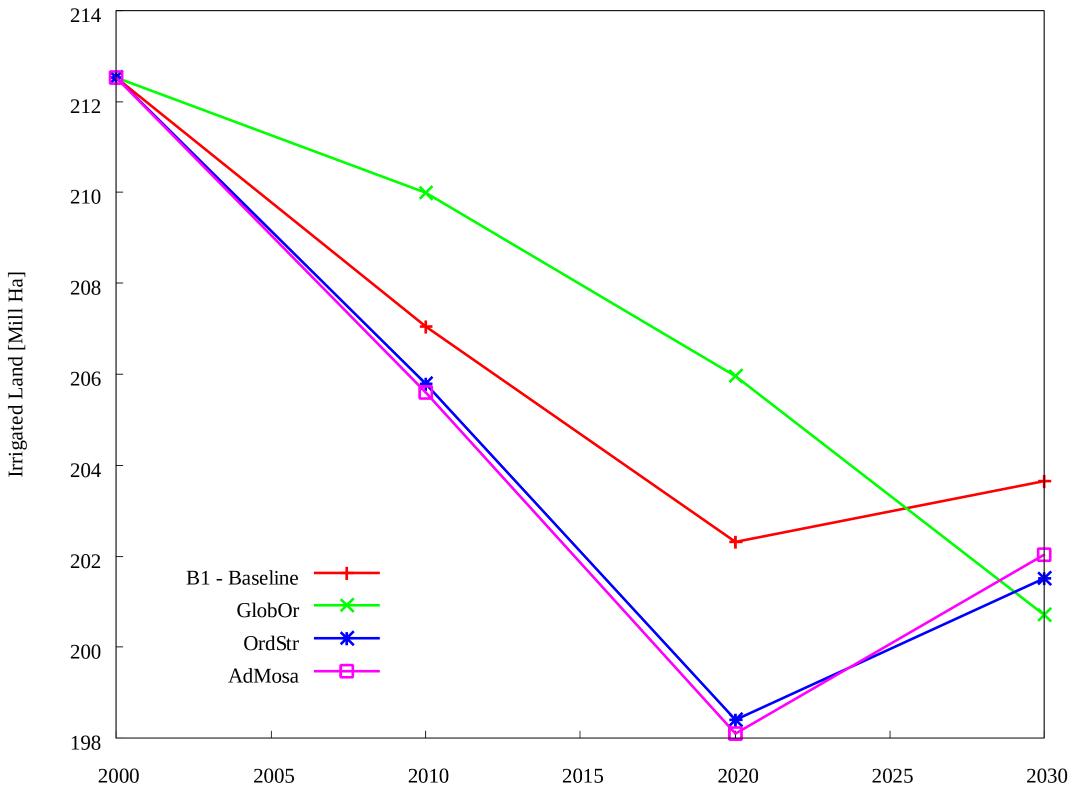

Figure 12: Predicted global irrigated area until 2030 under “Irrigation 2000”

The simulated global water use intensity, as a result of expected developments in irrigation water and land use, strongly increases under “Free irrigation” before it eventually almost stagnates after 2020, whereas under “Irrigation 2000” (Figure 13) the increase is less strong but constantly progresses over our simulation horizon. Notably, under the GO development scenario absolute and relative increases are comparably low.

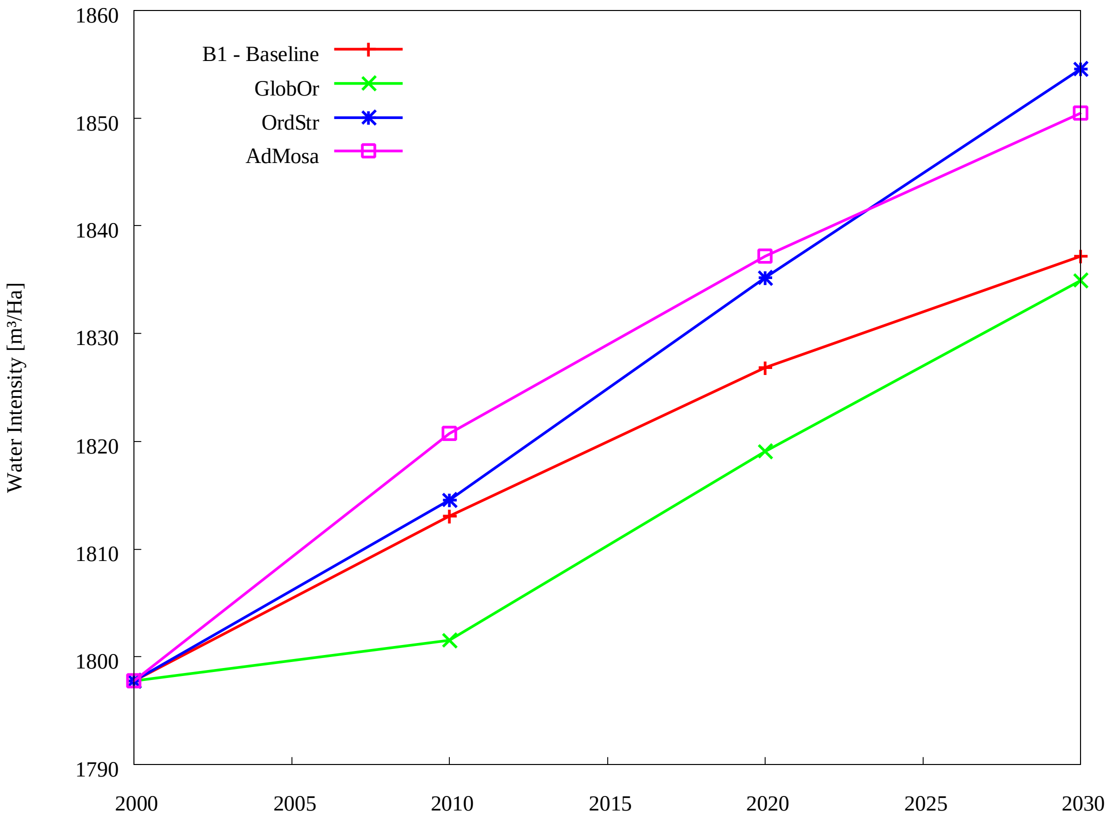

Figure 13: Predicted global irrigation intensity until 2030 under “Irrigation 2000”

Under “Free irrigation”, we project the same levels of water use intensity for all development scenarios around 2030, but with constant increase rates under GO, whereas all other development scenarios show a stagnation after 2020 (as mentioned before). However, the overall only moderate total increase in water use intensity between 2000 and 2030 is almost identical for all development scenarios, in a range of 4-5% (Figure 14).

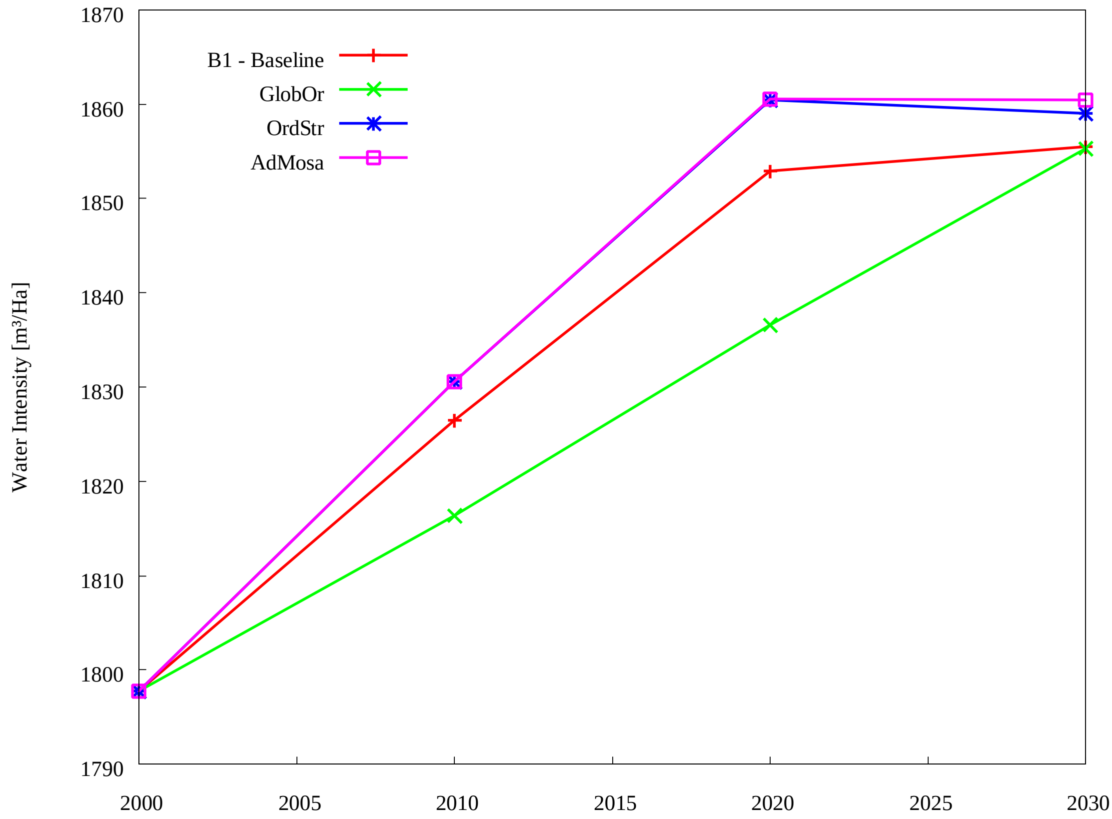

Figure 14: Predicted global irrigation intensity until 2030 under “Free irrigation”

Changes in irrigation water and land use and in water use intensity are not relevant to the “No irrigation” scenario and thus neglected here. Nevertheless, the inclusion of the “No irrigation” scenario is actually relevant for our analysis of water value and the contribution of irrigation to societal welfare, as further discussed in the next chapters.

Total economic surplus as the sum of producers´ and consumers´ surplus may be considered as an immediate measure of “socioeconomic welfare”. However, looking at the simulated global numbers we find no significant impact of the irrigation scenarios (see Figure 15 as example). Absolute and relative increase of total economic surplus is highest under GO.

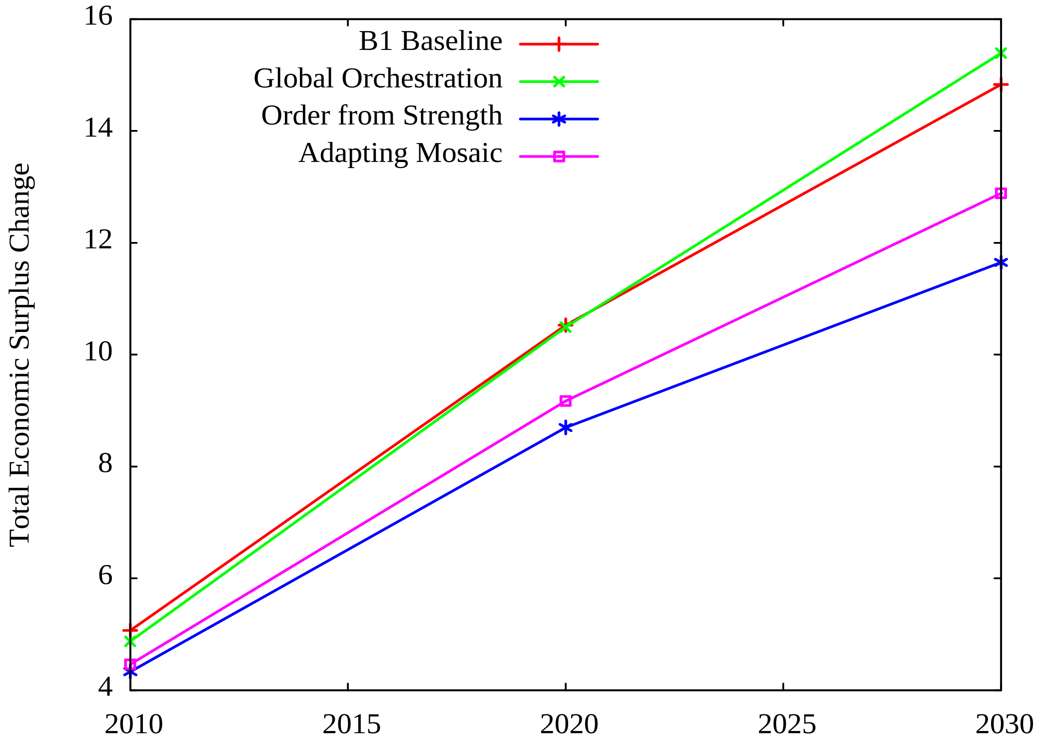

Figure 15: Predicted total global economic surplus until 2030 under “No irrigation”

IV / 7. Discussion

We start the discussion of our results with a look at general findings in relation to the particular development scenarios.

Looking at our simulation results one finds fluctuations in growth rates between subsequent time periods for one and the same variable, and under the same scenario. These fluctuations are likely the net effect of diverging or converging “exogenous” driving forces such as water availability and technical progress, as well as of interrelations among the endogenous model variables such as food demand and prices. The model we use does not provide the required evidence to quantitatively explain such rather complex linkages in a scientific manner.

Food price variables are somewhat in the centre of the modeling procedures as they represent an immediate dynamic interface between changes in supply and demand, potentially sending feedbacks that in turn may trigger further impacts “in both directions”.

With regard to crop price fluctuations we suppose that technical progress and food demand are the most influent drivers on the “anthropogenic side”. As the effects of these two drivers are of contrary nature, their combined positive or negative net effect depends on their comparative regional strength. As mentioned above, our model does only allow for interpretations based on individual variables´ results but does not deliver scientific evidence on this subject.

Hypothetically, technical progress slows down water requirements and crop prices. An increase in food demand, as caused by e.g. population growth and/or economic development, leads to increasing food prices and higher land and water requirements.

Generally highest demands for irrigation land and water are simulated under the B1 scenario (see Figure 16), despite lower crop demands compared to the GO scenario. Besides nonetheless high global crop demands the globalized approach of “centralized policies” supposedly enhances irrigated agriculture under B1.

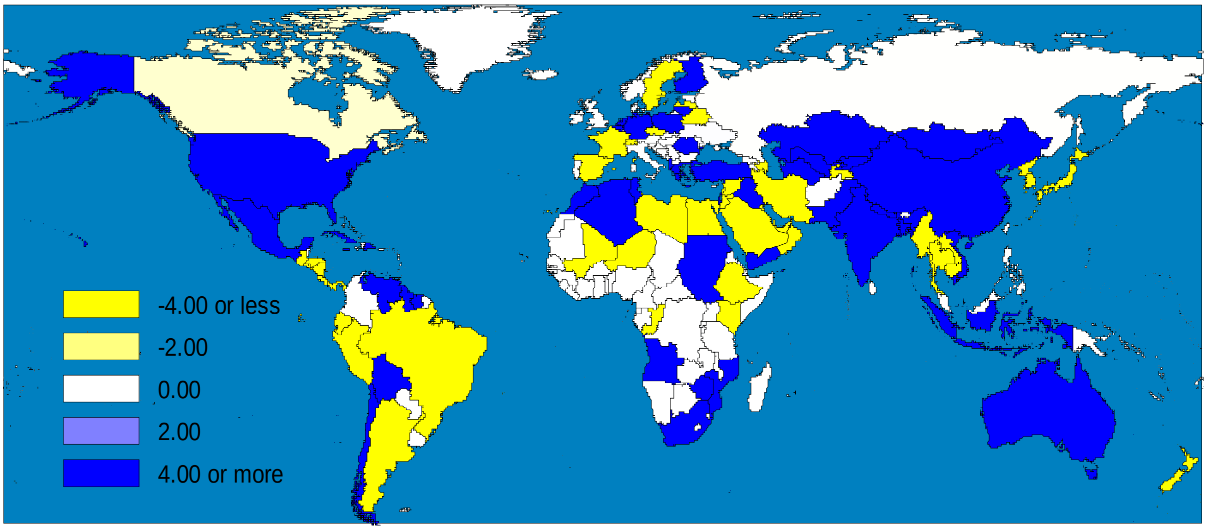

Figure 16: Development scenario B1: Predicted changes in irrigation water use until 2030 under “Free irrigation”

The GO scenario shows the second strongest growth of irrigation land and water use (after B1) if no exogenous restrictions are imposed on its expansion. The particularly high increase in crop demand under GO is likely to be a combined result of generally high economic growth, in particular in formerly poorer (developing) countries, and the “urban prioritization” trend. In addition, a growing integration of developing countries into global trade enhances the establishment of new markets, which in turn may have positive effects not only on the supply but also on the demand side.

Under the OS scenario, simulated global crop consumption is lower in comparison with the other development scenarios, which may be due to generally lower trade connectivity, lower economic development, and even food shortages as linked to regional poverty. Global resource use as well as water use intensity both represent the lowest levels among the development scenarios, which is likely related to the significantly lower projections of food demand for both, crop and livestock products. In addition, a more sustainable agricultural management due to the scenario focus on local to national security promotes a rather extensive use of resources. We also assume that rising poverty in a lot of regions affects global food consumption due to its linkage with lifestyles and diets, e.g. with regard to the low global average demand for livestock products under OS.

Results under the AM scenario with its explicitly ecological approach include a rather high intensity in water use per hectare. One reason may be the comparably lower crop yields, and the relative disadvantages due to the imposition of trade restrictions. Agricultural intensification may also be understood as a strategy to allocate a higher share of land to conservation uses. The overall increasing rates of worldwide irrigation over time are conditioned by the increasing global equity of socioeconomic development standards as favoured by free transfer of knowledge and technology.

With regard to the actual purpose of our study, the assessment of impacts due to the different "irrigation scenarios" is of great importance, not at last with respect to appropriate policy pathways.

Compared to "Free irrigation", a restriction of water use as assumed under "Irrigation 2000" triggers a more efficient and thus more sustainable use of resources at least on short to mid term (see Figures 9 and 10). This can be derived from the fact that global food demands of the same magnitude as under "Free irrigation" are met, but under "Irrigation 2000" less resource quantities are used to achieve this.

Explanations for this are likely to be seen in a triggering of other management strategies than irrigation to enhance crop yields. Under the given restrictions of "Irrigation 2000", the GO development scenario is likely to provide best conditions for a sustainable global balance between food supply and resource use on the long term, as growth rates of water and especially irrigation cropland projections are substantially lower than for the other development scenarios while achieving highest crop supply at the same time. Interestingly, under "Irrigation 2000" the increase rates of irrigation land and water use between 2020 and

2030 show a stronger growth for AM and OS than for B1 and GO, which even implies that (with ongoing restriction of irrigation expansion) irrigation land and water use beyond 2030 will most probably reach its highest values under the AM and OS scenarios (assuming constant trends of the “overall developments”). These trends are depicted in Figures 10 and 12 (see above).

When irrigation is completely ceased, as imposed under “No irrigation”, total cropland is accordingly higher than under “Irrigation 2000” and “Free irrigation” as crop demands have to be met by using a respectively higher amount of rainfed area (see Figures 7, 8, and 17).

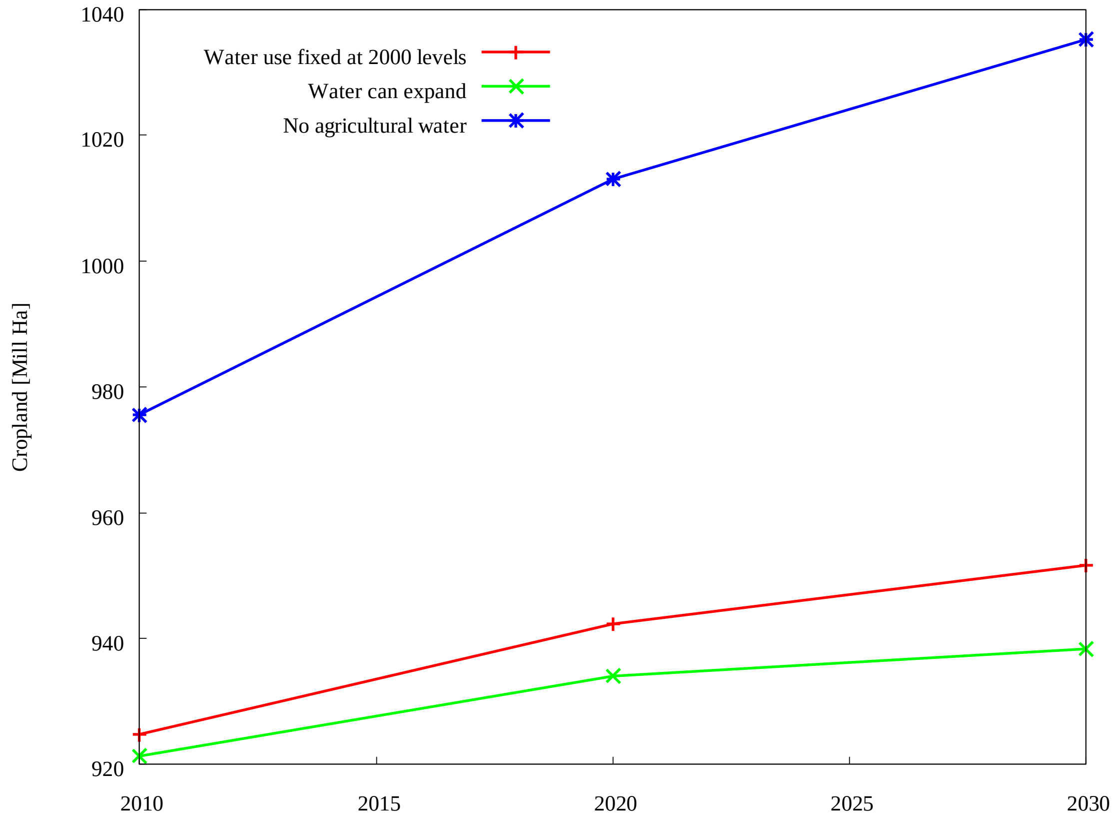

Figure 17: Development scenario GO: Predicted total global cropland area until 2030 under different irrigation scenarios

This increase in total cropland is to some extent mitigated by the simulated partial “substitution” of vegetarian food by animal food products (compare Figure 3).

Increases in food prices are generally strongest under “No irrigation” conditions (see Figure 4). This is most likely because technological standards in agriculture, and thus the potentials of technical progress, are generally lower. Consequently, crop production in many regions is connected with higher “efforts” than under preconditions of having any options to irrigate.

Differences in the relative expansion of total cropland including rainfed area are only rather small between the irrigation scenarios (compare Figures 7 and 8). This indicates a general enhancement of crop yields and rainfed production efficiency.

To assess the “price-impact” of alternative irrigation scenarios, we look at the absolute discrepancies in food price values (see Figures 4 and 5). These are highest under OS and lowest under GO. This indicates that irrigation has the lowest impact on food prices under GO (as probably explained by “optimal food conditions” due to high socioeconomic and technological standards, comprehensive trade interactions, and constantly low population growth), and the highest influence under OS conditions (due to relatively low socioeconomic and technological standards, but constantly high population growth, which emphasizes the importance of crop production for basic food supply).

Most interestingly (as well as surprisingly), simulation results clearly indicate that irrigation has no impact on global total economic surplus. This seems to be confirmed by the only small differences in global food consumption between “No irrigation” and other irrigation scenarios. However, several relativizing aspects can be pointed out in this context:

1.) The global character of such comparative analysis may hide actual effects and relationships occurring on smaller scales.

2.) Complex real-world linkages may undergo distortions when being implemented to large-scale models, as a consequence of abstractions and aggregations. Eventually, the results may depict only one combined net effect resulting from an interdisciplinary range of factors, which most likely is highly sensitive to even small changes in the values of interacting parameters, and even on much smaller scales. This would accordingly embody a high uncertainty of results.

3.) The lacking consideration of further environmental concerns, such as the valuation of recreation and ecosystem functions, the exposure of resources toward degradation, or the environmental impacts due to climatic changes, inhibits a “proper” accountancy for socioeconomic welfare at a whole.

Consequently, due to these uncertainties it seems inadequate to draw a comprehensive global assessment upon the questionable reliability of just one global variable, even though the depicted results appear to be bijective.

Separated from questions on what determinants mostly contribute to sectoral profit maximization or to total economic surplus, we instead want to assess the relative value of irrigation water and cropland in more detail by putting quantitative projections of food demand in relation to resource use. This approach enables us to further derive direct inferences on the future value of irrigation from a more differentiated point of view.

Considering the simulated crop production as the "minimum supply to account for food security" (i.e. global food demand is met in all its regional specifications including different preferences due to socioeconomic status), these food production quantities represent an essential output of the regional economies. We then put global food consumption, in crop-kcal per capita and day, into relation with the respective amounts of irrigation water and land. By doing so, we obtain an indicator that integrates information on food security, socioeconomic development, resource efficiency, and farming profitability. In the following we take a look at this "irrigation value" indicator in the context of different scenarios.

For both, the "Irrigation 2000" and "Free irrigation" runs, the highest values are found under the GO scenario. With regard to "Irrigation 2000" a similar importance of irrigation is detected for the B1 scenario, whereas values are significantly lower under AM and OS. The relative value of irrigation under OS (as the scenario with the lowest numbers) is about 82,5% of the one under OG for each, water and land. Focusing on "Free irrigation", AM and OS present the next highest values after GO. These are in a range of about 89-90% of the GO-results for both, water and land. The relative increase of these indicators over time (2010-2030) is more or less equal under all development scenarios at 6% for water and 11-11,5% for land under "Irrigation 2000", and at 6% for water and 11% for land under "Free irrigation".

However, the definition of "water value", "land value", or "irrigation value" varies by perspective. Looking at rising degradation problems such as depletion and contamination of water resources, and fertility loss of cropland, the picture becomes more differentiated. For example, risks of resource degradation under the GO scenario pose a global challenge according to the narrative storyline, though only rather few people are affected. Under the OS scenario in contrast, exposure toward degradation is considered a rather marginal problem from the global perspective but highly problematic among the fraction of poor countries.

For a valuation of water resources it is a legitimate claim to account for these aspects, and besides it already is common practice in many (watershed-scale) assessments that aim to improve water management (or drought management, respectively). In our study, the risk of degradation is supposed to be lowest under AM but we nevertheless certify the second-highest "value" of irrigation resources to be found under AM as well if irrigation can freely expand. This underlines the need to discuss not only about an optimal economic allocation of resources but also to agree on “common standards” of how to evaluate and “classify” environmental goods. A general conclusion could be that the science of environmental and resource economics should be integrated even more emphatically into the complex issues of “land use modeling” (as a compartment of “earth system modeling”). Surely the problem of scientific complexity inhibits any “all-embracing analysis”. But in our opinion even the very recognition of these interrelations is an important step forward to improve modeling and integrated assessments of land and water use.

IV / 8. Conclusions

Population growth and economic development increase demand for food and irrigation water. Changes in consumption patterns toward more water-intense agricultural products additionally affect regional and international water balances. Growing non-agricultural water and land demands decrease the availability of these resources for agriculture. Our simulation results indicate globally rising increase rates in water and land use around 2020, which we assume to be related to mainly changing food demand and consumption pattern as a combined consequence of population growth from the former period and economic development actually “becoming effective”. This economically motivated effect outbalances global concerns of sustainability, however supported by the fact that the large-scale resolution of our model´s resource-availability restriction is mainly not binding yet.

Food prices, and thus crop prices, are in direct interaction with farm decisions on crop and (irrigation or rainfed) management choice. However, with regard to irrigation land and water use these mechanisms become more complex, as further (e.g., biophysical and political) factors may play a role. To explain model results in more detail, simple thumb rules such as “high food demand leads to high water use and high crop prices” or “high technical progress decreases agricultural water demand” on the contrary, are often not sufficient.

In general, simulation results of growing water intensity do not necessarily imply negative conclusions, as this may be accompanied by substantial technological improvements. It thus may also express the strategy of using a relatively lesser amount of land at increased management intensities to increase overall productivity, i.e. due to a shift from rainfed to irrigated agriculture in favour of “releasing” cropland resources from agricultural uses.

In turn, simulated potentials of “global sustainability” have to be interpreted with care. Underlying causes that lead to these results may be, e.g. due to discrepancies between rich and poor countries. Consequently a resulting global sustainability does not necessarily mean regional sustainability, and thus may not be automatically considered an “optimal environmental solution”.

Important findings from our study include that globalization tends to enhance economic and technical development, while leading to relatively stable food prices. Irrigation decisions have only a low impact on food prices and on regional economies in general. Overall this indicates a relatively low value (or importance) of irrigation.

Decentralization in turn seems to relatively hinder (global) economic development, leading to a lower stability of food prices, and of resource-use balances in general. On the long term, resource demands are projected to potentially even get out of proportion. Irrigation decisions have a relatively higher impact on prices and are of greater importance for food security. These developments may be further intensified when being accompanied by strong population growth.

The application of different irrigation scenarios turned out to be of high relevance with regard to policy concerns. Interpretations of our results overall indicate positive potentials of (policy-) regulations by means of environmental, economic, and institutional instruments. A restriction of water use as assumed under “Irrigation 2000” triggers a more efficient and thus more sustainable use of resources. Additionally, the adoption of further improved management strategies (other than irrigation) to enhance crop yields is triggered as well. “Free irrigation” in turn leads to comparably higher absolute numbers under all development scenarios and importantly also to higher increase rates in the long term. This implies that a “free expansion” in terms of an unrestricted choice to, e.g. shifts between crop types and irrigation managements, does not enhance improvements of resource use efficiency in a “self-regulating” manner at all.

These findings provide useful basics for considerations of policy-based regulations, e.g. targeting at improvements of sustainable development. Nevertheless a successful implementation of such policies may further also depend on institutional structures, as well as on the potentials of knowledge and technology transfer.

Simulation results indicate a general enhancement of production efficiency in rainfed agriculture, even close to potentially measure up with irrigated agriculture. This gets somewhat confirmed by the finding that for our “irrigation value” indicator increase rates are in general significantly higher per unit of land than per unit of water. Nevertheless, “No irrigation” still forces a higher demand for (rainfed) cropland, as well as a decent shift from vegetarian to animal food consumption.

Generally, a future expansion of irrigation is projected to rather lose importance, with regard to food security, as well as for socioeconomic welfare gains. Simulation results on global total economic surplus reveal that irrigation does not significantly tribute to (macro-) economic welfare. Under the current model specifications, our results imply that monetary welfare gains, in terms of total economic surplus, are “decoupled” of irrigation decisions. When neglecting quantitative resource degradation, and under the given resource availability constraints (both as applied in our current model simulations), alternative irrigation scenarios do not affect economic development, but though most likely have an impact on sustainability concerns.

By analyzing the interdependencies resulting from the combination of irrigation and development-scenarios, we conclude that conditions as represented by the GO development-scenario are likely to embody the best conditions for a sustainable global balance between food supply and resource use on the long term, in particular under agricultural restrictions as imposed by the “Irrigation 2000” irrigation-scenario. Under GO we find the lowest (economic) dependency on irrigation, and accordingly the highest flexibility for “food production adaptations”. Though portraying a great potential for an “integrated sustainability” of economic growth and resource balance on global scale, one also has to consider severe environmental problems in some regions, which in turn are contradictive to “real-sustainability” and equity goals. In accordance with the GO-storyline we assume that this (partial) rise of inequality may eventually become a concern of global interest.

As a “counterpart” to the globalized GO scenario, the AM scenario with its explicit focus on environmental policies is predicted to be successful on short to mid-term, in terms of highly efficient irrigation water use (regarding both, sustainability and welfare effects), in conjunction with “minimized” degradation impacts. But importantly, on the long-term we simulate a high increase in resource use, supposedly to even grow out of proportion beyond 2030. This implies that initial sustainability and welfare effects may be of unstable nature. With respect to its scenario-storyline, occurring problems of resource degradation emphasize the conclusion that the AM development-scenario succeeds on short-term but tends to “fail” on long-term.

As shown, our comparison of the global state in food production and resource usage in 2030 under different scenario combinations enables conclusions on the future value of irrigation. With this study we want to provide scientific basics to support agricultural policies and appropriate measures for a well-balanced global development of economic and ecological concerns. We regard this target to be one basic condition for a sustainable functioning of the earth system in the long-term.

Our conclusions stem from an objective comparison of simulation results from a global PEM, which are computed using consistent datasets of recoverable origin. However, deficits with regard to data availability, temporal resolutions, and in particular spatial scales of our present analysis always have to be considered when evaluating the results.

Though it seems utopian to derive “best practices” or “safe policies” advice from such large-scale modeling efforts on irrigation methods, it is worthwhile to use them for an estimation of global trends to help providing a reasonable scientific basis for policy making.

A further outcome of our study is the research question on the advantages and disadvantages of the trade-offs described above: Does the expansion of rainfed land under supposedly higher management intensity reduce or enhance the risk of resource degradation, in direct comparison with a smaller but intensely irrigated amount of agricultural cropland? The irrigation-option may also set free land for other land use type, including biodiversity conservation. Within this study, the question of degradation risks and potentials to mitigate them with respect to a “competition” between rainfed and irrigated agriculture remains unanswered, and thus poses a challenge for further studies.

References

AgEBB (Agricultural Electronic Bulletin Board, Missouri) (2006), SEMO Crop Budget 2006, Missouri Irrigation Economics (University of Missouri Extension Southeast Missouri), Missouri. (http://agebb.missouri.edu/irrigate/economics/ index.htm).

Alcamo, J., M. Maerker, M. Floerke, and S. Vassolo (2003), Water and Climate: A Global Perspective, *Kassel World Water Series 6*, Center for Environmental Systems Research, University of Kassel, Germany.

Alexandratos, N., J. Bruinsma, G. Boedeker, J. Schmidhuber, S. Broca, B. Shetty, and M. G. Ottaviani (Eds.) (2006), World agriculture: towards 2030/2050 - Prospects for food, nutrition, agriculture and major commodity groups, FAO, Global Perspective Studies Unit, Rome.

Arnell, N. W. (1999), Climate change and global water resources, *Global Environmental Change, 9,* 31-49.

Arnell, N. W. (2004), Climate change and global water resources: SRES emissions and socio-economic scenarios, *Global Environmental Change, 14,* 31-52.

Beadle, C. L., and S. P. Long (1985), Photosynthesis - is it limiting to biomass production?, *Biomass, 8*, 119-168.

Bouwer, H. (2000), Integrated water management: emerging issues and challenges, *Agricultural Water Management, 45*, 217-228.

Bouwman, A. F., T. Kram, and K. Klein Goldewijk (Eds.) (2006), Integrated modelling of global environmental change - An overview of IMAGE 2.4, Netherlands Environmental Assessment Agency (MNP), Bilthoven.

Brouwer, C., K. Prins, M. Kay, and M. Heibloem (1988), Irrigation Water Management: Irrigation Methods, *FAO Irrigation Water Management Training manual no 5*.

Bruinsma, J. (Ed.) (2003), World agriculture: towards 2015/2030 – An FAO Perspective, FAO, Rome, and Earthscan Publications Ltd, London.

Buchanan, J. R., and T. L. Cross (Eds.) (2002), *Irrigation Cost Analysis Handbook,* Agricultural Extension Service, The University of Tennessee, PB1721.

Bugbee, B. G., and F. B. Salisbury (1988), Exploring the Limits of Crop Productivity: I. Photosynthetic Efficiency of Wheat in High Irradiance Environments, *Plant Physiology, 88*, 869-878.

Calzadilla, A., K. Rehdanz, and R. S. J. Tol (2010), The economic impact of more sustainable water use in agriculture: A computable general equilibrium analysis, *Journal of Hydrology, 384*, 292-305.

Clemmens, A. J., and D. J. Molden (2007), Water uses and productivity of irrigation systems, *Irrigation Science, 25*, 247-261.

Cornish, G. A., and C. J. Perry (2003), Water Charging in Irrigated Agriculture – Lessons from the Field, *Department for International Development (DFID), Report OD 150*, HR Wallingford.

Cowie, A., U. A. Schneider, and L. Montanarella (2007), Potential synergies between existing multilateral environmental agreements in the implementation of land use, land-use change and forestry activities, *Environmental Science & Policy, 10*, 335-352.

Demographia (2006), World Urban Population Density by Country & Area. (http://www.demographia.com/db-intlua-area2000.htm).

Doell, P., and S. Siebert (2002), Global modeling of irrigation water requirements, *Water Resources Research, 38(4), 8-1–8-10*, doi: 10.1029/2001WR000355.

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

Easter, K. W., and Y. Liu (2005), Cost Recovery and Water Pricing for Irrigation and Drainage Projects, *Agriculture and Rural Development Discussion Paper 26*, The International Bank for Reconstruction and Development / The World Bank, Washington DC.

EIA (Energy Information Administration) (2006), International Energy Annual (IEA) 2004 – long-term historical international energy statistics, Official Energy Statistics from the U.S. Government. (http://www.eia.doe.gov/iea/).

Falkenmark, M., and M. Lannerstad (2005), Consumptive water use to feed humanity – curing a blind spot, *Hydrology and Earth System Sciences, 9(1/2)*, 15-28.

FAO (Food and Agriculture Organization) (2000), FAOSTAT CD 2000, FAO Statistical Databases, U.N., Rome.

FAO (Food and Agriculture Organization) (2004), FAOSTAT CD 2004, FAO Statistical Databases, U.N., Rome.

FAO (Food and Agriculture Organization) (2007a), FAOSTAT online database: ProdSTAT-Crops, U.N., Rome. (http://faostat.fao.org/site/567/default.aspx).

FAO (Food and Agriculture Organization) (2007b), FAOSTAT online database: ResourceSTAT-Land, U.N., Rome. (http://faostat.fao.org/site/377/default.aspx).

FAO (Food and Agriculture Organization) (2009), FAOSTAT online database. (http://faostat.fao.org).

FAO Land and Water Development Division (2008), AQUASTAT Information System on Water and Agriculture Database, U.N., Rome. (http://www.fao.org/nr/water/aquastat/main/index.stm).

Fischer, G., H. van Velthuizen, M. Shah, and F. Nachtergaele (2002), Global Agro-ecological Assessment for Agriculture in the 21st Century: Methodology and Results, International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria, & FAO, Rome.

Foley, J. A., R. De Fries, G. P. Asner, C. Barford, G. Bonan, S. R. Carpenter, F. S. Chapin, M. T. Coe, G. C. Daily, H. K. Gibbs, J. H. Helkowski, T. Holloway, E. A. Howard, C. J. Kucharik, C. Monfreda, J. A. Patz, I. C. Prentice, N. Ramankutty, and P. K. Snyder (2005), Global Consequences of Land Use. *Science, 309,* 570-574.

Gardner, G. (1998), Irrigated Area Up Slightly, *In: Brown, L. R., M. Renner, C. Flavin, and L. Starke (Eds.) (1998), Vital Signs 1998 – The Environmental Trends That Are Shaping Our Future,* Worldwatch Institute, New York, 46-48.

Gleick, P. H. (2000), The World´s Water 2000-2001, *The Biennial Report on Freshwater Resources*, Island Press, Washington DC.

Havlík, P., U. A. Schneider, E. Schmid, H. Boettcher, S. Fritz, R. Skalský, K. Aoki, S. de Cara, G. Kindermann, F. Kraxner, S. Leduc, I. McCallum, A. Mosnier, T. Sauer, and M. Obersteiner (2010), Global land-use implications of first and second generation biofuel targets, *Energy Policy (in press)*, doi:10.1016/j.enpol.2010.03.030.

Heistermann, M., C. Mueller, and K. Ronneberger (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.

Hightower, M., and S. A. Pierce (2008), The energy challenge, *Nature, 452*, 285-286.

Howe, C. W. (1979), *National Resource Economics*, John Wiley and Sons, Inc., New York

Hussain, I. (2007), Direct and indirect benefits and potential disbenefits of irrigation: evidence and lessons, *Irrigation and Drainage, 56,* 179-194.

ICID (International Commission on Irrigation and Drainage) (2008), ICID Database. (http://www.icid.org/).

Iglesias, E., and M. Blanco (2008), New directions in water resources management: The role of water pricing policies, *Water Resources Research, 44, W06417,* doi:10.1029/2006WR005708.

IIASA (International Institute for Applied Systems Analysis) (2000), Global Agro-Ecological Zones (GAEZ), Laxenburg, Austria. (http://www.iiasa.ac.at/Research/LUC/GAEZindex.htm).

IIASA (International Institute for Applied Systems Analysis) (2005), EMF-22 Land and BC/OC subgroup initial scenarios exercise 12-14-05, Laxenburg, Austria.

IIASA (International Institute for Applied Systems Analysis) (2008), GGI Scenario Database. (http://www.iiasa.ac.at/Research/GGI/DB/).

IMF (International Monetary Fund) (2007), World Economic Outlook Database, April 2007 Edition. (http://imf.org/external/pubs/ft/weo/2007/01/data/ index.aspx).

IPCC (Intergovernmental Panel on Climate Change) (2000), IPCC Special Report Emission Scenarios: Summary for Policymakers, *A Special Report of IPCC Working Group III*.

ISI (Institute for Scientific Information) / Thomson Reuters (Thomson Scientific), ISI Web of Knowledge / Web of Science. (http://www.isiknowledge.com).

Izaurralde, R. C., J. R. Williams, W. B. McGill, N. J. Rosenberg, and M. C. Q. Jakas (2006), Simulating soil C dynamics with EPIC: model description and testing against long-term data, *Ecological Modelling, 192*, 362-384.

Johansson, R. C., Y. Tsur, T. L. Roe, R. Doukkali, and A. Dinar (2002), Pricing irrigation water: a review of theory and practice, *Water Policy, 4(2)*, 173-199.

Khan, S., A. Abbas, H. F. Gabriel, T. Rana, and T. Robinson (2007), Hydrologic and economic evaluation of water-saving options in irrigation systems, *Irrigation and Drainage, 57*, 1-14.

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

Liu, J., A. J. B. Zehnder, and H. Yang (2009), Global consumptive water use for crop production: the importance of green water and virtual water, *Water Resources Research, 45, W05428,* doi: 10.1029/2007WR006051.

Lobell, D. B., M. B. Burke, C. Tebaldi, M. D. Mastrandrea, W. P. Falcon, and R. L. Naylor (2008), Prioritizing Climate Change Adaptation Needs for Food Security in 2030, *Science, 319*, 607-610.

Lotze-Campen, H., C. Mueller, A. Bondeau, P. Smith, and W. Lucht (2005), How tight are the limits to land and water use? – Combined impacts of food demand and climate change, *Advances in Geosciences, 4*, 23-28.

Lundqvist, J., C. de Fraiture, D. Molden, G. Berndes, A. Berntell, M. Falkenmark, H. Holmen, L. Karlberg, and M. Lannerstad (2008), Saving Water: From Field to Fork – Curbing Losses and Wastage in the Food Chain (Draft for CSD, May 2008), *SIWI Paper 13*, Stockholm International Water Institute.

Massarutto, A. (2003), Water Pricing and Irrigation Water Demand: Economic Efficiency versus Environmental Sustainability, *European Environment*, *13*, 100-119.

McCarl, B. A., and T. H. Spreen (1980), Price Endogenous Mathematical Programming as a Tool for Sector Analysis, *American Journal of Agricultural Economics, 62*, 87-102.

Metschies, G. P. (Ed.) (2005), *International Fuel Prices 2005*, 4th Edition - 172 Countries, Deutsche Gesellschaft fuer Technische Zusammenarbeit (GTZ) / Federal Ministry for Technical Cooperation and Development, Germany (BMZ).

Millennium Ecosystem Assessment (MA) (2003), *Ecosystems and Human Well-being: A Framework for Assessment*, Island Press, Washington DC. (http://www.millenniumassessment.org/en/Framework.aspx).

Milly, P. C. D., J. Betancourt, M. Falkenmark, R. M. Hirsch, Z. W. Kundzewicz, D. P. Lettenmaier, and R. J. Stouffer (2008), Stationary is dead: Whither Water Management?, *Science*, *319*, 573-574.

Molden, D. (Ed.) (2007), Water for food, water for life: A comprehensive assessment of water management in agriculture, Earthscan, London and Int. Water Manage. Inst., Colombo.

Muralidharan, D., and K. C. Knapp (2009), Spatial dynamics of water management in irrigated agriculture, *Water Resources Research, 45, W05411,* doi:10.1029/2007WR006756.

Oki, T., and S. Kanae (2006), Global Hydrological Cycles and World Water Resources, *Science, 313,* 1068-1072.

Paul, N. (Ed.) (1997), Irrigation Technology Transfer in Support of Food Security (Proceedings of a subregional workshop in Harare, Zimbabwe, 14-17 April 1997), *FAO Water Reports – 14*.

Perry, C. J. (2001), Water at any price? Issues and options in charging for irrigation water, *Irrigation and Drainage, 50(1)*, 1-7.

Phocaides, A. (Ed.) (2000), *Technical Handbook on Pressurized Irrigation Techniques*, FAO, Rome.

Postel, S. L. (1998), Water for Food Production: Will There Be Enough in 2025, *BioScience, 48(8)*, 629-637.

Ramankutty, N., J. A. Foley, J. Norman, and K. McSweeney (2002), The global distribution of cultivable lands: current patterns and sensitivity to possible climate change, *Global Ecology & Biogeography, 11*, 377-392.

Reinbott, D. (2005), Irrigation Investment and Ownership Cost, Missouri Irrigation Economics (University of Missouri Extension Southeast Missouri), Agricultural Electronic Bulletin Board (AgEBB), Missouri. (http://agebb.missouri.edu/irrigate/economics/index.htm).

Rijsberman, F. R. (2006), Water Scarcity: Fact or Fiction?, *Agricultural Water Management, 80(1-3),* 5-22.

Rockstroem, J., C. Folke, L. Gordon, N. Hatibu, G. Jewitt, F. Penning de Vries, F. Rwehumbiza, H. Sally, H. Savenije, and R. Schulze (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.

Rockstroem, J., M. Falkenmark, L. Karlberg, H. Hoff, S. Rost, and D. Gerten (2009), Future water availability for global food production: The potential of green water for increasing resilience to global change, *Water Resources Research, 45, W00A12,* doi: 10.1029/2007WR006767.

Rosegrant, M. W., X. Cai, and S. A. Cline (2002), World Water and Food to 2025: Dealing with Scarcity, International Food Policy Research Institute, Washington DC Mimeo.

Russ, P., T. Wiesenthal, D. van Regenmorter, and J. C. Císcar (2007), Global climate policy scenarios for 2030 and beyond: Analysis of greenhouse gas emission reduction pathway scenarios with the POLES and GEM-E3 models, *JRC reference report EUR 23032 EN*, Joint Res. Cent., Inst. for Prospective Technol. Stud., Seville, Spain, doi: 10.2791/576.

Sauer, T. (2009), Exploring irrigation literature – a framework to assess agricultural water use, *submitted to Irrigation and Drainage*.

Sauer, T., P. Havlík, U. A. Schneider, E. Schmid, G. Kindermann, and M. Obersteiner (2010), Agriculture and resource availability in a changing world: the role of irrigation, *Water Resources Research, 46, W06503*, doi:10.1029/2009WR007729.

Schneider U. A., P. Havlík, E. Schmid, M. Obersteiner, T. Sauer, R. Skalský, and S. Fritz (2010), Food production impacts of alternative global development scenarios, *submitted to Agricultural Systems*.

Seale, J., A. Regmi, and J. Bernstein (2003), International Evidence on Food Consumption Patterns. *ERS / USDA, Technical Bulletin No. 1904*, ERS / USDA, Washington DC.

Seckler, D., U. Amarasinghe, D. Molden, R. de Silva, and R. Barker (1998), World Water Demand and Supply 1990 to 2025: Scenarios and Issues, *IWMI Research Reports – 19,* International Water Management Institute, Colombo, Sri Lanka.

Shiklomanov, I. A. (2000), Appraisal and assessment of world water resources, *Water International, 25(1),* 11-32.

Siebert, S., and P. Doell (2007), Irrigation water use: A global perspective, *In: Global Change: Enough Water for All?, edited by J. L. Lozan et al.*, pp. 104-107, Wiss. Auswertungen / GEO-Verlag, Hamburg.

Simonovic, S. P. (2002), World water dynamics: global modelling of water resources, *Journal of Environmental Management, 66,* 249-267.

Skalský, R., Z. Tarasovičová, J. Balkovič, E. Schmid, M. Fuchs, E. Moltchanova, G. Kindermann, and P. Scholtz (2008), Geo-bene global database for bio-physical modeling v. 1.0 (Concepts, methodologies and data), *Geo-bene Public Research Documents / IIASA Technical report,* Laxenburg, Austria. (http://www.geo-bene.eu/?q=node/1734).

Tilman, D., K. G: Cassman, P. A. Matson, R. Naylor, R., and S. Polasky (2002), Agricultural sustainability and intensive production practises, *Nature, 418,* 671-677.

Tilman, D., J. Fargione, B. Wolff, C. D´Antonio, A. Dobson, R. Howarth, D. Schindler, W. H. Schlesinger, D. Simberloff, and D. Swackhamer (2001), Forecasting agriculturally driven Global Environmental Change, *Science, 292*, 281-284.

Turner, J. H., and C. L. Anderson (Eds.) (1980), *Planning for an Irrigation System*, American Association for Vocational Instructional Materials, Engineering Center, Athens, Georgia.

UNDP (United Nations Development Programme) (2000), Human Development Report 2000, Oxford University Press, New York.

UNSD (United Nations Statistics Division) (2009), UNdata online database. (http://data.un.org).

USDA-NRCS (U.S. Department of Agriculture, Natural Resources Conservation Service) (2007), Energy Consumption Awareness Tool: Irrigation. (http://ipat.sc.egov.usda.gov/Help.aspx).

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

Voeroesmarty, C. J., P. Green, J. Salisbury, and R. B. Lammers (2000), Global Water Resources: Vulnerability from Climate Change and Population Growth, *Science, 290,* 284-288.

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

Wallace, J. S., and P. J. Gregory (2002), Water resources and their use in food production systems, *Aquatic Sciences*, *64*, 363-375.

Wichelns, D., and J. D. Oster (2006), Sustainable irrigation is necessary and achievable, but direct costs and environmental impacts can be substantial, *Agricultural Water Management, 86*, 114-127.

Williams, J. R. (1995), The EPIC Model, *In: Singh, V. P. (1995), Computer Models of Watershed Hydrology,* Water Resources Publications, Highlands Ranch, Colorado, 909-1000.

World Bank (2006), World Development Indicators 2006, Washington, DC. (http://devdata.worldbank.org/wdi2006/contents/home.htm).

You, L., and S. Wood (2006), An entropy approach to spatial disaggregation of agricultural production, *Agricultural Systems, 90,* 329-347.

Synthesis

This PhD thesis is about the implementation of irrigation concerns into a global integrated land use model. The main purpose behind this model extension was to analyze and quantify the complex feedbacks between irrigation decisions, technologies, agricultural markets, and resources, which may occur in combined form across different scales. One major research question was what land-use strategies or policies would be appropriate to mitigate problems of resource scarcity while at the same time striving to meet the overall targets of global food security and societal welfare. The integration of explicit irrigation systems in their particular biophysical, economic, and technical context into a global partial equilibrium model of the agricultural and forestry sectors is an innovative approach to improve large scale assessments of land use change. The linkage of the heterogeneity of irrigation techniques and natural resources with micro and macro-economic drivers is, to my knowledge, a unique feature in global land use modeling. It is given relevance due to the existing major differences in suitability and costs of irrigation systems, which previous global studies have neglected.

The first two parts of the dissertation are of rather theoretical, or respectively qualitative, nature whereas the remaining two parts are describing practical applications of the model to obtain quantitative insights on questions of global irrigation water use.

The objective of the first chapter was to create a helpful framework to facilitate research on irrigation topics by developing a tool to classify and assess relevant information for "irrigation questions". The second chapter presents a qualitative assessment in terms of hypotheses on interdependencies betweens irrigation factors that could not be implemented into the current model. In conjunction with the limited time schedule, problems of scale and the non-linearity of functional interdependencies between parameters, as well as the "non-proportionality" of such interdependencies with regard to regional differences, prohibited their integration into the model at current stage.

Both chapters point out the complexity of irrigation factors and their linkages, and the interdisciplinary, multi-level character of irrigation science. Consequently the purpose and expedience of using integrated assessment models becomes emphasized.

For the quantitative analyses, the GLOBIOM model was extended by a newly developed irrigation module, and applied to conduct two studies of different approaches. They both have in common that they deal with the valuation of future irrigation managements from a global perspective.

The first study represents a “scarcity approach” by studying the effects triggered by an artificial lowering of land and water availability. This is done for one development scenario only, but with the possibility of changes in the supply of water and cropland for agriculture. The second study employs a “water-productivity approach”, as water-related productivity of irrigated agriculture and welfare gains are analyzed, under different combinations of development and irrigation scenarios. Due to the different scenario assumptions, this approach has a stronger policy focus.

Important findings include that the option of alternative irrigation system choice becomes reflected in the global demand for irrigation water in terms of increased water use efficiency when water becomes scarce.

Both studies emphasize the importance of global technology transfer, which in turn again may be enhanced by means of policy interventions.

Against a scenario-induced background of globalization the global enhancement of economic and technical development and market interactions leads to relatively high increase of irrigation land and water use, and to comparably stable food prices. However, irrigation-decision-making “itself” in turn only has low impact on food prices and on regional economic concerns in general. In contrast more decentralization-focused scenarios, which rather slow down global economic development, lower the stability of food prices and resource-use balance. On the long-term resource demands are projected to potentially increase substantially. Irrigation-decisions themselves have a relatively higher impact on prices and are of greater importance for food security. When irrigation is completely ceased, total cropland is accordingly higher and increases in food prices are generally stronger.

The assessment of different irrigation-scenario impacts indicates that policy interventions, in terms of regulations due to environmental, economic, and institutional-based regulation, can be effective means to support targets of socioeconomic stability, ecological sustainability, and food security. Restrictions on irrigation are likely to trigger a more efficient use of resources. Additionally, the adoption of improved management strategies other than irrigation to enhance crop yields is triggered as well. Unrestricted “free irrigation” in turn may lead to higher relative and absolute increase of resource-use in general. Simulation results imply that an unrestricted expansion in terms of a free choice to e.g., shifts between crop types and irrigation managements does not enhance improvements of resource-use efficiency in a “self-regulating” manner at all.

The model does not simulate any impact of irrigation decisions on global total economic surplus. However, we assume that a consideration of environmental degradation impacts, which are neglected in the current studies, would most likely deliver more diverse results.

Conditions as represented by the GO development scenario are likely to embody the best conditions for a sustainable global balance between food supply and resource use on the long-term, in particular under agricultural restrictions as imposed by the “Irrigation 2000” irrigation-scenario. Under GO we find the lowest (economic) dependency on irrigation, and accordingly the highest flexibility for “food production adaptations”. However, simulated potentials of “global sustainability” have to be interpreted with care. Underlying causes that lead to these results may be, e.g. due to discrepancies between rich and poor countries. Consequently a resulting global sustainability does not necessarily mean regional sustainability, and thus may not be automatically considered an “optimal environmental solution”. As a “counterpart” to the globalized GO scenario, the AM scenario with its explicit focus on environmental policies is predicted to be successful only on short to mid-term, in terms of efficient irrigation water use. In contrary, on the long-term the initial sustainability and welfare-effects appear to be of unstable nature.

Concluding, the definition of “water value”, “land value”, or “irrigation value” differs with the point of view, i.e. whether one approaches from an economic, social, or ecological perspective. Within the presented studies, research questions on degradation impacts and potentials to mitigate them with respect to agricultural management options remain unanswered, and thus pose a challenge for further studies.

APPENDIX

Appendix–1

Formal description of GLOBIOM

Variables

D	demand quantity [tonnes, m3, kcal]
W	irrigation water consumption [m3]
Q	land use/cover change [ha]
A	land in different activities [ha]
B	livestock production [kcal]
P	processed quantity of primary input [tonnes, m3]
T	inter-regionally traded quantity [tonnes, m3, kcal]
E	greenhouse gas emissions [tCO2eq]
L	available land [ha]

Functions

φ^{demd}	demand function (constant elasticity function)
φ^{splw}	water supply function (constant elasticity function)
φ^{lucc}	land use/cover change cost function (linear function)
φ^{trad}	trade cost function (constant elasticity function)

Parameters

τ^{land} land management cost except for water [$ / ha]

τ^{live} livestock production cost [$ / kcal]

τ^{proc} processing cost [$ / unit (t or m3) of primary input]

τ^{emit} potential tax on greenhouse gas emissions [$ / tCO2eq]

d^{targ} exogenously given target demand (e.g. biofuel targets) [EJ, m3, kcal,…]

α^{land} crop and tree yields [tonnes / ha, or m3 / ha]

α^{live} livestock technical coefficients (1 for livestock calories, negative number for feed requirements [t/kcal])

α^{proc} conversion coefficients (-1 for primary products, positive number for final products [e.g. GJ/m3])

L^{init} initial endowment of land of given land use / cover class [ha]

L^{suit} total area of land suitable for particular land uses / covers [ha]

ω irrigation water requirements [m3/ha]

ε^{land}, ε^{live}, ε^{proc}, ε^{lucc} emission coefficients [tCO2eq/unit of activity]

Indexes

r	economic region (27 aggregated regions and individual countries)
t	time period (10 years steps)
c	country (203)
o	altitude class (0 – 300, 300 – 600, 600 – 1100, 1100 – 2500, > 2500, in meter above see level)
p	slope class (0 – 3, 3 – 6, 6 – 10, 10 – 15, 15 – 30, 30 – 50, > 50, in degree)
q	soil class (sandy, loamy, clay, stony, peat)
l	land cover/use type (cropland, grassland, managed forest, fast growing tree plantations, pristine forest, other natural vegetation)
s	species (37 crops, managed forests, fast growing tree plantations)
m	technologies: land use management (low input, high input, irrigated, subsistence, "current"), primary forest products transformation (sawnwood and woodpulp production), bioenergy conversion (first generation ethanol and biodiesel from sugar cane, corn, rapeseed and soybeans, energy production from forest biomass – fermentation, gasification, and CHP)
y	outputs (primary: 37 crops, sawlogs, pulplogs, other industrial logs, fuel wood, plantations biomass, processed products: forest products (sawnwood and woodpulp), first generation biofuels (ethanol and biodiesel), second generation biofuels (ethanol and methanol), other bioenergy (power, heat and gas)
e	greenhouse gas accounts: CO2 from land use change, CH4 from enteric fermentation, rice production, and manure management, and N2O from synthetic fertilizers and from manure management

I. Objective function

$$\text{Max } WELF_t = \begin{aligned}[t] &+\sum_{r,y}\left[\int \varphi^{demd}_{r,t,y}\left(D_{r,t,y}\right)\mathrm{d}(\cdot)\right]-\sum_{r}\left[\int \varphi^{splw}_{r,t}\left(W_{r,t}\right)\mathrm{d}(\cdot)\right] \\ &-\sum_{r,l,\tilde{l}}\left[\int \varphi^{lucc}_{r,l,\tilde{l},t}\left(\sum_{c,o,p,q} Q_{r,t,c,o,p,q,l,\tilde{l}}\right)\mathrm{d}(\cdot)\right] \\ &-\sum_{r,c,o,p,q,l,s,m}\left(\tau^{land}_{c,o,p,q,l,s,m}\cdot A_{r,t,c,o,p,q,l,s,m}\right) \\ &-\sum_{r}\left(\tau^{live}_{r}\cdot B_{r,t}\right)-\sum_{r,m}\left(\tau^{proc}_{r,m}\cdot P_{r,t,m}\right) \\ &-\sum_{r,\tilde{r},y}\left[\int \varphi^{trad}_{r,\tilde{r},t,y}\left(T_{r,\tilde{r},t,y}\right)\mathrm{d}(\cdot)\right] \\ &-\sum_{r,e}\left(\tau^{emit}_{t,e}\cdot E_{r,t,e}\right) \end{aligned} \tag{1}$$

Exogenous demand constraints

$$D_{r,t,y} \geq d^{targ}_{r,t,y} \tag{2}$$

II. Product balance

$$D_{r,t,y} \leq \sum_{c,o,p,q,l,s,m}\left(\alpha^{land}_{t,c,o,p,q,l,s,m,y}\cdot A_{r,t,c,o,p,q,l,s,m}\right)+\alpha^{live}_{r,t,y}\cdot B_{r,t}+\sum_{m}\left(\alpha^{proc}_{r,m,y}\cdot P_{r,t,m}\right)+\sum_{\tilde{r}} T_{\tilde{r},r,t,y}-\sum_{\tilde{r}} T_{r,\tilde{r},t,y} \tag{3}$$

III. Land use balance

$$\sum_{s,m} A_{r,t,c,o,p,q,l,s,m} \leq L_{r,t,c,o,p,q,l} \tag{4}$$

$$L_{r,t,c,o,p,q,l} \leq L^{init}_{r,t,c,o,p,q,l} + \sum_{\tilde{l}} Q_{r,t,c,o,p,q,\tilde{l},l} - \sum_{\tilde{l}} Q_{r,t,c,o,p,q,l,\tilde{l}} \tag{5}$$

$$Q_{r,t,c,o,p,q,l,\tilde{l}} \leq L^{suit}_{r,t,c,o,p,q,l,\tilde{l}} \tag{6}$$

recursivity equations (calculated only once the model has been solved for a given period)

$$L^{init}_{r,t,c,o,p,q,l} = L^{init}_{r,t-1,c,o,p,q,l} + \sum_{\tilde{l}} Q_{r,t-1,c,o,p,q,\tilde{l},l} - \sum_{\tilde{l}} Q_{r,t-1,c,o,p,q,l,\tilde{l}} \tag{7}$$

$$L^{suit}_{r,t,c,o,p,q,l,\tilde{l}} = L^{suit}_{r,t-1,c,o,p,q,l,\tilde{l}} + \sum_{\tilde{l}} Q_{r,t-1,c,o,p,q,\tilde{l},l} - \sum_{\tilde{l}} Q_{r,t-1,c,o,p,q,l,\tilde{l}} \tag{8}$$

IV. Irrigation water balance

$$\sum_{c,o,p,q,l,s,m} \left(\varpi_{c,l,s,m} \cdot A_{r,t,c,o,p,q,l,s,m} \right) \leq W_{r,t} \tag{9}$$

V. GHG emissions account

$$E_{r,t,e} = \sum_{c,o,p,q,l,s,m} \left(\varepsilon^{land}_{c,o,p,q,l,s,m,e} \cdot A_{r,t,c,o,p,q,l,s,m} \right) + \varepsilon^{live}_{r,e,t} \cdot B_{r,t} + \sum_{m} \left(\varepsilon^{proc}_{r,m,e} \cdot P_{r,t,m} \right) + \sum_{c,o,p,q,l,\tilde{l}} \left(\varepsilon^{lucc}_{c,o,p,q,l,\hat{l},e} \cdot Q_{r,t,c,o,p,q,l,\tilde{l}} \right) \tag{10}$$

Appendix–2

Global land-use implications of first and second generation biofuel targets

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Abstract

Recently, an active debate has emerged around greenhouse gas emissions due to indirect land use change (iLUC) of expanding agricultural areas dedicated to biofuel production. In this paper we provide a detailed analysis of the iLUC effect, and further address the issues of deforestation, irrigation water use and crop price increases due to expanding biofuel acreage. We use GLOBIOM - an economic partial equilibrium model of the forest, agriculture and biomass sectors with a bottom-up representation of agricultural and forestry management practices. The results indicate that second generation biofuel production fed by wood from sustainably managed existing forests would lead to a negative iLUC factor, meaning that overall emissions are 27% lower compared to the "No biofuel" scenario by 2030. The iLUC factor of first generation biofuels is generally positive, requiring some 25 years to be paid back by the GHG savings from the substitution of biofuels for conventional fuels. Second generation biofuels perform better also with respect to the other investigated criteria; on the condition that they are not sourced from dedicated plantations directly competing for agricultural land. If so, then efficient first generation systems are preferable. Since no clear technology champion for all situations exists, we would recommend targeting policy instruments directly at the positive and negative effects of biofuel production rather than at the production itself.

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Keywords

Biofuels, land use change, modeling

1 Introduction

Many countries have set up bioenergy policies to support and regulate the production and use of fuels from biomass feedstocks (e.g. US, EU, Brazil, China, and India). The principal justification for these policies is to decrease the dependency on fossil fuels, especially in oil importing countries. Increasing biofuel use may also help to decrease greenhouse gas emissions because the carbon that is emitted during their combustion was recently extracted from the atmosphere by growing plants (Farrell et al., 2006; Kim and Dale, 2006). In many countries, biofuels are expected to positively affect rural development and the vitality of agricultural operations. This holds true particularly in countries where agriculture currently receives high governmental subsidies. Additionally, one should note that biofuel additives to gasoline were initially pursued as a means to reduce air pollution from leaded gasoline (Nadim et al., 2000).

Three different types of biofuels currently play a major role at the global level, all belonging to the so-called “first generation” fuels: ethanol, fatty acid methyl ester (FAME or biodiesel) and pure plant oil (PPO). All have reached a considerable state of the art in production and are commercially available (Bringezu et al., 2007). Most of the worldwide biofuel production is ethanol, which is mainly produced in the USA and Brazil from either corn or sugar cane. In Europe, potato, wheat or sugar beet is the common feedstock for ethanol. However, ethanol plays only a minor role in European biofuel production, with the large majority coming from biodiesel produced from rapeseed. These biofuels have been subject to numerous life cycle assessments focusing on energy and greenhouse gas emission balances (for a review see e.g. OECD (2008)). Although the ranges of the GHG savings estimates are large, they tend to be positive for all the principal first generation biofuels, like sugarcane ethanol, rapeseed biodiesel or palm oil biodiesel, with the exception of corn and wheat ethanol where several studies also show potentially small negative effects. These assessments however did not include emissions caused by land use changes. Recent studies show that local GHG emission offsets from these fuels may be compromised by increasing emissions elsewhere due to intensification and deforestation (Fargione et al., 2008; Searchinger et al., 2008).

Second generation biofuels, represented for example by ethanol and methanol produced from woody biomass, are more energy efficient and more flexible regarding their feedstock. The possibility to use cellulosic and heterogeneous biomass suggests lower costs and a better environmental performance (e.g. Granda et al., 2007; Hill, 2007). Although second generation biofuel technology is still in a developmental stage and not available on a commercial basis (Kaltschmitt, 2001), promising research advances and demonstration projects (see Hamelinck and Faaij, 2006; Hamelinck et al., 2005) have already triggered ambitious future policy targets regarding their role within the overall energy portfolio – along with funding for further research and development (e.g. US Energy Independence and Security Act of 2007, USDOE, 2008). Feedstock for second generation can be a by- or co-product or even waste (Cantrell et al., 2008; Sklar, 2008), or be supplied by dedicated plantations. The latter ones can be established on marginal lands (Tilman et al., 2006; Zomer et al., 2008), or enter into direct competition with conventional agricultural production (Field et al., 2008; Gurgel et al., 2007) and other services. Biofuels are hotly debated today because their overall impacts are uncertain and difficult to assess. Difficulties arise since direct biofuel benefits are linked to indirect land use impacts and may lead to adverse externalities regarding GHG emission balances, ecosystem services, and security of food and water (Koh and Ghazoul, 2008). Therefore, a proper assessment of biofuel impacts has to integrate many different scales. On the one hand, a global representation of agricultural and forest commodity markets is needed because these commodities are traded internationally and trade is the fundamental driver of indirect land use changes. On the other hand, biofuel assessments need a relatively high spatial and technical disaggregation to adequately account for heterogeneous land qualities, technological differences and possible adaptations. For the overall environmental performance, it makes a great difference whether biofuels lead for instance to the replacement of tropical rainforests in Brazil or to the restoration of degraded farm lands in India.

Existing assessments of biofuels can be grouped regarding their spatial, technological, and impact scope and their underlying assessment methods. Natural science, engineering based, and geographic studies often compute technical potentials (Smeets et al., 2007). While market adjustments are usually neglected, technological choices and land use impacts are exogenously dictated. Depending on data availability, the employed methods are well suited to portray the heterogeneity of land and existing technologies. Economic studies compute economic potentials of biofuels (Schneider and McCarl, 2003) and range from farm level to global general equilibrium assessments. Farm level models are generally limited to specific regions and use constant resource rents and commodity prices (Bennett and Anex, 2008). Market adjustments and indirect land use effects are not adequately included. At the other extreme, global general equilibrium models (Yang et al., 2008) use a top-down macroeconomic approach that integrates market adjustments. However, their account of indirect land use impacts and associated externalities is very coarse at best.

The diverse strengths and weaknesses of disciplinary studies and individual models imply that credible answers to the full impacts of biofuels might only be obtained through integrated global assessments. Such assessments should link engineering, geographic, and economic tools and address different land qualities, management adaptations, and global market feedbacks. In this paper, we take a step towards a comprehensive impact assessment of biofuels. Particularly, we use detailed geographic data to represent the natural variation in land quality at the global level. We employ complex biophysical process models to simulate, inter alia, possible agricultural management adaptations and their impacts on yields, GHG emissions, and water requirements under different land qualities. Explicit technological data for agricultural and forest management alternatives as well as first and second generation biofuel processes are simultaneously integrated in a bottom-up, partial equilibrium model of the global agricultural and forest sectors, GLOBIOM. This model is used here to assess different global biofuel scenarios regarding their market feedbacks and their indirect land use impacts and associated environmental consequences. The scenarios cover both first and second generation production technologies, and investigate several different settings with respect to the feedstock sourcing, hence covering a large part of the spectrum of current and future biofuel options.

The rest of the paper is structured as follows: in the next section we provide a description of the methodology applied, starting by briefly presenting the general aspects of the applied model and the unifying data infrastructure. Then we present the individual model components in detail, and close that section by providing information about our assessment of the global potentials for short rotation plantation bioenergy feedstock. Section 3 contains our numerical simulations, where we first define the baseline assumptions and the investigated scenarios, and then present the obtained results. The most important results are then summarized and put into perspective through discussion in Section 4. Section 5 concludes this paper.

2 Methods and Data

2.1 Description of GLOBIOM

The Global Biomass Optimization Model (GLOBIOM) is a global recursive dynamic partial equilibrium model integrating the agricultural, bioenergy and forestry sectors with the aim to provide policy analysis on global issues concerning land use competition between the major land-based production sectors. The general concept and structure of GLOBIOM is similar to the US Agricultural Sector and Mitigation of Greenhouse Gas (ASMGHG) model (Schneider et al., 2007). The global agricultural and forest market equilibrium is computed by choosing land use and processing activities to maximize the sum of producer and consumer surplus (Equation (1) in Appendix) subject to resource, technological, and policy constraints, as described by McCarl and Spreen (1980). Prices and international trade flows are endogenously determined for respective aggregated world regions. The flexible model structure enables one to easily change the model resolution; currently two region definitions are being simultaneously used, either eleven regions corresponding to the regions definition by the Greenhouse Gas Initiative (GGI) at the International Institute fo Applied Systems Analysis (IIASA) (GGI Scenario Database, 2007), or 27 regions, representing a disaggregation of the eleven regions adapted to enable linkage with the POLES (Prospective Outlook on Long-Term Energy Systems) model (Criqui et al., 1999).
The market is represented by implicit product supply functions based on detailed, geographically explicit, Leontief production functions, and explicit, constant elasticity, product demand functions. Explicit resource supply functions are used only for water supply.
In the following, before we begin the detailed description of production sectors and land use options covered in GLOBIOM, we briefly present the concept of Homogeneous Response Units around which the majority of input parameters, and the model itself, are structured.

2.2 Data concept and processing

Land resources and their characteristics are the fundamental elements of our modelling approach. In order to enable global bio-physical process modelling of agricultural and forest production, a comprehensive database has been built (Skalský et al., 2008), which contains geo-spatial data on soil, climate/weather, topography, land cover/use, and crop management (e.g. fertilization, irrigation). The data were compiled from various sources (FAO, ISRIC, USGS, NASA, CRU UEA, JRC, IFRPI, IFA, WISE, etc.) and significantly vary with respect to spatial, temporal, and attribute resolutions, thematic relevance, accuracy, and reliability. Therefore, data were harmonized into several common spatial resolution layers including 5 and 30 Arcmin as well as country layers. Subsequently, Homogeneous Response Units (HRU) have been delineated by geographically clustering according to only those parameters of the landscape, which are generally not changing over time and are thus invariant with respect to land use and management or climate change. At the global scale, we have included five altitude classes, seven slope classes, and five soil classes. In a second step, the HRU layer is intersected with a 0.5° × 0.5° grid and country boundaries to delineate Simulation Units (SimU) which contain other relevant information such as global climate data, land category/use data, irrigation data, etc. For each SimU a number of land management options are simulated using the bio-physical process model EPIC (Environmental Policy Integrated Climate Model; Izaurralde et al., 2006; Williams, 1995). And the SimUs are the basis for estimation of land use/management parameters in all other supporting models as well.

The HRU concept assures consistent aggregation of geo-spatially explicit bio-physical impacts in the economic land use assessment. In GLOBIOM, we can choose at which level of resolution the model is run, and aggregate the inputs consistently. As shown in the Appendix, each land related activity and all land resources are currently indexed by country, altitude, slope, and soil class. The information relevant to the 0.5° × 0.5° grid layer has been averaged to keep the model size and computational time within reasonable limits.

2.3 Model structure

The model directly represents production from three major land cover types: cropland, managed forest, and areas suitable for short rotation tree plantations.[1] Crop production accounts for more than 30 of the globally most important crops. The average yield level for each crop in each country is taken from FAOSTAT. Management related yield coefficients according to fertilizer and irrigation rates are explicitly simulated with EPIC for 17 crops (barley, dry beans, cassava, chickpea, corn, cotton, ground nuts, millet, potatoes, rapeseed, rice, soybeans, sorghum, sugarcane, sunflower, sweet potatoes, and wheat). These 17 crops together represent nearly 80 % of the 2007 harvested area as reported by FAO. Four management systems are considered

[1] Grassland production is so far represented only indirectly without explicit linkage to the livestock feed requirements. Work is ongoing on to improve this aspect in the next version of the model.

(irrigated, high input - rainfed, low input - rainfed and subsistence management systems) corresponding to the International Food and Policy Research Institute (IFPRI) crop distribution data classification (You and Wood, 2006). Only two management systems are differentiated for the remaining crops (bananas, other dry beans, coconuts, coffee, lentils, mustard seed, olives, oil palm, plantains, peas, other pulses, sesame seed, sugar beet, and yams) – rainfed and irrigated. Rainfed and irrigated crop yield coefficients, and crop specific irrigation water requirements for crops not simulated with EPIC, and costs for four irrigation systems for all crops, are derived from a variety of sources as described in Sauer et al. (2008). The linkage between primary (crop) production and the land resources is represented in Equation (4) of the Appendix. The irrigation water balance is represented by accounting equation (9) and in the objective function, Equation (1). Thus, water scarcity is expressed through the parameterization of the water supply function.

(Insert Figure 1)

Crop supply can enter one of three processing/demand channels: consumption, livestock production and biofuel production (Figure 1). Demand is modelled by constant elasticity functions parameterized using FAOSTAT data on prices and quantities, and own price elasticities as reported by Seale et al. (2003). An aggregated regional livestock production representation is used, where a bundle of livestock products (bovine meat, chicken meat, equine meat, pig meat, sheep and goat meat, turkey meat, milk, and eggs) is assimilated to a generic commodity - “animal calories”. The respective feed requirements have been calculated from the Supply Utilisation Accounts, FAOSTAT. Demand for livestock products is represented through upward sloping demand curves. Biofuel options from crops include first generation technologies for a) ethanol from sugarcane and corn, and b) biodiesel from rapeseed and soybeans. The processing data, conversion coefficients and cost, are based on Hermann and Patel (2007) for ethanol, and on Haas et al. (2006) for biodiesel. Market demand for ethanol and biodiesel is represented through vertical demand functions (Equation (2) in the Appendix), the supply-demand balance according to Equation (3).

Primary forest production from traditional managed forests is characterized also at the level of SimUs. The most important parameters for the model are mean annual increment, maximum share of saw logs in the mean annual increment, and harvesting cost. These parameters are shared with the G4M model – a successor of the model described by Kindermann et al. (2006). More specifically, mean annual increment for the current management, is obtained by downscaling biomass stock data from the Global Forest Resources Assessment (FAO, 2006a) from the country level to a 0.5° × 0.5° grid using the method described in Kindermann et al. (2008). The downscaled biomass stock data is subsequently used to parameterize increment curves. Finally, the saw logs share is estimated by the tree size, which in turn depends on yield and rotation time. Harvesting costs are adjusted for slope and tree size as well.

Five primary forest products are defined: saw logs, pulp logs, other industrial logs, traditional fuel wood, and biomass for energy. Saw logs, pulp logs and biomass for energy are further processed. Sawn wood and wood pulp production and demand parameters rely on the 4DSM model described in Rametsteiner et al. (2007). FAO data and other secondary sources have been used for quantities and prices of sawn wood and wood pulp. For processing cost estimates of these products an internal IIASA database and purchased data (e.g. RISI database for locations of individual pulp and paper mills, with additional economic and technical information, http://www.risiinfo.com) were used. Biomass for energy can be converted in several processes: combined heat and power production, fermentation for ethanol, heat, power and gas production, and gasification for methanol and heat production. Processing cost and conversion coefficients are obtained from various sources (Biomass Technology Group, 2005; Hamelinck and Faaij, 2001; Leduc et al., 2008; Sørensen, 2005). Demand for woody bioenergy production is implemented through minimum quantity constraints, similar to demand for other industrial logs and for firewood, shown in the Appendix (see Equation 2).

Woody biomass for bioenergy can also be produced on short rotation tree plantations. To parameterize this land use type in terms of yields, we carried out our own evaluation of the land availability and suitability, described in detail in the next sub-section. Calculated plantation costs involve the establishment cost and the harvesting cost. The establishment related capital cost includes only sapling cost for manual planting (Carpentieri et al., 1993; Herzogbaum GmbH, 2008). Labour requirements for plantation establishment are based on Jurvélius (1997), and consider land preparation, saplings transport, planting and fertilization. These labour requirements are adjusted for temperate and boreal regions to take into account the different site conditions. The average wages for planting are obtained from ILO (2007).

Harvesting cost includes logging and timber extraction. The unit cost of harvesting equipment and labour is derived from various datasets for Europe and North America (e.g. FPP, 1999; Jiroušek et al., 2007; Stokes et al., 1986; Wang et al., 2004). Because the productivity of harvesting equipment depends on terrain conditions, a slope factor (Hartsough et al., 2001) was integrated to estimate total harvesting cost. The labour cost, as well as the cost of saplings, is regionally adjusted by the ratio of mean PPP (purchasing power parity over GDP), (Heston et al., 2006).

As represented graphically in Figure 1, and analytically in Equations (5)-(8) in the Appendix, we allow for endogenous change in the land cover/use within the available land resources. Expansion into land cover/use types not covered in the model is not allowed, and thus the total land area remains fixed over the whole simulation horizon. When carrying out simulations over several periods, changes made in one period, are consistently transferred into the next period, introducing recursive dynamics into the model. Land use change options are on the one hand limited through general restrictions on conversion from one land use to another; e.g. cropland expansion into other natural vegetation is not allowed anywhere. On the other hand, land suitability criteria linked to production potentials exclude selectively land use conversion to a particular land use type in a particular SimU. Land use suitability is taken into account either indirectly through estimated crop and forest productivity, or directly by not only calculating the production potentials but also by explicitly delineating suitable areas. This detailed direct suitability analysis has been carried out for short rotation tree plantations and is presented below.

As expressed by Equation 10 (see Appendix) and by the objective function, GLOBIOM allows for accounting, and eventually taxing, of the major greenhouse gas emissions/sinks related to agriculture and forestry. The calculation of emission coefficients depends on the emission source. N2O emissions from application of synthetic fertilizers are calculated according to the IPCC Guidelines (IPCC, 1996), on the basis of fertilizer use as simulated in EPIC, or for crops which are not yet simulated, using fertilizer application rates derived from IFA (1992) and FAOSTAT. Coefficients for CH4 emissions from rice production, and from enteric fermentation and manure management, are derived from EPA (2006) by recalculating the total values per activity level. CO_2 savings/emission coefficients for the various bioenergy paths are calculated using parameters from CONCAWE/JRC/EUCAR (2007) and Renewable Fuels Agency (2008). Greenhouse gas accounts of land use change activities are based on the carbon contents in equilibrium states of the different land cover classes. Carbon content in above and below-ground living biomass for forests is taken from Kindermann et al. (2008). Carbon content in the biomass of short rotation plantations is calculated based on our own estimates of their productivity. Finally, for parameterization of carbon in grasslands and in other natural vegetation, we use the biomass map by Ruesch and Gibbs (2008). The carbon content in cropland is neglected, because it is relatively small and diverse, and no sufficient data is available. CO_2 coefficients for emissions and sinks due to land use change are calculated as the difference in carbon content between the initial and the new land cover classes.

The final model calibration, supposed to correct data imperfections and get the baseline solution close to the observed values, was performed by adjusting the cost parameters of selected activities so that for the baseline activity levels, their marginal costs equal marginal benefits, as assumed by microeconomic theory. The controlled activities are SimU specific crop areas, and regional primary forest products supply and animal calorie supply.

The model is written and solved in GAMS IDE.

2.4 Analysis of the land reserve

The estimation of area potentials for biomass plantations followed an approach proposed by Zomer at al. (2008). It included thresholds of tree growth based on aridity, temperature, elevation, population density, and existing land cover. The Aridity Index developed by Zomer et al. (2008) uses the ratio between mean annual precipitation and mean annual evapotranspiration. We obtained the derived aridity map directly from the authors of the study. The temperature limitation threshold was modified and data with a higher temporal resolution was included. Calculation of the temperature threshold was based on data provided by the European Centre for Medium Range Weather Forecasting (ECMWF) that can be downloaded from the JRC MARS FOOD archive (see http://mars.jrc.it/marsfood/ecmwf.htm). The original average temperature of ten day periods was averaged over the growing season. Growing season was defined as time of the year where average temperature is equal or larger than 5 °C. By iteration we defined a threshold value of 10 °C average temperature in growing season that matched with the observed northern tree line in GLC 2000 in North America and most parts of Siberia.

High elevation areas with elevation of more than 3500 meters were excluded from potential plantation area. These were based on a Digital Elevation Map of 1km (based on SRTM 90m

Digital Elevation Data available at http://srtm.csi.cgiar.org). In addition, population densities of above 1000 people per km2 were excluded from plantation potential; mostly areas in China and India but also the island of Java fall into this category. However, it depends very much on the form of settlements; even lower population densities could make the establishment of large scale plantations very unlikely. The population map was based on gridded population data from CIESIN (2005).

The land that remained unaffected by the constraints mentioned above was classified into four categories derived from GLC 2000 Land Cover Classes (Table 1).

(Insert Table 1)

The land suitable for afforestation in the four land cover classes as well as the average net primary productivity (NPP) values were extracted per SimU. The NPP values were based on potential NPP from Cramer et al. (1999). The NPP, truncated for the highest values corresponding to 5 % of area in each region, was then used to scale the maximum mean annual increments derived from FAO and other various databases (e.g. Alig et al., 2000; Chiba and Nagata, 1987; FAO, 2006b; Mitchell, 2000; Stanturf et al., 2002; Uri et al., 2002; Wadsworth, 1997; Webb et al., 1984) proportionally for each SimU, providing finally the SimU specific potentials.

3 Model application

3.1 Baseline assumptions

As GLOBIOM operates in partial equilibrium, several parameters enter the 2030 projections as exogenous drivers. Wood and food demand is driven by gross domestic product (GDP) and population changes. In addition, food demand must meet minimum per capita calorie intake criteria, which are differentiated with respect to the source between crop and livestock calories. Demand is calculated for the different regions on the basis of projections presented in FAO (2006a). The regional population development is taken from the B2 scenario of the Special Report on Emissions Scenarios (SRES) as provided by the GGI Scenario Database (2007). On the supply side, we make a conservative assumption of zero “autonomous” technological progress in crop improvement, which would otherwise exogenously shift the supply curve either upwards or downwards. However, as we represent several crop management systems and allow for endogenous switches between rainfed and irrigated agriculture, the average yield is still sensitive to the market signals.

The bioenergy baseline is defined according to POLES simulation results corresponding to an updated version of Russ et al. (2007), see Table 2. In this baseline, heat and power generation increase nine times between 2000 and 2030 to reach finally 447 million tonnes of oil equivalent (toe) of dry biomass. Also the total liquid biofuel production is projected to increase dramatically, from 0.6 % of the total transport energy consumption in 2000 to some 7.5 % of the 2030 consumption. On the other hand, the direct biomass use for energy is predicted to increase relatively slowly, by 26 %, representing however by far the largest share bioenergy carrier. In GLOBIOM, the bioenergy baseline is represented directly by minimum demand constraints.

(Insert Table 2)

3.2 Scenarios

The scenario analysis in this paper focuses on liquid biofuels and therefore the demand for other bioenergy is assumed not to change. In the baseline, some 60 % of liquid biofuels are assumed to be provided by the first generation technologies and 40 % by the second generation technologies in 2030. Three other alternative scenarios are considered to analyze the effect of the biofuel conversion pathway and to compare it with the situation of a world with biofuel consumption corresponding to the 2005 levels. All four scenarios are described in Table 3.

(Insert Table 3)

Second generation biofuels are not commercially produced yet and their effects and potential relative advantage over the first generation biofuels will depend on where the feedstock comes from, whether it is a by-product or even waste biomass, or whether it is the principal product. In the latter case, the results are likely to depend also on whether this biomass is planted on marginal lands, as some argue that it will be the case, or whether it enters into direct competition with conventional agricultural production. Therefore we consider three different options for the second generation feedstock production:

1. Biomass for second generation biofuels comes from short rotation tree plantations, which can be established either on currently existing cropland or grassland. In this setting plantations enter in competition for land with agricultural production as no agricultural land reserve is assumed.
2. Biomass for second generation is derived only from wood produced in currently existing production, or to production converted, forests, as sawlogs residues or purposely harvested wood for energy. In this case direct competition with agricultural production is eliminated; however, there is competition with the production of conventional forest products.
3. Biomass for second generation biofuels may come from short rotation tree plantations established on non-agricultural land (other natural vegetation). Direct competition with agricultural or forest production is mitigated in this scenario.

The effects of the above defined scenarios with respect to land use change, resulting greenhouse gas emissions, water and commodity prices are presented in the next sub-section. To keep the scope of that sub-section in reasonable limits, we focus on the end of the simulation period - year 2030, often compared with the base year 2000.

3.3 Results

3.3.1 Land use change – impact on deforestation

GLOBIOM accounts for major land uses. Our scenarios indicate that the most significant land-use changes are expected to be observed with respect to deforestation. Table 4 presents deforestation projections according to the respective scenario assumptions. Deforestation is driven by increased food and bioenergy production, while other drivers of deforestation such as illegal logging are purposely excluded from this analysis. In the “No-Biofuels” scenario the accumulated deforestation area by 2030 amounts to 100 million hectares (Mha) for Option 1. However under Option 3, where it is allowed to source the biomass for power and heat generation from plantations established on “other natural lands”, it does not reach more than 77 Mha. In the first generation biofuel scenario some 145 Mha deforestation are predicted under Option 1&2, while Option 3 requires by 11 % less forests to be cleared. This indicates that the knock-on leakage effect of cropland and grassland expansion on deforestation is higher compared to a situation where additional other natural land can be used for short rotation plantations easing pressure from agricultural land expanding into forests. The relative difference between the baseline and the pure first generation biofuel case is rather small for Option 1, and largest for Option 3. Additional deforestation occurs when biofuels are introduced. However, an exception is Option 2, where the second generation pathway leads to an even lower deforestation compared to the no biofuel scenario. This is due to the fact that the feedstock for second generation stems mostly from wood harvesting in existing forests which increases their relative value compared to cropland. When forests are more competitive, deforestation is lower. However, in this option some 350 Mha of otherwise unmanaged forests come into production causing potentially collateral ecosystem damage.

The impact of first and second generation biofuels on deforestation depends on the assumptions on feedstock for second generation processes and the respective land availability. If second generation biofuels are to be produced on current agricultural land (cropland and pastures) using short rotation biomass plantations they will indirectly cause some 13 Mha of traditional forest to be deforested above the amount which would be needed if first generation biofuels were used. This is due to the fact that the biophysical yields of sugar cane (C4 plant) are modelled to exceed those of woody plantations if planted on current crop- and grasslands. On the other hand, the balance would point into the opposite direction if second generation biofuels were produced from wood from traditional forests managed in a sustainable way; in that case first generation biofuels would cause some 50% less land to be deforested compared to first generation biofuels.

(Insert Table 4)

As a general policy rule, if some marginal non-agricultural land could be used for biofuel production (Option 3), the overall pressure on deforestation would be lowest and second generation biofuels are performing much better with respect to deforestation than first generation biofuels. The overall lowest deforestation is predicted when existing production forests are used for bioenergy purposes *via* second generation biofuels.

3.3.2 GHG emissions from LUC

In our analysis, we aim at dynamic full greenhouse gas accounting. However due to basic data constraints we make two simplifying assumptions: (1) Agricultural practices do not have an impact on soil carbon emissions. (2) In the case of deforestation, defined as expansion of cropland into the forest, the total carbon contained in above and below ground living biomass is emitted.

In general, results presented in Table 5 suggest that second generation biofuels improve the global carbon balance even through the LUC related carbon accounts. Under Option 1 and Option 2, the net emissions are respectively by 7 % and 27 % lower in the “Second generation” scenario than in the “No biofuels” scenario. Despite the fact that Option 3 leads to less deforestation than Option 1, its net emissions from land use change are higher than under Option 1, and also higher than the “No biofuels” emissions. This result is mostly due to the fact that under Option 1, the model chooses to establish 79 % of the plantations in “Other Natural Vegetation” whit an average net carbon gain of 8 t per ha over 30 years, not creating sufficient sink to compensate for the deforestation. (Under Option 1, 72 % of plantations are established on cropland with an average carbon gain of 140 t CO_2 over 30 years.)

(Insert Table 5)

We confirm the previously expressed worries that first generation biofuels have negative effects on the global carbon balance through iLUC emissions; our simulations suggest that the cumulative net carbon emissions from LUC would be in 2030 by some 70-80 % higher in scenario “First generation” than in scenario “No biofuels”. The performance is again the worst under Option 3.

To put the iLUC emissions into perspective with respect to the savings in emissions due to substitution of fossil fuels by biofuels, pay back time was adopted as a convenient indicator by several authors (e.g. Fargione et al., 2008; Gibbs et al., 2008; Searchinger et al., 2008). Pay back time is defined as the period over which the annual GHG savings due to substitution of fossil fuels by biofuels equalize the usually fast emissions from land use change. The LUC emissions are calculated from Table 5 as the difference between the biofuel scenarios and the ”No biofuels” scenario. Our results for first generation biofuels, suggest a pay back period of 22-27 years and thus compare well with the findings of the above mentioned authors (Table 6). We have of course to bear in mind that they represent the average values of converting various ecosystems ranging from tropical forests to temperate grasslands, and that the majority of biofuel comes from an efficient Brazilian sugar cane production.

(Insert Table 6)

None of the second generation Options does create any large GHG emission debts. The first two Options actually create net carbon benefits from iLUC, and the small carbon debt generated under Option 3 can be paid back within two years.

3.3.3 Water

Irrigation water use is an indicator of intensification and production system change in agriculture and thus strongly related to mitigating the indirect land use change effects of biofuel policies. On average demand for irrigation water is projected to increase by one third even without biofuel expansion. The overall irrigation water use due to first generation biofuels would at maximum lead to some 3 % increase. This increase would be one percent higher under Option 3 than under Options 1&2, because of the lower “No biofuels” reference of the former one. Second generation biofuels do not increase the water demand under Option 2 compared to “No biofuels” scenario.

On the other hand, the introduction of second generation biofuels is under Option 1 the most water demanding scenario out of all scenarios, increasing irrigation water consumption by some 4 % compared to the “No-biofuels” scenario. This is mainly due to the fact that lower yields from growing trees require more land, which needs to be compensated by higher agriculture yields through increased irrigation.

In general terms the ranking of the land use options and choice of technology is the same as for the deforestation results (Table 4). As expected the “No biofuel” scenarios lead to least water consumption followed by second generation, while first generation requires most irrigation water use – except under the land use Option 1. Relative to the overall increase of irrigation water demand by one third, estimated in our model even for the “No biofuels” scenario, and relative to the technological efficiency gains possible through improved irrigation techniques, the additional global water demand for bioenergy is rather small. However, bioenergy induced competition over water resources could be potentially quite intense in particular in arid and semi-arid regions.

3.3.4 Prices

Prices of both first and second generation biofuels start in the simulations at some USD 700 per toe. The prices of first generation biofuels are projected to increase by some 14 % over the simulation period and do not differ considerably for the different scenarios (Table 7). On the other hand, the second generation biofuel prices depend considerably on the assumptions we make about the origin of the feedstock. As the most advantageous option appear again biofuels from plantations established on other than agricultural or primary forest land. The most expensive option, with prices nearly tripling between 2000 and 2030 are biofuels based on feedstock from traditional forests.

(Insert Table 7)

The strongest effect on crop prices, and thus potentially food security, has development of second generation biofuels on agricultural land, creating additional increase by some seven percentage points compared to the “No biofuels” scenario. On the other hand, if second generation biofuels were sourced from traditional forests, the biofuel production would have negligible effect on crop prices and would outperform the first generation. However, the impact of second generation on wood prices for the forest sector would be in the range of 20 % for Option 2.

Crop prices compared to the “No-biofuel” case are by some 4 % higher if first generation is used for each land use option. Additional land reserve availability in form of the currently non-agricultural and non-forest lands, would have positive impact also on the crop price development; the crop price index values are the lowest under Option 3.

4 Discussion

The sustainability debate on biofuels has largely centred around the possible GHG savings and their impact on global food prices and subsequent association with immediate hunger. To a lesser degree the debate has touched upon the issue of water use. We have therefore applied a bottom-up partial equilibrium framework of the global agriculture, forest and biomass sectors to address these issues. Our findings however,must be interpreted within the limits of the model applied. Scenarios were formulated in such a way that the issue of indirect land use change from biofuel use can be consistently evaluated. We therefore refrained (in the presentation of the scenario results) from the inclusion of biofuel production in poly-generation mode which would produce electricity and heat as marketable co-products. Such analysis would require specific investigation on access to these markets from respective biofuel producers and was deemed out of the scope of this study.

In general, our results indicate that first generation biofuels are performing worst in terms of deforestation (Options 2&3), GHG emissions from land-use, irrigation water use (Options 2&3) and relative price increases of agricultural crops (Options 2&3). However, if there are constraints on expansion of the bioenergy sector into forests and other natural lands (land use Option 1) for sourcing woody biomass from managed natural forests and dedicated plantations, respectively, then especially sugarcane based ethanol is superior to second generation biofuels in all aspects studied except for the net land use change GHG emission balance. In particular, the Brazilian ethanol program with its high cane yields and conversion efficiency appears as an interesting example in this respect. For Brazil, our land use Option 1 (cropland and grassland scenario) might be the most appropriate approximation if the avoided deforestation and conservation plans that have been announced by the government will effectively be implemented.

Option 2, which focuses on the expansion of biomass sourcing from existing primary and secondary forests, adopts an occidental paradigm of forest management to be expanded to the pan-tropical belt. There are considerable knowledge gaps and a lack of experience to manage highly species rich tropical forests in a sustainable manner, not only from a biodiversity point of view, but also from a sustainable timber supply standpoint. Our integrated modelling approach assumed a gap disturbance type of regeneration modus similar to European nature like forest management practices in temperate forests. There are however two main draw-backs with this approach. One being high costs of wood production and harvesting due to large infrastructure investments (our estimates indicate the second generation prices more than doubled compared with Option 1) and the danger of subsequent colonization and risk of uncontrolled slash and burn agricultural activities. The other is the conversion of primary old growth forests to production forests, which if wrongly managed might lead to a degradation of ecosystem services, in particular biodiversity. In terms of GHG savings, the second generation bioenergy under Option 2 is the best performer of all scenarios, due to substantially lower deforestation (90 Mha), even lower than the "No biofuels" scenario under this option (97 Mha).

There is substantial uncertainty over the global land reserve which could optionally be deployed for the production of agricultural commodities, serve as a carbon sink via afforestation, be used for biomass production or serve to produce other ecosystem services depending on local needs. Option 3 mimics the effect of such a production reserve which still might exist in 2030. This option is superior to the other two land use options in terms of irrigation water use, deforestation (except for the scenario "Second generation" under Option 2), and crop prices. However, with respect to the currently most debated indicator (GHG savings), this option turns out to be the most inefficient one. The main reason for this result is the rather conservative estimate of current carbon stock on this other land category, which is in line with IPCC default values, and also the level of estimated afforestation plantation yields play a role.

These parameters might change substantially in the future, in particular when new estimations of carbon stocks based on radar imagery from the ALOS sensor become available. For this land category, which makes up a substantial area of some 510 Mha, we lack however, information on other ecosystem values. Much of these lands might actually not become available due to constraints on ecosystem value preservation beyond carbon and bioenergy. Some of this land might also already be under fuel wood use, which in turn is indirectly captured in our model by the assumption of high carbon losses when clearing these lands.

The scenarios presented in this paper are "pure" biofuel scenarios and therefore the indirect land use emissions projections have to be viewed as unabated. This means that the emissions from deforestation could be avoided by providing a carbon incentive payment or by levying a carbon tax. Thus, indirect land use emissions from biofuels are not an unavoidable evil, but could effectively be managed by appropriate policies. Choke prices for avoiding deforestation are almost entirely in the range of 100 $ per ton of carbon. This in turn, however, would raise fuel and food prices considerably and also necessitate additional irrigation. For the latter, we are currently not able to provide analysis as to whether these amounts of irrigation water could actually be supplied on a sustainable basis.

Biofuels, even if they will constitute some 7.5 % of total transport energy by 2030, will only add up to a quarter of the total bioenergy sector. According to the POLES baseline scenario, the lion share of biomass will go to direct uses along with heat and power production. Liquid fuels could be produced in poly-generation mode and substitute some of the primary biomass inputs or fossil fuel inputs to produce these energy services. Across the entire biomass sector there are large technological improvement gaps to be closed. These improvements would probably be sufficient to supply all the necessary wood bioenergy to produce second generation biofuels. However, these forms of bioenergy are currently, from an institutional and economic point of view, not accessible for large scale industrial production of biofuels via second generation. Nonetheless, more focus and attention should be given to these types of biomass (mis-)use when regulating biofuels. Regulation of biofuels should thus be comprehensive and be framed in a complete land use approach. The (socio-)economic and GHG savings returns of improving the sustainability of energy access to the poor who rely on fuel wood would be much higher than from making industrial biofuel production more efficient. This is already envisaged in the emerging biofuel sustainability standards currently developed under the coordination of the Round Table for Sustainable Biofuels. Thus, there should be a provision in the life-cycle assessment of biofuels to allow for improvements on the iLUC factor by providing more sustainable energy services to communities impacted by large-scale biofuel projects.

The model structure enables us to directly assess irrigation water needs, which is the single largest use of blue water over the globe (70 % of all withdrawals, UN, 2006). Fresh water resources are getting scarcer in many parts of the world because of changes in regional water cycles (e.g. droughts), water mismanagement, and increasingly polluted ecosystems. Competition for water is also increasing among agriculture, industry and domestic consumption, especially in countries with increasing population pressure. Irrigation water consumption is an indicator for the intensification and production system change in agriculture. Our projections of increase in irrigation water consumption due to biofuel production remain on the order of percents, hence relatively insignificant at the global scale. These are in line with results presented in other studies (e.g. Rosegrant et al., 2008). Nevertheless, we find that the expansion of irrigation is crucial to maintain the deforested area and crop prices within reported ranges. Our model does not include all relevant constraints which might prohibit this production systems shift in reality. Most of these factors are related to building the respective institutional and physical infrastructure. If these constraints apply, the area deforested increases along with crop and biofuel prices. Thus, any policy promoting biofuels should at least monitor the impacts on water consumption or better yet provide technological improvements to increase irrigation services and crop water productivity. Localization of biofuel production will play an important role too. Any additional competition for water resources may have dramatic impacts in regions where the physical water scarcity persists, and where live nowadays some 1.2 billion people (Molden et al., 2007). But also the biofuel productivity per litre of irrigation water varies considerably between regions as shown by De Fraiture et al. (2008). According to their results, 70 litres of irrigation water are necessary to produce 1 litre of sugarcane ethanol in Brazil, but 3200 litres are required for the same litre of ethanol produced in India.

In recent years, various studies have been published analysing the impact of biofuel policies on global agriculture commodity markets. Eickhout et al. (2008) have compiled an overview of recently published work on the impact of bioenergy on several commodity prices. They conclude that the modelling set-up varies per exercise, but also the modelling approaches are different. Despite difficulties of comparison it can be concluded that our results on price increases fall well within the median impact strength of the studies i.e. the two to maximum five percent range of price increases on the level of an aggregate crop price index for a policy of 7.5 % biofuel mix in all transport fuels. It has to be noted that this price impact is a long-run impact neglecting possible short run effects such as abrupt increases in biofuels due to a policy shock in combination with global weather extreme events such as large scale crop failures in major crop exporting countries. The question whether in the long-run a lower one digit price shock due to biofuel production will lead to less or more undernutrition on a global scale is a question yet to be answered and will surely depend on the context in which biofuels will be introduced. On the one hand biofuels have the tendency to increase food prices and thus reduce the purchasing power of the very poor. On the other hand, price increases might lead to technology improvements and increased farm incomes. The economies of the very poor countries, which are most affected by increased food prices, are mostly dominated by the agricultural sector. Thus, it has yet to be shown which price effect is larger: the direct one pushing consumer prices up, or the indirect one potentially increasing income from agricultural commodity sales, for at least a share of the population. Clearly, biofuel policies can be targeted at mitigating the impacts on undernutrition. The most straight forward policy would be through yield and market access improvement programs for agriculture in developing countries.

5 Conclusion

A new economic global land use model, GLOBIOM, has been presented and applied in this paper, to assess first and second generation biofuels expansion under various settings, focusing on the indirect land use change effects in terms of GHG emissions, irrigation water use, and crop and biofuel prices. The findings presented in this paper have to be considered within the limits of the model and assumptions we have adopted. The first limitation is related to uncertainties of input datasets. For example, Ramankutty et al. (2008) estimate the 90% confidence range of global cropland area to lie between 1220 and 1710 million hectares. Availability of consistent economic data at the global scale represents another challenge. There are also structural limitations within the model i.e. a more detailed representation of the livestock sector would improve the assessment of land competition. Despite these limitations we show that the model is able to provide a consistent integrated assessment of land use related environmental and economic effects.

From a GHG emission perspective, we find that second generation biofuels perform the best. However, there are some caveats to be made here. In the case that second generation biofuels are produced from dedicated short rotation plantations on current agricultural land, they perform worse than first generation in all aspects except GHG emissions (gross deforested area, irrigation water use, commodity prices). Rendering second generation biofuels as a sustainable option would mean that feedstocks do not compete with food production. Wood from sustainably managed forests, residues, and wastes must be mobilized, or marginal and abandoned land is to be brought in to production. However, these feedstocks and land are to be selected carefully as their production may infer with other sustainability criteria like biodiversity conservation, erosion protection or even fuelwood supply for local communities.

To conclude, our analysis shows that biofuel expansion itself is not a silver bullet as it creates a complex system of not only positive but also negative effects/externalities. We have observed that the same level of biofuel production can either be associated with a net carbon sink through land use change, or it may increase net deforestation drastically and create a carbon debt for more than 20 years. The first outcome (net carbon sink) would, in the presented case, not be obtained through a general biofuel mandate because it is accompanied by bioenergy costs twice as high as the second outcome (carbon debt), and thus would be avoided by the industry. To achieve the environmentally positive outcome, forest ecosystem services would have to be explicitly targeted. Similarly, a biofuel induced food price increase will not benefit the poorest populations without appropriate public action. Neither the rural poor, with often limited market access, nor the urban poor, who are typically consumers rather than producers of agricultural commodities, will automatically benefit from the potentially positive income effects of rising prices. Thus, we recommend policy action to focus directly on the positive and negative, environmental and social effects linked with biofuel production, rather than on biofuel production itself.

References

Alig, R. J., D. M. Adams, B. A. McCarl and P. J. Ince, 2000. Economic potential of short-rotation woody crops on agricultural land for pulp fiber production in the United States. Forest Products Journal. 50: 67-74.

Bennett, A. S. and R. P. Anex, 2008. Farm-gate production costs of sweet sorghum as a bioethanol feedstock. Transactions of the ASABE. 51: 603-613.

Biomass Technology Group, 2005. Handbook Biomass Gasification, H.A.M. Knoef. ISBN: 90-810068-1-9.

Bringezu, S., S. Ramesohl, K. Arnold, M. Fischedick, J. v. Geibler, C. Liedtke and H. Schütz, 2007. Towards a sustainable biomass strategy. What we know and what we should know. Wuppertal Paper no. 163 Wuppertal Institute for Climate, Environment and Energy,

Cantrell, K. B., T. Ducey, K. S. Ro and P. G. Hunt, 2008. Livestock waste-to-bioenergy generation opportunities. Bioresource Technology. 99: 7941-7953.

Carpentieri, A. E., E. D. Larson and J. Woods, 1993. Future biomass-based electricity supply in Northeast Brazil. Biomass and Bioenergy. 4: 149-173.

Chiba, S. and Y. Nagata, 1987. Growth and yield estimates at mountainous forest plantings of improved Populus maximowiczii. In: Research report of biomass conversion program. No.3 "High yielding technology for mountainous poplars by short- or mini-rotation system I", January. Agriculture, Forestry and Fisheries Research Council Secreariat, Ministry of Agriculture, Forestry and Fisheries. Japan. ISSN: 0193-4549.: 36-47.

CIESIN, 2005. Center for International Earth Science Information Network, Columbia University; and Centro Internacional de Agricultura Tropical (CIAT). Gridded Population of the World Version 3 (GPWv3): Population Density Grids. Palisades, NY: Socioeconomic Data and Applications Center (SEDAC), Columbia University. http://sedac.ciesin.columbia.edu/gpw. http://sedac.ciesin.columbia.edu/gpw

Cramer, W., D. W. Kicklighter, A. Bondeau, B. Moore, C. Churkina, B. Nemry, A. Ruimy, A. L. Schloss and the Participants of the Potsdam NPP Model Intercomparison, 1999. Comparing global models of terrestrial net primary productivity (NPP): overview and key results. Global Change Biology. 5: 1-15.

Criqui, P., S. Mima and L. Viguier, 1999. Marginal abatement costs of CO2 emission reductions, geographical flexibility and concrete ceilings: An assessment using the POLES model. Energy Policy. 27: 585-601.

De Fraiture, C., M. Giordano and Y. Liao, 2008. Biofuels and implications for agricultural water use: Blue impacts of green energy. Water Policy. 10: 67-81.

Eickhout, B., G. J. v. d. Born, J. Notenboom, M. v. Oorschot, J. P. M. Ros, D. P. v. Vuuren and H. J. Westhoek, 2008. Local and global consequences of the EU renewable directive for biofuels. MNP Report 500143001 / 2008,

EPA, 2006. Global Anthropogenic Non- CO2 Greenhouse Gas Emissions: 1990-2020. United States Environmental Protection Agency, Washington, DC.

FAO, 2006a. Global Forest Resources Assessment 2005. Progress towards sustainable forest management. Food and Agriculture Organization of the United Nations, Rome.

FAO, 2006b. Global planted forests thematic study: results and analysis. Planted Forests and Trees Working Paper 38. FAO, Rome.

Fargione, J., J. Hill, D. Tilman, S. Polasky and P. Hawthorne, 2008. Land clearing and the biofuel carbon debt. Science. 319: 1235-1238.

Farrell, A. E., R. J. Plevin, B. T. Turner, A. D. Jones, M. O'Hare and D. M. Kammen, 2006. Ethanol can contribute to energy and environmental goals. Science. 311: 506-508.

Field, C. B., J. E. Campbell and D. B. Lobell, 2008. Biomass energy: the scale of the potential resource. Trends in Ecology and Evolution. 23: 65-72.

FPP, 1999. Holzernte in der Durchforstung; Leistungszahlen Kosten - OeBF Seiltabelle Sortimentverfahren (SKM-TAB). Kooperationsabkommen Forst-Platte-Papier, Vienna, Austria.

GGI Scenario Database, 2007. International Institute for Applied System Analysis (IIASA) GGI Scenario Database, 2007. Available at: http://www.iiasa.ac.at/Research/GGI/DB/.

Gibbs, H. K., M. Johnston, J. A. Foley, T. Holloway, C. Monfreda, N. Ramankutty and D. Zaks, 2008. Carbon payback times for crop-based biofuel expansion in the tropics: The effects of changing yield and technology. Environmental Research Letters. 3.

Granda, C. B., L. Zhu and M. T. Holtzapple, 2007. Sustainable liquid biofuels and their environmental impact. Environmental Progress. 26: 233-250.

Gurgel, A., J. M. Reilly and S. Paltsev, 2007. Potential land use implications of a global biofuels industry. Journal of Agricultural and Food Industrial Organization. 5.

Haas, M. J., A. J. McAloon, W. C. Yee and T. A. Foglia, 2006. A process model to estimate biodiesel production costs. Bioresource Technology. 97: 671-678.

Hamelinck, C. N. and A. P. C. Faaij, 2001. Future Prospects for Production of Methanol and Hydrogen from Biomass. Utrecht University, Copernicus Institute, Science Technology and Society, Utrecht, Netherlands.

Hamelinck, C. N. and A. P. C. Faaij, 2006. Outlook for advanced biofuels. Energy Policy. 34: 3268-3283.

Hamelinck, C. N., G. Van Hooijdonk and A. P. C. Faaij, 2005. Ethanol from lignocellulosic biomass: Techno-economic performance in short-, middle- and long-term. Biomass and Bioenergy. 28: 384-410.

Hartsough, B. R., X. Zhang and R. D. Fight, 2001. Harvesting cost model for small trees in natural stands in the Interior Northwest. Forest Products Journal. 51: 54-61.

Hermann, B. G. and M. Patel, 2007. Today's and tomorrow's bio-based bulk chemicals from white biotechnology: A techno-economic analysis. Applied Biochemistry and Biotechnology. 136: 361-388.

Herzogbaum GmbH, 2008. Forstpflanzen-Preisliste 2008. HERZOG.BAUM Samen & Pflanzen GmbH. Koaserbauerstr. 10, A - 4810 Gmunden. Austria (also available at www.energiehoelzer.at).

Heston, A., R. Summers and B. Aten, 2006. Penn World Table Version 6.2. Center for International Comparisons of Production, Income and Prices at the University of Pennsylvania. September 2006. http://pwt.econ.upenn.edu/php_site/pwt62/pwt62_form.php,

Hill, J., 2007. Environmental costs and benefits of transportation biofuel production from food- and lignocellulose-based energy crops. A review. Agronomy for Sustainable Development. 27: 1-12.

IFA, 1992. World Fertilizer Use Manual. International Fertilizer Industry Association, ISBN 2-9506299-0-3, Germany.

ILO, 2007. Occupational Wages and Hours of Work and Retail Food Prices, Statistics from the ILO October Inquiry. International Labor Organisation, ISBN:9220201747 (Also available at http://laborsta.ilo.org/).

IPCC, 1996. Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories. Intergovernmental Panel on Climate Change, United Nations Environment Programme, Organization for Economic Co-Operation and Development, International Energy Agency, Paris.

Izaurralde, R. C., J. R. Williams, W. B. McGill, N. J. Rosenberg and M. C. Q. Jakas, 2006. Simulating soil C dynamics with EPIC: Model description and testing against long-term data. Ecological Modelling. 192: 362-384.

Jiroušek, R., R. Klvač and A. Skoupý, 2007. Productivity and costs of the mechanised cut-to-length wood harvesting system in clear-felling operations. Journal of Forest Science. 53: 476-482.

Jurvélius, M., 1997. Labor-intensive harvesting of tree plantations in the southern Philippines. Forest harvesting case -study 9. RAP Publication: 1997/41. Food and Agriculture Organization of the United Nations, Bangkok, Thailand. http://www.fao.org/docrep/x5596e/x5596e00.HTM.

Kaltschmitt, M., 2001. Grundlagen der Festbrennstoffnutzung - Begriffsdefinitionen. In: M. Kaltschmitt and H. Hartmann, Energie aus Biomasse - Grundlagen, Techniken und Verfahren. Berlin, Springer: 770.

Kim, S. and B. E. Dale, 2006. Ethanol fuels: E10 or E85 - Life cycle perspectives. International Journal of Life Cycle Assessment. 11: 117-121.

Kindermann, G. E., I. McCallum, S. Fritz and M. Obersteiner, 2008. A global forest growing stock, biomass and carbon map based on FAO statistics. Silva Fennica. 42: 387-396.

Kindermann, G. E., M. Obersteiner, E. Rametsteiner and I. McCallum, 2006. Predicting the deforestation-trend under different carbon-prices. Carbon Balance and Management. 1.

Koh, L. P. and J. Ghazoul, 2008. Biofuels, biodiversity, and people: Understanding the conflicts and finding opportunities. Biological Conservation. 141: 2450-2460.

Leduc, S., D. Schwab, E. Dotzauer, E. Schmid and M. Obersteiner, 2008. Optimal location of wood gasification plants for methanol production with heat recovery. International Journal of Energy Research. 32: 1080--1091 [2008].

McCarl, B. A. and T. H. Spreen, 1980. Price Endogenous Mathematical Programming as a Tool for Sector Analysis. American Journal of Agricultural Economics. 62: 87-102.

Mitchell, C. P., 2000. Development of decision support systems for bioenergy applications. Biomass and Bioenergy. 18: 265-278.

Molden, D., K. Frenken, R. Barker and C. de Fraiture, 2007. Trends in water and agricultural development. In: Water for Food, Water for Life: A Comprehensive Assdessment of Water Management in Agriculture, Earthscan, London and International Water Management Institute, Colombo.

Nadim, F., P. Zack, G. E. Hoag and S. Liu, 2000. United States experience with gasoline additives. Energy Policy. 29: 1-5.

OECD, 2008. Biofuel Support Policies: An Economic Assessment, OECDpublishing.

Rametsteiner, E., S. Nilsson, H. Böttcher, P. Havlik, F. Kraxner, S. Leduc, M. Obersteiner, F. Rydzak, U. Schneider, D. Schwab and L. Willmore, 2007. Study of the Effects of Globalization on the Economic Viability of EU Forestry. Final Report of the AGRI Tender Project: AGRI-G4-2006-06 [2007]. EC Contract Number 30-CE-0097579/00-89.

Rosegrant, M. W., T. Zhu, S. Msangi and T. Sulser, 2008. Global scenarios for biofuels: Impacts and implications. Review of Agricultural Economics. 30: 495-505.

Ruesch, A. and H. K. Gibbs, 2008. New IPCC Tier-1 Global Biomass Carbon Map For the Year 2000. Available online from the Carbon Dioxide Information Analysis Center http://cdiac.ornl.gov, Oak Ridge National Laboratory, Oak Ridge, Tennessee,

Russ, P., T. Wiesenthal, D. van Regenmorter and J. C. Císcar, 2007. Global Climate Policy Scenarios for 2030 and beyond - Analysis of Greenhouse Gas Emission Reduction Pathway Scenarios with the POLES and GEM-E3 models. JRC Reference Reports. Joint Research Centre - Institute for Prospective Technological Studies, Seville, Spain,

Sauer, T., P. Havlík, G. Kindermann and U. A. Schneider, 2008. Agriculture, Population, Land and Water Scarcity in a changing World - the Role of Irrigation. Congress of the European Association of Agricultural Economists, Gent, Belgium.

Schneider, U. A. and B. A. McCarl, 2003. Economic potential of biomass based fuels for greenhouse gas emission mitigation. Environmental and Resource Economics. 24: 291-312.

Schneider, U. A., B. A. McCarl and E. Schmid, 2007. Agricultural sector analysis on greenhouse gas mitigation in US agriculture and forestry. Agricultural Systems. 94: 128-140.

Seale, J., A. Regmi and J. Bernstein, 2003. International Evidence on Food Consumption Patterns. ERS/USDA, Technical Bulletin No.1904. ERS/USDA, Washington, D.C.

Searchinger, T., R. Heimlich, R. A. Houghton, F. Dong, A. Elobeid, J. Fabiosa, S. Tokgoz, D. Hayes and T. H. Yu, 2008. Use of U.S. croplands for biofuels increases greenhouse gases through emissions from land-use change. Science. 319: 1238-1240.

Skalský, R., Z. Tarasovičová, J. Balkovič, E. Schmid, M. Fuchs, E. Moltchanova, G. Kindermann and P. Scholtz, 2008. GEO-BENE global database for bio-physical modeling v. 1.0 - concepts, methodologies and data. The GEO-BENE database report. International Institute for Applied Systems Analysis (IIASA), Austria,

Sklar, T., 2008. Ethanol from wood waste an opportunity for refiners. Oil and Gas Journal. 106: 54-59.

Smeets, E. M. W., A. P. C. Faaij, I. M. Lewandowski and W. C. Turkenburg, 2007. A bottom-up assessment and review of global bio-energy potentials to 2050. Progress in Energy and Combustion Science. 33: 56-106.

Sørensen, A. L., 2005. Economies of Scale in Biomass Gasification Systems. Interim Report IR-05-030, IIASA

Stanturf, J. A., C. van Oosten, D. A. Netzer, M. D. Coleman and C. J. Portwood, 2002. Ecology and silviculture of poplar plantations. In: J. G. Isebrands, J. E. Eckenwalder and J. Richardson, Poplar culture in North America, part A, chapter 5. Ottawa, NRC Research Press, National Research Council of Canada: 153-206.

Stokes, B. J., D. J. Frederick and D. T. Curtin, 1986. Field trials of a short-rotation biomass feller buncher and selected harvesting systems. Biomass. 11: 185-204.

Tilman, D., J. Hill and C. Lehman, 2006. Carbon-negative biofuels from low-input high-diversity grassland biomass. Science. 314: 1598-1600.

Uri, V., H. Tullus and K. Lõhmus, 2002. Biomass production and nutrient accumulation in short-rotation grey alder (Alnus incana (L.) Moench) plantation on abandoned agricultural land. Forest Ecology and Management. 161: 169-179.

USDOE, 2008. DOE to Invest up to $4.4 Million in Six Innovative Biofuels Projects at U.S. Universities. DOE Press Release,

Wadsworth, F. H., 1997. Forest Production for Tropical America, USDA. Forest Service. Agriculture Handbook 710, USA: 563.

Wang, J., C. Long, J. McNeel and J. Baumgras, 2004. Productivity and cost of manual felling and cable skidding in central Appalachian hardwood forests. Forest Products Journal. 54: 45-51.

Webb, D. B., P. J. Wood, J. P. Smith and G. S. Henman, 1984. A Guide to Species Selection for Tropical and Sub-Tropical Plantations. Tropical Forestry Papers No. 15. Commonwealth Forestry Institute, Oxford, UK.

Williams, J. R., 1995. The EPIC Model. In: V. P. Singh, Computer Models of Watershed Hydrology, Water Resources Publications, Highlands Ranch, Colorado: 909-1000.

Yang, J., H. Qiu, J. Huang and S. Rozelle, 2008. Fighting global food price rises in the developing world: The response of China and its effect on domestic and world markets. Agricultural Economics. 39: 453-464.

You, L. and S. Wood, 2006. An entropy approach to spatial disaggregation of agricultural production. Agricultural Systems. 90: 329-347.

Zomer, R. J., A. Trabucco, D. A. Bossio and L. V. Verchot, 2008. Climate change mitigation: A spatial analysis of global land suitability for clean development mechanism afforestation and reforestation. Agriculture, Ecosystems and Environment. 126: 67-80.

Table 1: Land suitable for afforestation in different GLC 2000 Land Cover Classes.

Category	GLC Classes	Afforestation Potential [Mha]
Forest	All forest categories of GLC-2000 including the mosaic Forest/Natural Vegetation	3,151
Agriculture/Cropland	All managed and cultivated areas including mosaics Cultivated managed/Natural Vegetation, Cultivated Managed / Forest Cover	1,171
Grassland	Herbaceous Cover	299
Other Natural Vegetation	Shrubland and Sparse Shrubs / Sparse Grass	510

Table 2: Baseline global bioenergy production as estimated by POLES

Energy carrier	Units	2000	2010	2020	2030
Heat and Power	Mtoe of dry biomass	51	107	266	447
Direct biomass use	Mtoe of dry biomass	950	1019	1125	1201
Liquid fuels - first generation	Mtoe of fuel	10	101	140	165
Liquid fuels - second generation	Mtoe of fuel	0	3	13	112

Table 3: Scenarios considered in the analysis.

Scenario name	Description
Baseline	Original POLES scenario
First generation	Above 2005 values all additional biofuels produced from first generation processes
Second generation	Above 2005 values all additional biofuels produced from second generation processes
No biofuels	No increase in liquid bioenergy share above 2005 values

Table 4: Cumulative deforested area due to cropland expansion in 2030 (Mha) driven by food and bioenergy production.

Scenario name	Option 1: Crop and Grassland	Option 2: Production Forests	Option 3: Marginal Land
Baseline	150	122	105
First generation	145	144	130
Second generation	158	90	100
No biofuels	100	97	77

Table 5: Cumulative net emissions from land use change for 2000-2030 (Mt CO_2eq).

Scenario names	Option 1: Crop and Grassland	Option 2: Production Forests	Option 3: Marginal Land
Baseline	28786	27624	30513
First generation	35827	35626	39137
Second generation	19636	14653	23170
No biofuels	21210	20006	21905

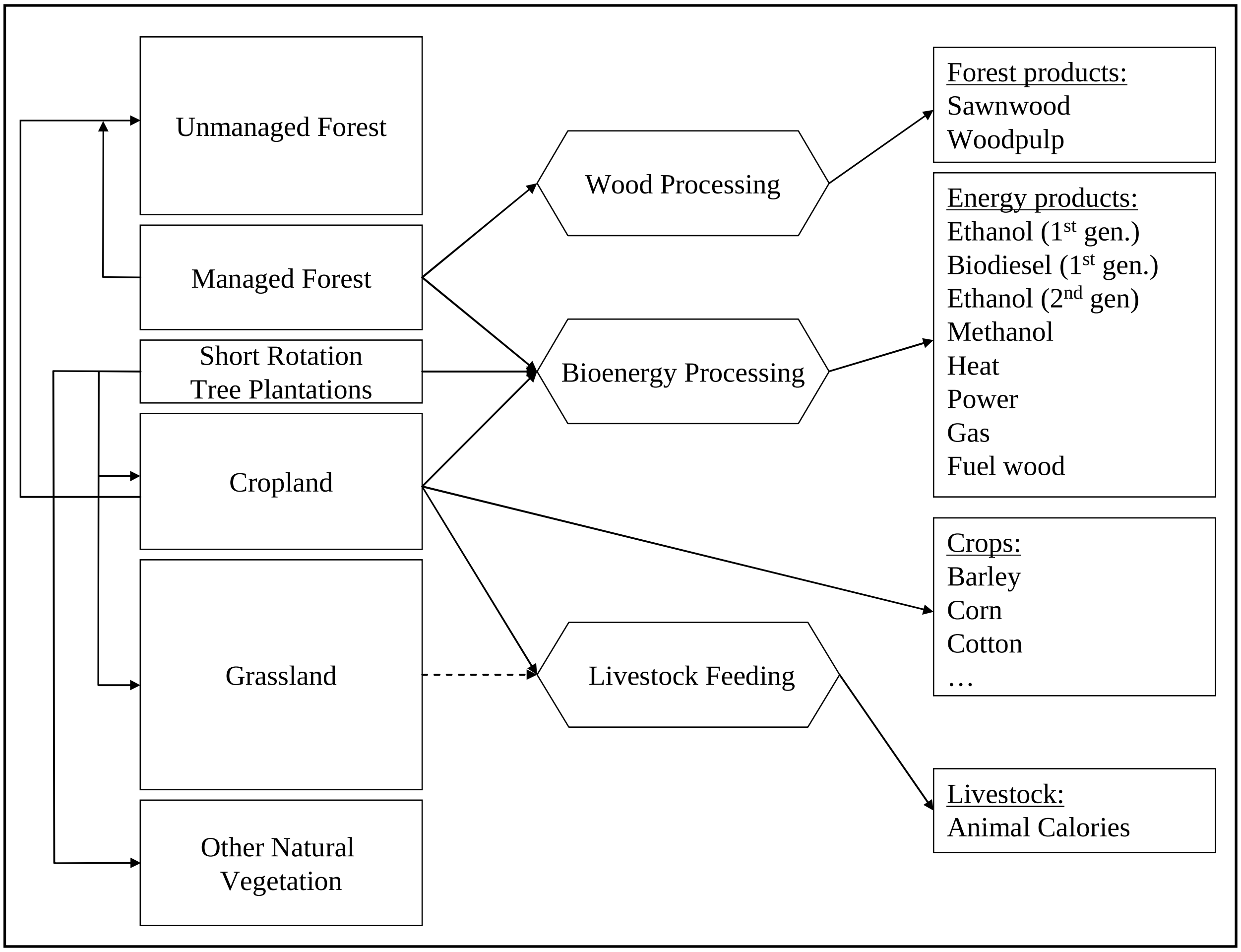
Table 6: Carbon payback time for different options.

Scenario names	Option 1: Crop and Grassland	Option 2: Production Forests	Option 3: Marginal Land
Baseline	11	10	13
First generation	22	24	27
Second generation	0	0	2

Table 7: Impact of different production options on fuel and crop prices in 2030 relative to 2000 prices.

Scenario names	Option 1: Crop and Grassland		Option 2: Production Forests		Option 3: Marginal Land	
	Fuel price	Crop price	Fuel price	Crop price	Fuel price	Crop price
Baseline	1.18	1.29	1.35	1.25	1.12	1.21
First generation	1.14	1.27	1.14	1.27	1.14	1.24
Second generation	1.38	1.30	2.84	1.23	1.21	1.23
No biofuels	1.10	1.23	1.10	1.23	1.09	1.21

Figure 1: GLOBIOM land use and product structure.



Appendix–3

Impacts of population growth, economic development, and technical change on global food production and consumption

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Abstract

Over the next decades mankind will demand more food from fewer land and water resources. This study uses a global, partial equilibrium, and bottom-up model of the agricultural and forest sectors to quantify the food production impacts of four alternative development scenarios from the Millennium Ecosystem Assessment and the Special Report on Emission Scenarios. Partially and jointly considered are land and water supply impacts from population growth, and technical change, as well as forest and agricultural commodity demand shifts from population growth and economic development. The income impacts on food demand are computed with dynamic elasticities. Model simulations show that per-capita food levels increase in all examined development scenarios with minor impacts on food prices. Global agricultural land increases by up to 18 percent until 2030. Deforestation restrictions strongly impact the price of land and water resources but have little consequences for the global level of food production and food prices. While projected income changes have the highest partial impact on per-capita food consumption levels, population growth leads to the highest increase in total food production. The impact of technical change is amplified or mitigated by adaptations of land management intensities.

1 Introduction

Food, land, and water constitute three of the most fundamental resources for mankind. These resources are under pressure by population growth, economic development, and environmental change. Essentially, tomorrow's farmers need to produce more food with fewer resources. Beyond meeting market demands, global food production has important interferences with several fundamental objectives of societies including the reduction of malnutrition and poverty, improved access to a healthy diet, better management and allocation of fresh water resources, increased use of renewable energy, and the protection of climate, ecosystems, and biological diversity. These interferences are affected by resource competition, technical progress, producer adaptation, commodity demand, global trade, and policies. Because food production is closely linked to major societal objectives, insights into its likely path and interferences within future development are of great concern to society and policymakers. To adequately capture the complex interferences between food production and overall development, integrated scientific model based assessments are demanded.

A variety of past studies have examined the impacts of global development on food production. These studies involve a wide spectrum of scientific disciplines, methods, models, and data. Geographic and biophysical assessments often focus on the heterogeneity of production conditions and their consequences. Engineering assessments in the land use sector deal primarily with technological development and associated opportunities. Economic assessments attend to farm-level and / or commodity market implications of development. In addition, there are policy oriented assessments which examine legal instruments and challenges for the regulation of land use and land use externalities. Studies which combine the economic, technical, biophysical, and legal aspects of agricultural development fall within the realm of integrated assessment studies (e.g., Bouwman et al. 2006, Rosegrant et al. 2002, Rosenzweig et al. 2004). These relatively comprehensive studies are able to quantify the net impacts of development over a diverse set of individual drivers and are a clear advancement over single factor based studies. Regarding development, the integrated studies attempt to simultaneously represent economic development, population growth, technical progress, environmental change, and possible policy pathways. However, integrated assessments are only valuable if their results can be adequately understood, interpreted, and compared to other studies. Different studies which lead to the same aggregated results but differ greatly in individual components do not promote confidence in scientific assessments and modeling.

In this study, we use an integrated land use assessment model to quantify and decompose the impacts of four commonly used development scenarios on global food production. The global agricultural and forest sector optimization model combines at a relatively high resolution the heterogeneity of agricultural conditions and choices with the feedback from internationally linked, global commodity markets. In analyzing the food production implications of three Millennium Ecosystem Assessment scenarios and the revised B1 scenario from the Special Report on Emission Scenarios, we follow several major objectives. First, we want to estimate regional food production impacts for each of the four development scenarios on per-capita food supply and the average ratio between vegetarian and non-vegetarian food. This ratio has received increasing attention for its effects on land scarcity, greenhouse gas emissions, and human health. However, quantitative projections of dietary changes with integrated assessment models are rare. Furthermore, our study results can be used to cross-check the consistency of assumptions made for the Millennium Ecosystem Scenarios and thus, provide methodological insights for the design of future development scenarios. As a second major objective, we want to decompose the total food production impacts of five exogenous drivers (population growth, gross national product development, technical change, land scarcity, water scarcity) and two alternative policies on deforestation of primary forests. To our knowledge, such decomposition has not been done for integrated assessments of global food production but is useful for several purposes. It increases understanding and facilitates interpretation of the aggregated results of this food production development study. In addition, decomposition helps to compare and better interpret previous studies which only provided aggregate food production development. Knowledge about the partial impacts of development factors also reveals which factors dominate the overall impacts and might therefore be most relevant to national and international policymakers.

2 Global challenges for food production

Throughout history, human populations have experienced deficiencies in food production. Growing populations in the past have caused local over exploitation of natural resources leading to the extinction or collapse of several ancient societies (Diamond 2005). However, today's resource scarcity is not only an acute problem in isolated locations; it is also a global threat. Three arguments may illustrate the global dimension of this threat. First, the collective use of resources for food production over all countries has reached substantial proportions. In 2005, agriculture occupied about 38 percent of the global land area (FAOSTAT 2005) yielding an average agricultural land endowment of 0.77 hectare per capita. Without technical progress and agricultural intensification and with current rates of population growth, agriculture would need an area equivalent to 1/2 and 2/3 of the current terrestrial land area by 2030 and 2070, respectively, in order to maintain current food consumption levels per capita. Considering distinctive developments in technology, agricultural management, and food consumption preferences, Rijsberman (2006) still estimate global increases in cropland requirements of 29-34 percent by 2025. Similar calculations can be made with respect to fresh water and energy resources. However, existing projections of fresh water demands (e.g., Doell and Siebert 2002, Molden 2007, Postel 1998, Rosegrant et al. 2002) differ substantially because of methodological and data differences regarding water productivity, land degradation, and technical efficiency (Sauer et al., 2010).

The second argument supporting a global dimension of food production challenges is that although some regions experience more problems than others, today’s societies are increasingly connected. Globalization opens the door to more international trade. Thus, regional commodity supply shortage or surplus can be transferred to and mitigated by world markets. Furthermore, globalization has reached governments. Since the establishment of the United Nations in 1945, many different international treaties have been adopted, which may particularly affect global food production and distribution. Environmental treaties relevant to food production include the convention on wetlands (RAMSAR convention), the Climate Change convention, and the convention on biological diversity (CBD convention). These treaties may limit possible expansion of agricultural land. However, expansion of cropland might be necessary to fulfill the eight millennium development goals defined by the world leaders at the United Nations

Millennium Summit in 2002 since they include targets for the reduction of hunger and malnutrition.

A third argument is that the cumulative impacts of local land use decisions may cause significant global environmental feedback, foremost through climate change (Alcamo et al., 2003; Foley et al., 2005; Tilman et al., 2001). There are both positive and negative agricultural impacts which influence the availability and fertility of land (Ramankutty et al., 2002), the length of the growing season (Lobell et al., 2008), fresh water endowments, pest occurrences, CO_2-fertilization, and the frequency of extreme events related to draughts, flooding, fire, and frost. Although global commodity trade and environmental policies are important drivers for resource utilization, a variety of additional factors influence the net impact of future development on land use and food supply. These factors include technical progress, land use intensities, land quality variations, resource endowments, and food demand characteristics. Technical progress and management intensification can reduce land scarcity. While improved technologies shift the production possibility frontier outwards, intensification moves production along a frontier by substituting one resource with another (Samuelson 1948). Irrigation, for example, increases water requirements but decreases land requirements per calorie. Intensification is often related to land but could be related to any other resource. Agricultural production can be intensified by employing more water, fertilizer, pesticides, machinery, or labor. Note that through intensification resources can become a substitute or complement. Similar antipodal effects can occur with commodity trade. Regional pressures on resource may decrease through commodity imports but increase due to specialization.

The variation of land quality also interacts with development. On the one hand, population growth increases food demand and therefore the demand for agricultural land. Since rationally acting agents use the most suitable resource first, additional agricultural land is likely to be less productive. On the other hand, population growth increases predominantly urban land areas (United Nations 2004). This expansion potentially removes high quality agricultural areas since cities are usually built on fertile land (von Thünen 1875). Furthermore, increased agricultural intensity due to population growth may increase land degradation over time. This could trigger a positive feedback loop where increased degradation leads to more degradation through intensification. Fourth, income growth especially in low income regions raises demand for animal based food more than demand for vegetarian food. Since animal food production involves an additional element in the food chain, it may increase land requirements per calorie by a factor of 10 or more relative to vegetarian food (Gerbens-Leenes and Nonhebel 2005). Thus, an increased demand of animal food is likely to increase total agricultural land use and management intensities with the above described implications.

3 A global agricultural and forest sector optimization model

To assess the complex interdependencies between population growth, economic and technological development, and the associated relative scarcities of land and water, we use the Global Biomass Optimization Model (GLOBIOM). GLOBIOM is a mathematical programming model of the global agricultural and forest sectors. Data, concept and mathematical structure of this model are described in Havlík et al. (2010). The core model equations are given in mathematical form in the appendix. The objective function of GLOBIOM simulates the global agricultural and forest market equilibrium by maximizing economic surplus over all included regions and commodities subject to restrictions on resource endowments, technologies, and policies. The scope and resolution of regions, commodities, management options, and resources is shown in Table 1 and Table 2. Particularly, agricultural and forest product markets are represented by 28 international regions covering the entire world. The definition of regions is consistent with 11 larger regions used in energy (Messner and Strubegger 1995) and pollution abatement models (Amann 2004) of IIASA's Greenhouse Gas Initiative and with the definition of more detailed regions from the POLES model (Criqui et al. 1999). Common region definitions facilitate the linkage of GLOBIOM with energy models in the context of climate and energy sustainability assessments.

Commodity demand is specified as downward-sloping function with constant elasticities. The model accounts for the annual net trade between all 28 regions. Demand data include observed prices-quantity pairs for domestic demand, imports and exports, own-price elasticities of demand. For agricultural products, prices and quantities are taken from FAO (2007). Own-price elasticities of agricultural commodity demand are taken from Seale et al. (2003). The specification of demand for forest commodities is based on data developed by Rametsteiner *et al*. (2007). The model explicitly depicts factor endowments in each region for a) agricultural, forest, and other natural lands and b) land suitable for irrigation. Irrigation water supply is depicted as constant elasticity, upward-sloping function.

Agricultural and forest production activities are portrayed in more detail than commodity markets and distinguish 165 individual countries with 137 land quality classes, 18 crop and 7 forest commodities, 5 irrigation alternatives, and numerous land qualities (Table 2). The land quality classes are referred to as homogenous response units (HRU) and are based on differences in altitude, soil texture, and slope. The highest diversity in land quality is observed in Indonesia with 97 HRUs. Livestock production in each region is represented as one composite activity keeping production from major individual activities, their feed and land requirements in fixed proportions. Crop and livestock production data are taken from FAO (2007), where national averages are used as base reference levels for yields, harvested areas, prices, production, consumption, trade, and supply utilization. Management specific crop yields and crop specific irrigation water requirements are simulated with the environmental policy integrated climate (EPIC) model (Williams 1995). These yields are calibrated such that the area-weighted average yield aggregated over all observed management options in a country equals the reported yield from FAO. The costs and technical restrictions for five irrigation systems are derived from a variety of sources and are described in more detail in Sauer et al. (2010). Traditional forest management is based on the 4DSM model developed by Rametsteiner *et al*. (2007). Production costs are compiled from an internal database at IIASA's Forestry Program.

When the uncalibrated GLOBIOM is solved for the base period, it does not closely reproduce observed activity levels. There are a variety of reasons for deviations. First, some data which influence land use decisions are difficult or impossible to obtain. These include impacts of crop rotations on yields, costs, labor, and machinery, which are often not available beyond a number of individual case studies. Second, some data are inaccurate because of measurement errors, inconsistent data collection methods, or insufficient resolution of the data. Third, our model operates at the sector level and does not explicitly portray many farm specific details, commodity qualities, and other local differences. Fourth, we assume competitive markets and rational behavior. To bring base solutions close to observation, we calibrate the direct costs for land management alternatives. Following classical economic theory, we linearly adjust the cost of each management option such that at base year commodity and factor prices, marginal revenues equal marginal costs (Wiborg et al. 2005). Trade costs for observed trading routes are calibrated with a non-linear cost function such that the solved trade levels for the base period are close to observed net exports.

The GLOBIOM modeling approach can be put in perspective with alternative methods. Previous land use assessments may be distinguished regarding a) the flow of information in top-down and bottom-up systems, b) the dominating analysis technique in engineering, econometric, and optimization approaches, c) the system dynamics in static equilibrium, recursive dynamic, and fully dynamic designs, d) the spatial scope in farm level, regional, national, multi-national, and global representations, and e) the sectoral scope in agricultural, forestry, multi-sector, and full economy models. Additional differences involve various modeling assumptions about market structure and the applied resolution over space, time, technologies, commodities, resources, and environmental impacts and associated data. For details on existing land use models, we refer to Lambin et al. (2000), Heistermann et al. (2006) and van der Werf and Peterson (2007). Applying classifications a) to e), our model can be characterized as bottom-up, optimization, recursive dynamic, global, agricultural and forest sector model.

4 Scenarios of Global Development

In this study, we assess and decompose global food production impacts of four global development scenarios. These scenarios have been used to study climate and energy sector development within an exercise organized for the Energy Modeling Forum 22: Climate policy scenarios for stabilization and in transition. We include the scenarios *Global Orchestration*, *Order from Strength*, and *Adaptation Mosaic* of the Millennium Ecosystem Assessment (MEA, Carpenter and Pingali 2005) and a revised B1 baseline emission scenario of the Special Report on Emissions Scenarios (SRES, Nakicenovic and Swart 2000). Global Orchestration focuses on increased globalization emphasizing economic growth and public goods provision. The Order from Strength scenario has a regionalized approach focusing on national security and self-sustenance, whereas the Adapting Mosaic scenario focuses on local adaptation and flexible governance. The B1 scenario is characterized by increasing use of clean and efficient technologies with global-scale cooperation.

Each scenario includes specific values on regional population growth and migration, gross domestic product development, and on the combined impacts of technical and environmental change. These values are exogenous to GLOBIOM and are summarized at global level in Table 3. Crop and livestock productivity changes are close to 1 percent increase per year and decline over time. The values are country and commodity specific rates compiled by the International Food and Policy Research Institute for each of the four development scenarios. The estimates of population growth also decline over time reflecting demographic transition. Population changes are also used to calculate exogenous shifts in resource endowments for land and water (last two row sections in Table 3). Land endowment changes are approximated by dividing the decadal change in population by regional specific urban population densities. We assume that increased urbanization decreases arable land because cities are usually located in agriculturally productive areas. By 2030, urbanization acquires an area of about 3 percent of the current cropland area. Values differ slightly across development pathways depending on the assumed rates of population growth. Population growth is also assumed to shift the agricultural water supply function. The total non-agricultural water use increases between 228 km3 (Global Orchestration) and 277 km3 (Order from Strength). It should be noted that all aggregates hide the underlying regional values, which may substantially differ across the four examined development pathways.

The exogenous development parameters affect five important parameters in GLOBIOM: a) the commodity demand function shift due to population growth, b) the commodity demand function shift due to per-capita income change, c) crop and livestock productivities, d) changes in regional land endowments due to population growth, and e) changes in regional fresh water availability due to population growth (see Appendix for mathematical representation). Population growth is assumed to shift the commodity demand functions in equivalent proportions. For example, a 10 percent population growth would increase agricultural and forest commodity demand by 10 percent at original prices. However, because commodity prices are endogenous in GLOBIOM and may change, the solved commodity demand levels may change more or less than 10 percent. The identification of income changes on food demand function shifts is more challenging and income elasticities play a significant role (Cicera and Masset, 2010). For this study, income elasticities have been computed to reproduce region-specific Engel curves reflecting diversity of diet dynamics. Most countries converge to a final consumption target of 3400-3600 kcal/cap/day after their nutritional transition but the composition of this target between vegetal and animal calories is based on the observed trends in each region for the base year (see Valin et al., 2010 for details). Therefore, nutritional requirements per habitant change faster with higher economic growth, which introduces an additional level of variation across scenarios. Neglecting the dynamics of these elasticities can lead to strong bias in projections of food demand (Yu et al., 2004). For instance, growth in meat consumption in China is likely to slow down drastically for the next decades (Alexandratos, 2006), which requires a highly non linear profile for income elasticity on meat for this country.

To distinguish the partial contribution of individual development drivers, we simulate each driver individually and jointly with others. Furthermore, we separate two settings on possible land use change policies. While the first setting allows deforestation of pristine forests in developing regions to gain new cropland, the alternative does not. In both settings, pristine forests can be converted to managed forests and vice versa. Managed forests cannot be converted to crop land or pasture. In total, we employ 4 basic development storylines, 2 land expansion alternatives, and compare 5 partial vs. 1 joint impact simulation. For each of these 48 combinations, we solve the global agricultural and forest sector model recursively from 2000 to 2030 in ten year increments. Land distributions at the end of a period serve as starting point for the next period.

5 Empirical Results

This section summarizes the simulation results from above-described scenarios. To provide a succinct summary within the scope of an article, we focus on aggregate measures. The use of aggregates has three additional advantages beyond brevity. First, as argued in Onal and McCarl (1991), sector models, while using more resolved data, perform better on the aggregated level. Second, aggregates implicitly contain many individual measures simultaneously. Third, the desirability of alternative development paths – in a potential Pareto optimality sense - can only be judged at the aggregated level.

5.1 Global Impacts of Development on Land, Water, and Food

Table 4 summarizes globally aggregated agricultural production parameters from the solution output of GLOBIOM. All values are from the scenario with all 5 development drivers implemented simultaneously (LWPIT). The row first section shows the arable land area in year 2000 and subsequent changes. If agricultural land expansion into pristine forests is allowed (Def setting), global cropland increases between 9 and 18 percent until 2030. The revised B1 baseline scenario results in the highest land use change. In this scenario, productivity change is relatively low but income and population change is relatively high. Hence, the increased food demand results in the highest expansion of cropland. For all scenarios with constrained deforestation, total cropland increases less but still exceeds the loss from urbanization after 2010.

Irrigation is an important adaptation option for farmers. The more water-deficient a region, the higher are yield differences between irrigated and rainfed cropping systems. In GLOBIOM, yield differences are based on biophysical simulations and differ across diverse land categories, climate zones, crops, and management regimes. However, the decision to irrigate is influenced not only by local characteristics but also by international commodity market feedbacks. Marginal revenues from irrigation depend on the product of yield differentials and commodity prices. Higher commodity prices increase the economic attractiveness of irrigation. On the other hand, increased water scarcity increases the marginal costs of irrigation. Table 4 shows the quantitative impacts of development on two measures: a) the change in irrigated area and b) the change in irrigation water use. We find decreases in irrigated area across all development scenarios. On the other hand, total agricultural water use shows a mixed response with initial decreases in 2010 and 2020 but subsequent increase in 2030. The mixed response illustrates the complex and diverse interdependency between land and water for food production. Decreases in agricultural water use indicate that increasing water opportunity costs from increased water demands outside the agricultural sector outweigh the increased marginal revenues from irrigation. The negative net impact on irrigation also contains the effect of productivity change. Increased productivity decreases land scarcity and therefore reduces agricultural water demands. If agricultural land expansion into pristine forests is disallowed, the decline in irrigation areas and agricultural water use is less than otherwise. The highest water use is found under the revised B1 scenario for the same reasons which cause the comparably high expansion in cropland.

The last four row sections of Table 4 show factor and commodity price impacts of development. All prices have been converted to indexes relative to the price level in 2000. Changes in global food prices reflect equilibrium adjustments from supply and demand shifts aggregated over all regions and food commodities. For all scenarios, both vegetarian and non-vegetarian food prices change very little. This indicates that the upward pressure on food prices from increased food demand and scarcer resources is compensated by the downward pressure on prices from increased productivity. Restricted deforestation leads to slightly higher food prices than otherwise. It should be noted that we did not assess future demands for alternative land use, which may include demands for bioenergy plantations. Such additional demands would cause additional upward pressure on food prices and lead to much more substantial price changes.

In contrast to low changes in average global food prices, we find relatively strong impacts on land and water prices. Water prices increase up to 75 percent by 2030. Land prices more than triple for some development scenarios. While prevention of deforestation has little impact on water prices, it does notably impact crop land prices. Across all development scenarios, the price increase is at least 100 percent less if expansion of cropland into pristine forests is allowed. The different sensitivity of land and water relates to the marginal productivity gains of the two factors. An additional unit of land increases the marginal revenue by the product of yield and commodity price. On the other hand, an additional unit of irrigation land increases the marginal revenue by the yield differential between irrigated and rainfed yields times commodity price. The smaller the increase in yield from irrigation, the lower is the value of water relative to land. Furthermore, the value of water in GLOBIOM may be understated because we do not consider weather uncertainties but rather use average weather conditions.

5.2 Partial Impacts of Development on Global Food Production

The qualitative impacts of population growth, economic development, and technical progress on food production and consumption are well-known. Particularly, total food production increase as result of technical progress, positive demand shifts, and increased availability of agricultural land. In contrast, higher scarcities of agricultural resources and negative demand shifts cause negative impacts on food production. Population growth without income growth will increase total food production but decrease the per-capita level of food production because the required expansion of agricultural production implies increasing marginal costs.

This section quantifies the partial impacts of individual drivers of development on global food production for each of the examined four development storylines. We distinguish between impacts on vegetarian and non-vegetarian food because these two food types differ in three important aspects. First, vegetarian food generally requires less land per calorie than does non-vegetarian food (Gerbens-Leenes and Nonhebel 2005). Second, positive income changes in developing countries increase the demand for non-vegetarian food considerably more than for vegetarian food. Thus, the net impact of development on the share of animal product based food is ambiguous. Third, the ratio between vegetarian and non-vegetarian food has important implications on the healthiness of the average diet.

The partial food consumption impacts are shown in Table 5, Figure 1, and Figure 2. All values in the 8 rightmost columns of Table 5 give the change in global per-capita food energy consumption relative to the year 2000. The initial per-capita food energy consumption levels in 2000 equal 2702 kcal per capita and day for all development scenarios. For all partial impact settings, which include the effect of population growth (P, LWP, LWPI, and LWPIT), the projected population values are used. For all other settings (L, W, LW, T, and I), we assume the year 2000 population values. Figure 1 graphically illustrates the absolute 2030 per-capita food energy intake values from Table 5 for the restricted deforestation setting.

The individual partial effects of land and water scarcity on per-capita food production show moderate decreases in the consumption of vegetarian food across all scenarios hardly exceeding 5 percent. Animal food consumption remains almost unchanged. Thus, the ratio between vegetarian and non-vegetarian food changes slightly towards a more vegetarian food diet. Table 5 reveals that the prohibition of deforestation has very little impact. Furthermore, in Table 1 we clearly see that the combined effect of increased land and water scarcity (LW) is much smaller than the sum of the two individual effects (L+W). This indicates a relatively complementary relationship between land and water. Such a relationship exists on irrigated lands because an urbanization of irrigated lands decreases water and land simultaneously. The impacts of land and water scarcity are similar across all development scenarios.

The third individual partial impact relates to the effect of population growth on food demand. Technologies, income and resource levels are held at year 2000 values. While total food energy production increases more under population growth than under income or technical change, the per–capita values decrease below the values of all other impacts. Figure 2 illustrates this trade-off graphically. The left arrangement of bars shows the per-capita food intake values for each development driver but projected to a population of the year 2000. For example, for the population impact, this means that the total food consumption level corresponds to GLOBIOM solutions with food demand functions of the population in 2030. The per-capita consumption level, however, is then computed by dividing the total food consumption level with the population in 2000. The decrease in per-capita food consumption from population growth results from increasing marginal costs of food production. For most scenarios with the exclusive population growth setting, we find a small shift towards vegetarian food.

At first glance, the benefits of technical change on per-capita food production seem to low. However, technical progress interacts with management intensities. GLOBIOM results contain the net impact of exogenous technical change and endogenous management intensities. Economically speaking, if there is a general yield increase, land would become less valuable. This could trigger a shift towards less intensive management, which partially offset the yield increase. Thus, the impacts of technical change as single driver may be much smaller than it would be in combination with other drivers which increase land scarcity. Technical change also increases the animal food share in the food diet. While theoretically consistent, the magnitude of this increase is small. The Global Orchestration scenario has the highest productivity increases and hence increases per-capita food consumption more than all other development scenarios.

The last of the examined partial impacts of development is demand growth due to income (GDP) change. We observe a substantial increase in per-capita food consumption, with highest values under the revised B1 and the Global Orchestration scenario. For the Order from Strength and the Adapting Mosaic scenarios, the income effects are lower. The income change has the highest impact among all exogenous development parameters on the animal food share reaching about 5 percentage points by 2030 (Figure 1). For all development scenarios, we find that the income based increase in total food energy production would not be sufficient the per-capita food energy consumption levels of year 2000 with a population size of 2030. This can be seen in Figure 2. For example, for the B1 scenario, the income based increase in food energy consumption projected increases the average per-capita food energy consumption from 2700 kcal per day to 3000. If the total consumption increase would be divided by the 2030 population, per-capita food energy consumption would decrease to levels below 2400 kcal per day.

The joint implementation scenario (LWPIT) shows the net impact on per-capita global food energy consumption, when all development impacts are combined. With few exceptions, all net impacts are positive implying that the global average food availability per capita will increase until 2030. There is a clear ranking between the four development scenarios. The Global Orchestration scenario leads to the highest per-capita food availability followed by the revised B1 scenario. Adapting Mosaic yields the third highest overall per-capita consumption level. The Order of Strength scenario achieves the lowest increase in food availability with less than 5 percentage points relative to the year 2000. Deforestation restrictions have little influence and do not change per-capita food availability by more than 1 percent.

5.3 Regional Food Consumption Impacts

While the previous section has shown overall positive food supply impacts of all four examined storylines, this section takes a look at regional differences. To ease this task, we aggregate the model's 28 consumption regions into 11 broader region groups (Table 6). The initial per-capita food energy intake values in year 2000 are given in brackets on the left most columns. The values in the eight right columns are expressed in percent relative to the energy intake in 2000. Thus, a value of 100 implies no change in total per-capita food energy intake relative to the intake in year 2000. All values are from simulations with all development drivers simultaneously implemented.

As Table 6 reveals, in most cases the per-capita food energy intake increases. Across all cases, changes range from a 5 percent decrease to a 34 percent increase relative to the situation in year 2000. While regions with high food consumption levels such as North America and Western Europe experience relatively little change in their average food energy intake, only some of the less developed regions show higher increases. For example, the increase in per-capita food consumption in South Asia, which has the second lowest food intake levels in 2000, is substantially below the increase in Latin America and the Caribbean, a region whose average food energy intake is already 19 percent higher in year 2000. The region with the lowest food intake values in year 2000 is Sub-Saharan Africa. It increases average food energy intake values by 2030 between 11 and 32 percent. African and Latin American countries have the highest change in the revised B1 scenario. Asian countries fare best under the setting of Global Orchestration. The Order from Strength scenario achieves the smallest gains in per-capita food consumption in all regions. The impact of deforestation restrictions on per-capita food consumption is small for most regions. Only for Sub-Saharan Africa and Other Pacific Asia, the differences are notable and range between 3 and 7 percentage points.

There are notable differences between the four alternative development scenarios. The revised B1b scenario has a high global benefit with the highest food intake improvements in Latin America, Sub-Saharan Africa, and Other Pacific Asia. Relatively balanced benefits across regions are found for the Global Orchestration pathway. Across the four alternatives, Global Orchestration produces the also highest gains in many regions including the developed regions, Central Eastern Europe, the former Soviet Union, Planned Asia and China, Other Pacific Asia, and South Asia. The Order from Strength pathway shows for most regions only a moderate increase in food demand. Hence, the per-capita availability of food remains fairly unchanged. Only in four regions, increases in food intake exceed 10 percent by 2030. In South Asia average food energy intake decreases slightly. The fourth examined development pathway is called Adapting Mosaic and is characterized by relatively severe impacts of global change and a focus on local strategies. The food production impacts of Adapting Mosaic are similar to the Order from Strength scenario. However, the relatively local approach also yields a few regions with somewhat better results, i.e. Planned Asia and China and Other Pacific Asia.

6 Summary and Conclusions

International development has been feared to impose considerable challenges to global food production because more food has to be produced with fewer agricultural resources. This paper uses a global, partial equilibrium, and bottom-up model of land use to assess these interdependencies between land, water, and food in the context of different global development scenarios. The chosen modeling approach differs from relatively coarse macroeconomic assessments using top-down, computable general equilibrium models by depicting detailed land qualities and agricultural management adaptations. The approach also differs from data rich geographic analyses, which keep important international market feedbacks through price changes exogenous. In contrast to previous assessments and an earlier version of this study, we use dynamic GDP elasticities depicting an empirically estimated Engel curvature between food consumption and income. This leads to strongly decreasing income elasticities of food consumption beyond 3000 kcal food intake per person and day. Another novel feature of this analysis is the decomposition of food production and consumption impacts into partial effects of different drivers.

From the application of this model to four alternative development scenarios, we gain several insights. First, total global food production, consumption, and price levels are relatively stable across all scenarios and within the investigated time horizon until 2030. Decreases in per-capita consumption are rare and do not exceed 5 percent. Stable results are also obtained for a land use policy setting, where deforestation of pristine forests is prohibited. The downside of stability is that in some regions it implies a continuation of malnutrition problems. In other regions with inadequate nutrition levels, improvements are likely. Furthermore, the complex interactions between different drivers of land use decisions cause non-linear impacts. Regional changes deviate from average global changes.

A second important insight is that restricted arable land expansion has little impact on food prices but relatively high impacts on prices for land and water. Increased food demand through population or income growth along with reduced resource endowments increase both food commodity prices and factor prices for food production. Technical progress in agriculture, on the other hand, decreases food commodity prices but increases production factor prices. Higher crop yields per ha increase marginal revenues of land. Thus, while the investigated development impacts put multiple upward pressure on resource prices, food prices are mitigated through technical change. The second insight also suggests that the environmental benefits from reduced deforestation benefits may not severely threaten food availability. If land expansion is limited, farmers could adapt by intensifying production on existing lands.

A third insight from this study relates to the partial contribution of individual drivers to food production and consumption levels. Across all four examined development scenarios, the per-capita income changes have the highest positive impact on per-capita food consumption levels and exceed the individual impacts of technical change. Population growth without income and technical change leads to the strongest decline in per-capita food consumption. Model results also show that the combined effects are often quite different from the sum of individual effects.

Several limitations and simplifications to this work need to be mentioned. First, GLOBIOM is a data intensive bottom-up mathematical programming model of the agricultural and forestry sectors and its results cannot be better than the available data. The solution values are point estimates without confidence interval. Our analysis does not portray adjustments in industrial sectors beyond the impacts contained in the exogenous GDP values. We do not consider homogenous response unit specific water endowments. Agricultural water availability is represented through regional supply functions and increases in non-agricultural water demand are fully competitive with agricultural water demands. Furthermore, crop yields are results from a simulation model with average weather conditions. The impacts of extreme weather events are not included. Water management adaptations do not consider water storage options. Furthermore, our analysis ignores the dynamics of soil quality and the benefits of soil restoration and the losses from soil degradation. Possible climate change impacts on agriculture until 2030 are neglected. Finally, we only include a bioenergy demand baseline. The inclusion of stronger bioenergy policies may substantially reduce global food production potentials.

References

Alcamo, J., M. Maerker, M. Floerke, and S. Vassolo (2003), Water and Climate: A Global Perspective, Kassel World Water Series 6, Center for Environmental Systems Research, University of Kassel, Germany.

Alexandratos, N.; Bruinsma, J.; Boedeker, G.; Schmidhuber, J.; Broca, S.; Shetty, P. & Ottaviani, M. (2006), 'World agriculture: towards 2030/2050. Interim report. Prospects for food, nutrition, agriculture and major commodity groups', FAO.

Amann M. (2004) The RAINS model. Documentation of the model approach prepared for the RAINS peer review 2004. International Institute for Applied Systems Analysis, Laxenburg, Austria.

Bouwman, A. F., T. Kram, and K. Klein Goldewijk (Eds.) (2006), Integrated modelling of global environmental change - An overview of IMAGE 2.4, Netherlands Environmental Assessment Agency (MNP), Bilthoven.

Carpenter S and P. Pingali (2005). Millenium ecosystem assessment—scenarios assessment. Island, Washington, DC.

Cirera, X. & Masset, E. (2010), 'Income distribution trends and future food demand', *Philosophical Transactions of the Royal Society B: Biological Sciences* 365(1554), 2821-2834.

Criqui, P., Mima, S., and L. Viguier. (1999). “Marginal abatement costs of CO2 emission reductions, geographical flexibility and concrete ceilings: an assessment using the POLES model.” *Energy Policy* 27(10):585-601.

Dalhuisen,J.M., R.J.G.M.Florax, H.L.F.Groot, and P.Nijkamp. (2003). "Price and Income Elasticities of Residential Water Demand: A Meta-Analysis." *Land Economics*. 79:292-308.

Diamond, Jared (2005). *Collapse: How Societies Choose to Fail or Succeed*. New York: Viking Books. ISBN 1-586-63863-7.

Doell, P., and S. Siebert (2002), Global modeling of irrigation water requirements, Water Resources Research, 38(4), 8-1–8-10, doi: 10.1029/2001WR000355.

FAOSTAT. 2005. Available online at faostat.fao.org.

Foley, J. A., R. De Fries, G. P. Asner, C. Barford, G. Bonan, S. R. Carpenter, F. S. Chapin, M. T. Coe, G. C. Daily, H. K. Gibbs, J. H. Helkowski, T. Holloway, E. A. Howard, C. J. Kucharik, C. Monfreda, J. A. Patz, I. C. Prentice, N. Ramankutty, and P. K. Snyder (2005), Global Consequences of Land Use. Science, 309, 570-574.

Gerbens-Leenes,W. and S.Nonhebel. (2005). "Food and land use. The influence of consumption patterns on the use of agricultural resources." *Appetite*. 45:24-31.

Heistermann,M., C.Muller, and K.Ronneberger. (2006). "Land insight? Achievements, deficits and potentials of continental to global scale land-use modeling." *Agriculture Ecosystems & Environment*. 114:141-158.

Lambin,E.F., M.D.A.Rounsevell, and H.J.Geist. (2000). "Are agricultural land-use models able to predict changes in land-use intensity?" *Agriculture, Ecosystems & Environment*. 82:321-331.

Lobell, D. B., M. B. Burke, C. Tebaldi, M. D. Mastrandrea, W. P. Falcon, and R. L. Naylor (2008), Prioritizing Climate Change Adaptation Needs for Food Security in 2030, Science, 319, 607-610.

Messner, S., Strubegger, M., (1995): User's Guide for MESSAGE III, WP-95-69, International Institute for Applied Systems Analysis, Laxenburg, Austria.

Molden, D. (Ed.) (2007), Water for food, Water for life: A Comprehensive Assessment of Water Management in Agriculture, IWMI (International Water Management Institute), Washington DC.

Nakicenovic N. and Swart, R.J. (2000) Emissions Scenarios 2000 – Special Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge.

Onal,H. and B.A.Mccarl. (1991). "Exact Aggregation in Mathematical-Programming Sector Models." *Canadian Journal of Agricultural Economics-Revue Canadienne D Economie Rurale*. 39:319-334.

Samuelson, P.A. (1948) “International Trade and the Equalisation of Factor Prices”, *The Economic Journal* 58(230):163-184.

Postel, S. L. (1998), Water for Food Production: Will There Be Enough in 2025, BioScience, 48(8), 629-637.

Ramankutty, N., J. A. Foley, J. Norman, and K. McSweeney (2002), The global distribution of cultivable lands: current patterns and sensitivity to possible climate change, Global Ecology & Biogeography, 11, 377-392.

Rametsteiner, E., S. Nilsson, H. Boettcher, P. Havlik, F. Kraxner, S. Leduc, M. Obersteiner, F. Rydzak, U.A. Schneider, D. Schwab, L. Willmore (2007). Study of the Effects of Globalization on the Economic Viability of EU Forestry. Final Report of the AGRI Tender Project: AGRI-G4-2006-06 [2007]. http://ec.europa.eu/agriculture/analysis/external/viability_forestry/index_en.htm

Rijsberman, F. R. (2006), Water Scarcity: Fact or Fiction?, Agricultural Water Management, 80(1-3), 5-22.

Rosegrant M.W., X. Cai and S.A. Cline (2002) *Global Water Outlook to 2025: Averting an Impending Crisis*, A Report Summary of the 2020 Vision for Food, Agriculture and the Environment Initiative, International Food Policy Research Institute, Washington DC and International Water Management Institute, Colombo

Rosegrant, M. W., X. Cai, and S. A. Cline (2002), World Water and Food to 2025: Dealing with Scarcity, International Food Policy Research Institute, Washington DC Mimeo.

Rosenzweig, C., Strzepek, K. M., Major, D. C., Iglesias, A., Yates, D. N., McCluskey, A., & Hillel, D. (2004). Water resources for agriculture in a changing climate: international case studies. Global Environmental Change, 14, 345–360.

Sauer, T., P. Havlík, U. A. Schneider, E. Schmid, G. Kindermann, and M. Obersteiner (2010), Agriculture and resource availability in a changing world: the role of irrigation, Water Resources Research, 46, W06503, doi:10.1029/2009WR007729.

Seale, J., A. Regmi, and J. Bernstein (2003). "International Evidence on Food Consumption Patterns." ERS/USDA, Technical Bulletin No.1904, ERS/USDA, Washington, D.C.

Skalsky, R., Z. Tarasovičová, J. Balkovič, E. Schmid, M. Fuchs, E. Moltchanova, G. Kindermann, and P. Scholtz (2008). GEO-BENE global database for bio-physical modeling v. 1.0 – concepts, methodologies and data. The GEO-BENE database report. International Institute for Applied Systems Analysis (IIASA), Austria, pp. 58.

Tilman, D., J. Fargione, B. Wolff, C. D´Antonio, A. Dobson, R. Howarth, D. Schindler, W. H. Schlesinger, D. Simberloff, and D. Swackhamer (2001), Forecasting agriculturally driven Global Environmental Change, Science, 292, 281-284.

United Nations (2004). World urbanization prospects: The 2003 revision. Department of Economic and Social Affairs, Population Division, New York

Valin, H., Havlik, P., Mosnier, A., Obersteiner, M. (2010), 'Food consumption patterns under climate change mitigation policies', Paper presented at the at the 1st Joint EAAE/AAEA Seminar "The Economics of Food, Food Choice and Health", Freising, Germany, September 15 – 17, 2010

Van der Werf, E. & Peterson, S. (2007), "Modeling linkages between climate policy and land use: An overview". FEEM Working Papers 56.2007, Fondazione Eni Enrico Mattei, Milano, Italy.

Voeroesmarty, C. J., P. Green, J. Salisbury, and R. B. Lammers (2000), Global Water Resources: Vulnerability from Climate Change and Population Growth, Science, 290, 284-288.

von Thünen, Jh.H. (1875). Der isolierte Staat in Beziehung auf Landwirtschaft und Nationalökonomie. Eds. Hermann Schumacher, 3. Edition, Wiegandt, Hempel & Parey, Berlin. p 400.

Wiborg, T., B.A. McCarl, S. Rasmussen, and U.A. Schneider (2005), "Aggregation and Calibration of Agricultural Sector Models Through Crop Mix Restrictions and Marginal Profit Adjustments."

Williams, J. R., 1995. The EPIC Model. In: Singh, V. P., Computer Models of Watershed Hydrology, Water Resources Publications, Highlands Ranch, Colorado, 909-1000.

Yu, W.; Hertel, T.; Preckel, P. & Eales, J. (2004), 'Projecting World Food Demand Using Alternative Demand Systems', *Economic Modelling* 21, 99--129.

Table 7 Geopolitical Resolution of GLOBIOM

Model Region	Contained Countries
CANADA	Canada
USA	USA
MEXICO	Mexico
CENTR_AMER	Bahamas, Barbados, Belize, Bermuda, Costa Rica, Cuba, Dominica, Dominican Republic, El Salvador, Grenada, Guatemala, Haiti, Honduras, Jamaica, Antilles, Nicaragua, Panama, St. Lucia, St. Vincent, Trinidad Tobago
SOUTH_AMER	Argentina, Bolivia, Chile, Colombia, Ecuador, Guyana, Paraguay, Peru, Suriname, Uruguay, Venezuela
BRAZIL	Brazil
ROWE	Gibraltar, Iceland, Norway, Switzerland
EU_NORTH	Denmark, Finland, Ireland, Sweden, United Kingdom
EU_MIDWEST	Austria, Belgium, France, Germany, Luxembourg, Netherlands
EU_BALTIC	Estonia, Latvia, Lithuania
EU_SOUTH	Cyprus, Greece, Italy, Malta, Portugal, Spain
EU_CENTREAST	Bulgaria, Czech Republic, Hungary, Poland, Romania, Slovakia, Slovenia
EU_OTHER	Albania, Bosnia Herzegovina, Croatia, Macedonia, Serbia-Montenegro
TURKEY	Turkey
MIDEAST_NAFR	Algeria, Bahrain, Egypt, Iran, Iraq, Israel, Jordan, Kuwait, Lebanon, Libya, Morocco, Oman, Qatar, Saudi Arabia, Syria, Tunisia, United Arabic Emirates, Yemen
SUBSAH_AFR	Angola, Benin, Botswana, Burkina Faso, Burundi, Cape Verde, , Chad, Comoros, Ivory Coast, Djibouti, Eritrea, Ethiopia, Gambia, Ghana, Guinea, Guinea-Bissau, Kenya, Lesotho, Liberia, Madagascar, Malawi, Mali, Martinique, Mauritania, Mozambique, Niger, Nigeria, Rwanda, São Tomé and Príncipe, Senegal, Seychelles, Sierra Leone, Somalia, Sudan, Swaziland, Tanzania, Togo, Uganda, Zambia, Zimbabwe
CONGOBASIN	Cameroon, Central African Republic, Democratic Republic of the Congo, Republic of the Congo, Equatorial Guinea, Gabon
SOUTH_AFRICA	South Africa
FORMER_USSR	Armenia, Azerbaijan, Belarus, Georgia, Kazakhstan, Kyrgyzstan, Moldova, Russian Federation, Tajikistan, Turkmenistan, Ukraine, Uzbekistan
RSAS	Afghanistan, Bangladesh, Bhutan, Maldives, Nepal, Pakistan, Sri Lanka
INDIA	India
CHINA	China
JAPAN	Japan
RSEA_PAC	Cambodia, North Korea, Laos, Mongolia, Vietnam,
S_KOREA	South Korea
RSEA_OPA	Brunei, Indonesia, Malaysia, Myanmar, Philippines, Singapore, Thailand
AUSTRALIA	Australia, New Zealand
PACIFIC_ISL	Fiji Islands, Kiribati, Papua New Guinea, Samoa, Solomon Islands, Tonga, Vanuatu

Table 8 Scope of GLOBIOM

Index	Elements
Land Use Types	Arable and grass lands, plantations, managed forests, native forests, other natural vegetation
Explicit Resources	Land, irrigation land, water
Cost items	Production cost, trade cost, land use change cost
Crops	Barley, cassava, chickpeas, corn, cotton, dry beans, ground nuts, millet, oil palm fruit, potatoes, rapeseed, rice, soya, sorghum, sugarcane, sunflower, sweet potatoes, wheat
Livestock Products	Animal food calories with fixed proportions of bovine meat, pig meat, sheep and goat meat, chicken meat, equine meat, fresh milk, turkey meat, and eggs from hens and other birds
Forest Commodities	Sawn wood, wood pulp, fuel wood, other industrial wood
Other Commodities	Methanol, ethanol, Biodiesel, Heat, Power, Biogas
Management	Subsistence, low intensity rainfed, high intensity rainfed, furrow irrigation, sprinkler irrigation, drip irrigation, surface irrigation

Table 9 Exogenous Development Scenario Drivers in GLOBIOM

Impact	Year	IIASA rB1b	MEA GlbOrc	MEA OrdStr	MEA AdpMos
Population [Billion]	2000	6.10	6.10	6.10	6.10
	2010	6.94	6.76	6.98	6.98
	2020	7.67	7.31	7.83	7.81
	2030	8.25	7.73	8.55	8.51
Average Gross Domestic Product [$1000/cap]	2000	4.73	4.73	4.73	4.73
	2010	5.56	5.79	5.24	5.26
	2020	7.23	7.76	6.02	6.16
	2030	9.41	10.53	6.81	7.37
Average Annual Crop Productivity Factor [% change relative to year 2000]	2000	0.00	0.00	0.00	0.00
	2010	4.81	6.42	4.72	4.96
	2020	9.34	12.85	9.31	9.80
	2030	11.81	19.00	11.32	12.44
Average Annual Livestock Productivity Factor [% change relative to year 2000]	2000	0.00	0.00	0.00	0.00
	2010	4.18	4.91	4.22	4.43
	2020	8.02	9.79	8.36	8.76
	2030	10.33	14.16	10.57	11.39
Arable Land Loss from Urbanization [Mill ha]	2010	14.32	12.25	15.14	15.14
	2020	27.08	23.07	30.00	29.78
	2030	37.38	31.99	42.67	42.02
Change in Non-Ag Water Use [km3]	2010	96.8	85.6	101.7	101.7
	2020	182.8	163.8	200.4	199.4
	2030	249.5	227.6	276.8	274.8

Table 10 GLOBIOM Results: Impacts of Development on Agricultural Sector (all development drivers implemented simultaneously, LWPIT Scenario)

Agricultural Sector Impact	Year	IIASA B1b		MEA GlbOrc		MEA OrdStr		MEA AdpMos	
		NoD	Def	NoD	Def	NoD	Def	NoD	Def
Arable Area [Mill ha]	2000	938.77							
Change to year 2000 [Mill ha]	2010	21.1	30.6	15.2	25.2	16.9	28.6	18.4	29.2
	2020	74.3	90.2	39.3	49.5	59.5	77.3	59.8	78.3
	2030	147.8	169.5	83.8	92.9	123.2	141.7	127.6	147.9
Irrigated Area [Mill Ha]	2000	226.89							
Change to year 2000 [Mill ha]	2010	-6.8	-5.3	-6.3	-4.9	-9.6	-7.3	-9.6	-6.2
	2020	-8.3	-3.5	-9.2	-6.9	-14.7	-9.3	-15.4	-8.2
	2030	-6.2	-3.2	-9.1	-5.0	-10.1	-7.5	-9.1	-7.4
Irrg. Water Uptake [km3]	2000	408.67							
Change to year 2000 [km3]	2010	-8.9	-6.3	-6.9	-4.6	-12.7	-8.1	-12.9	-8.5
	2020	-4.7	3.6	-5.2	-2.2	-14.1	-2.3	-14.1	-0.6
	2030	2.2	8.9	-2.4	5.4	-2.0	4.7	0.7	4.0
Crop Price [2000=1]	2010	1.05	1.05	1.03	1.03	1.06	1.05	1.05	1.05
	2020	1.06	1.04	1.00	0.98	1.06	1.04	1.05	1.03
	2030	1.08	1.04	0.98	0.96	1.08	1.04	1.07	1.03
Livestock Price [2000=1]	2010	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99
	2020	0.99	0.99	0.98	0.97	0.99	0.99	0.99	0.98
	2030	0.99	0.99	0.97	0.97	0.99	0.98	0.99	0.98
Water Price [2000=1]	2010	1.11	1.12	1.11	1.12	1.08	1.10	1.09	1.10
	2020	1.42	1.39	1.27	1.26	1.29	1.30	1.31	1.32
	2030	1.75	1.69	1.52	1.53	1.66	1.60	1.68	1.64
Land Price [2000=1]	2010	1.43	1.35	1.30	1.22	1.36	1.29	1.36	1.30
	2020	3.12	2.08	2.11	1.58	2.46	1.86	2.53	1.91
	2030	4.28	2.96	3.14	2.29	3.59	2.61	3.62	2.67

Table 11 GLOBIOM Results: Impacts of Development on per-capita Food Energy Intake relative to 2000 Population (L, W, T, I) or Projected Population (P, LWPTI) [2000=100]

Development Impact	Food Type	Year	IIASA B1b		MEA GlbOrc		MEA OrdStr		MEA AdpMos	
			NoD	Def	NoD	Def	NoD	Def	NoD	Def
Land Scarcity (L)	Vegetarian	2010	95.5	95.6	95.5	95.5	95.5	95.6	95.5	95.6
		2020	95.3	95.4	95.4	95.5	95.3	95.4	95.3	95.4
		2030	93.6	94.3	95.1	95.2	94.9	95.1	94.9	95.1
	Non-Vegetarian	2010	99.7	99.7	99.7	99.7	99.7	99.7	99.7	99.7
		2020	99.7	99.7	99.7	99.7	99.7	99.7	99.7	99.7
		2030	99.2	99.3	99.7	99.7	99.7	99.7	99.7	99.7
Water Scarcity (W)	Vegetarian	2010	95.6	95.5	95.5	95.6	95.5	95.6	95.6	95.5
		2020	95.5	95.5	95.5	95.5	95.5	95.5	95.5	95.5
		2030	94.6	94.7	95.4	95.3	95.4	95.4	95.4	95.4
	Non-Vegetarian	2010	99.7	99.7	99.7	99.7	99.7	99.7	99.7	99.7
		2020	99.7	99.7	99.7	99.7	99.7	99.7	99.7	99.7
		2030	99.6	99.6	99.8	99.8	99.8	99.8	99.8	99.8
Population Growth (P)	Vegetarian	2010	94.8	94.8	95.1	95.2	94.9	94.9	94.9	94.9
		2020	93.0	93.4	94.6	94.7	93.3	93.7	93.4	93.7
		2030	91.2	91.9	93.5	93.7	91.9	92.3	91.9	92.4
	Non-Vegetarian	2010	95.8	95.8	97.0	97.0	95.7	95.7	95.7	95.7
		2020	92.4	92.5	95.3	95.3	92.3	92.4	92.4	92.5
		2030	90.3	90.3	94.1	94.2	89.1	89.1	89.5	89.6
Technical Progress (T)	Vegetarian	2010	97.4	97.4	98.2	98.3	97.3	97.4	97.5	97.5
		2020	99.2	99.3	100.8	100.9	99.0	99.2	99.3	99.4
		2030	99.9	100.1	103.4	103.5	100.0	100.0	100.4	100.5
	Non-Vegetarian	2010	100.6	100.6	100.7	100.7	100.6	100.6	100.6	100.6
		2020	101.1	101.2	101.5	101.5	101.1	101.2	101.2	101.2
		2030	101.4	101.4	102.5	102.5	101.6	101.6	101.8	101.8
Income Change (I)	Vegetarian	2010	100.1	100.2	100.2	100.2	98.6	98.6	99.0	99.1
		2020	104.5	104.5	104.4	104.5	101.5	101.6	102.5	102.6
		2030	106.7	107.4	107.2	107.4	103.5	103.6	104.9	105.0
	Non-Vegetarian	2010	108.9	108.9	108.2	108.2	105.5	105.5	106.2	106.2
		2020	118.0	118.0	116.8	116.8	110.8	110.8	112.6	112.6
		2030	124.0	124.0	123.4	123.8	115.1	115.1	118.5	118.5
Joint Impact (LWPIT)	Vegetarian	2010	100.9	101.1	102.0	102.2	99.3	99.5	99.8	100.0
		2020	105.4	106.5	108.1	108.8	101.7	102.7	103.1	104.0
		2030	109.3	111.1	113.3	114.5	103.1	104.6	105.4	106.9
	Non-Vegetarian	2010	105.3	105.3	106.2	106.2	101.8	101.8	102.9	102.9
		2020	110.8	111.2	113.3	113.4	103.7	104.0	105.8	106.0
		2030	114.7	115.3	119.2	119.4	104.6	105.1	108.6	108.8

Table 12 GLOBIOM Results: Impact of Development and Regional per-capita total food energy intake based on projected Population (LWPIT Scenario) [2000=100]

Region (kcal/cap/day of 2000)	Year	IIASA B1b NoD	IIASA B1b Def	MEA GlbOrc NoD	MEA GlbOrc Def	MEA OrdStr NoD	MEA OrdStr Def	MEA AdpMos NoD	MEA AdpMos Def
North America (3635)	2010	99.7	99.7	100.3	100.3	99.9	99.9	100.0	100.0
	2020	99.7	100.0	101.2	101.7	99.7	100.0	99.7	100.0
	2030	99.6	99.6	101.6	102.0	99.2	99.5	99.7	99.7
Western Europe (3361)	2010	101.8	101.8	102.3	102.3	101.5	101.5	101.4	101.4
	2020	103.3	103.5	105.0	105.0	103.2	103.3	103.1	103.2
	2030	103.8	104.5	107.2	107.5	103.9	104.4	104.1	104.5
Pacific OECD (2743)	2010	100.0	100.3	101.0	101.0	100.4	100.4	100.4	100.4
	2020	101.6	101.7	102.8	103.0	102.0	102.0	102.0	102.0
	2030	101.7	101.9	103.1	103.3	103.4	103.5	103.4	103.4
Central Eastern Europe (3171)	2010	106.5	106.5	105.8	105.8	104.1	104.1	104.6	104.6
	2020	108.7	108.9	109.8	110.4	106.9	107.0	107.4	107.5
	2030	109.8	110.1	112.6	112.9	108.4	108.9	109.1	109.7
Former Soviet Union (2743)	2010	97.8	97.8	108.0	108.0	104.0	104.0	105.0	105.0
	2020	108.7	109.6	115.6	115.6	110.1	110.2	111.6	111.6
	2030	112.8	113.2	118.6	118.6	111.9	112.4	113.5	113.6
Planned Asia and China (2785)	2010	101.8	101.8	101.7	101.8	99.4	99.4	100.0	100.0
	2020	106.3	107.3	108.6	108.8	101.6	102.3	103.2	103.7
	2030	110.2	110.9	114.1	114.7	103.2	103.9	106.5	106.9
South Asia (2395)	2010	96.3	96.1	98.9	98.9	95.6	95.5	96.1	95.9
	2020	101.7	101.7	105.7	105.6	97.6	98.0	99.7	99.9
	2030	105.9	105.9	111.0	111.2	98.9	99.2	102.1	102.4
Other Pacific Asia (2669)	2010	106.2	107.7	111.6	112.5	106.3	107.7	107.7	109.1
	2020	113.1	116.8	121.3	125.3	111.7	115.1	114.6	118.0
	2030	116.8	124.2	127.9	134.1	113.9	120.3	117.9	124.9
Middle East and Northern Africa (2662)	2010	102.1	102.1	102.2	102.2	101.0	101.0	101.3	101.3
	2020	106.1	106.2	106.4	106.4	102.8	102.9	103.6	103.6
	2030	111.0	111.2	110.5	110.6	104.7	104.7	105.7	105.9
Latin America and Caribbean (2857)	2010	115.2	115.2	108.2	108.2	104.4	104.4	105.4	105.4
	2020	126.1	127.4	120.1	120.5	112.3	113.1	114.4	115.4
	2030	129.6	131.1	127.9	128.8	117.3	118.4	119.9	121.2
Sub-Saharan Africa (2091)	2010	106.1	106.6	105.6	106.5	102.3	103.5	103.0	103.8
	2020	113.8	116.6	114.7	116.4	106.9	109.3	108.1	110.1
	2030	126.8	132.1	127.6	129.9	111.1	114.7	113.7	117.2

Notes on Figure 1

Vegetarian and animal food intake is shown on the left axis, the animal food share on the right axis.

For all scenarios where the impact of population growth is included (P, LWP, LWPI, LWPIT), the per capita food intake is based on the 2030 population. For all other scenarios the per capita food intake is based on the 2000 population.

Notes on Figure 2

The depicted results are computed by dividing the total food energy consumption values by different population sizes. For the scenarios, where the impact of population growth is included (P, LWP, LWPI, LWPIT), the total food energy consumption values are obtained from model simulations based on the year 2030 population. For all other scenarios, the total food energy consumption values are obtained from model simulations based on the year 2000 population. The per-capita food consumption values are computed by dividing total food energy consumption values by a) the population in year 2000 (bars above the “population 2000” label), b) the population in year 2030 (bars above the “population 2030” label), and c) by the population size that was used for the computation of total food consumption (bars above the “scenario specific” label).

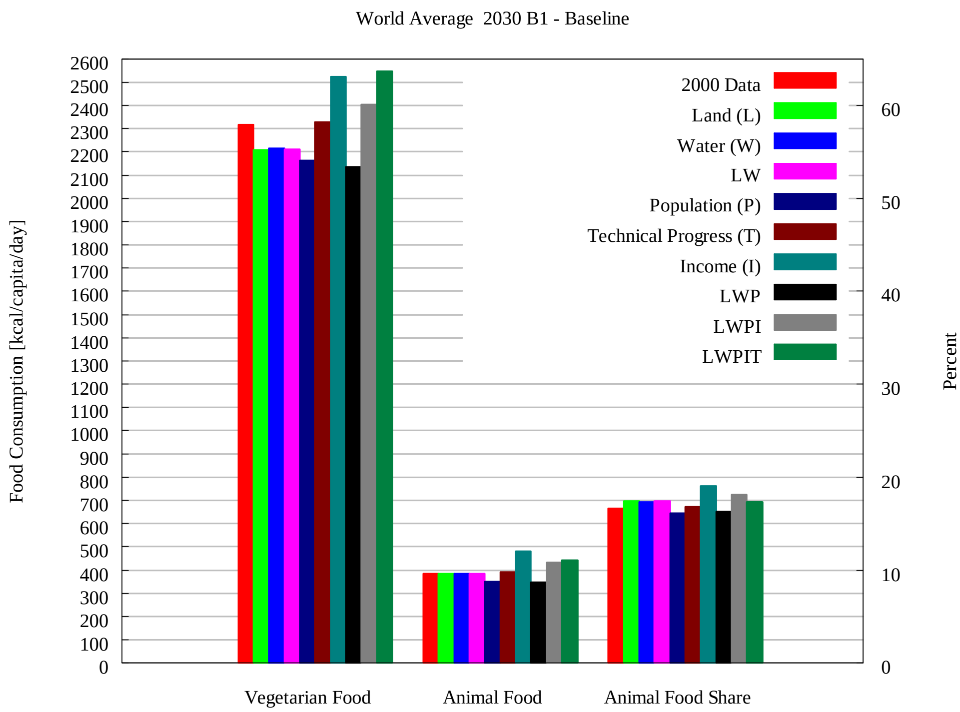

Figure 3 Panel A: Global average food energy intake of vegetarian and animal source food in 2030 for the revised SRES B1 and different scopes of impact implementation

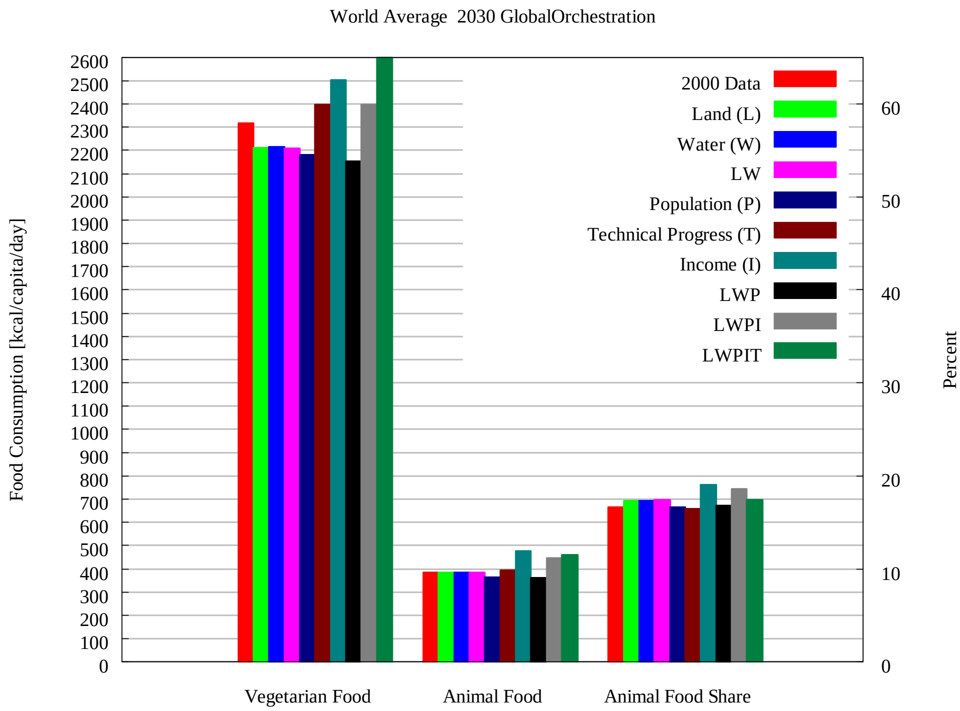

Figure 1 Panel B: Global average food energy intake of vegetarian and animal source food in 2030 for the Global Orchestration scenario and different scopes of impact implementation

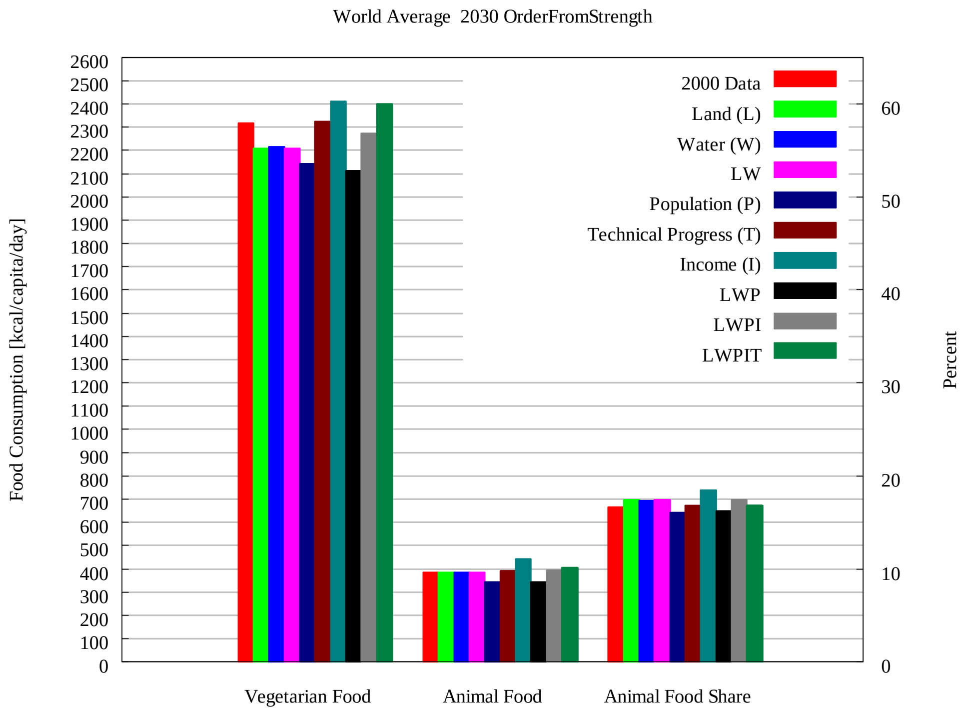

Figure 1 Panel C: Global average food energy intake of vegetarian and animal source food in 2030 for Order from Strength scenario and different scopes of impact implementation

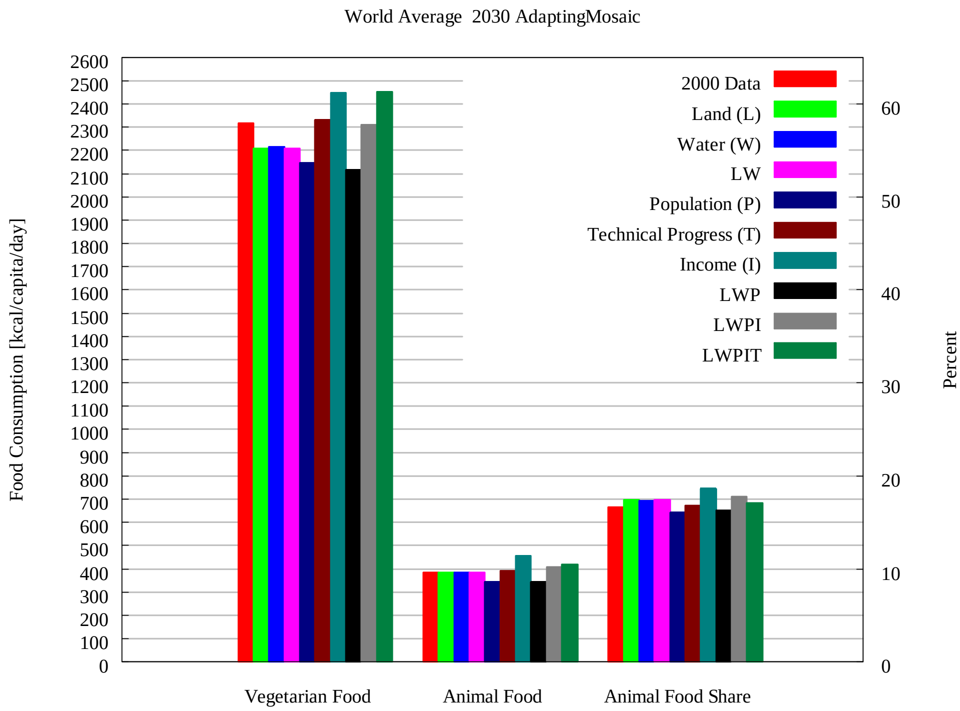

Figure 1 Panel D: Global average food energy intake of vegetarian and animal source food in 2030 for the Adapting Mosaic and different scopes of impact implementation

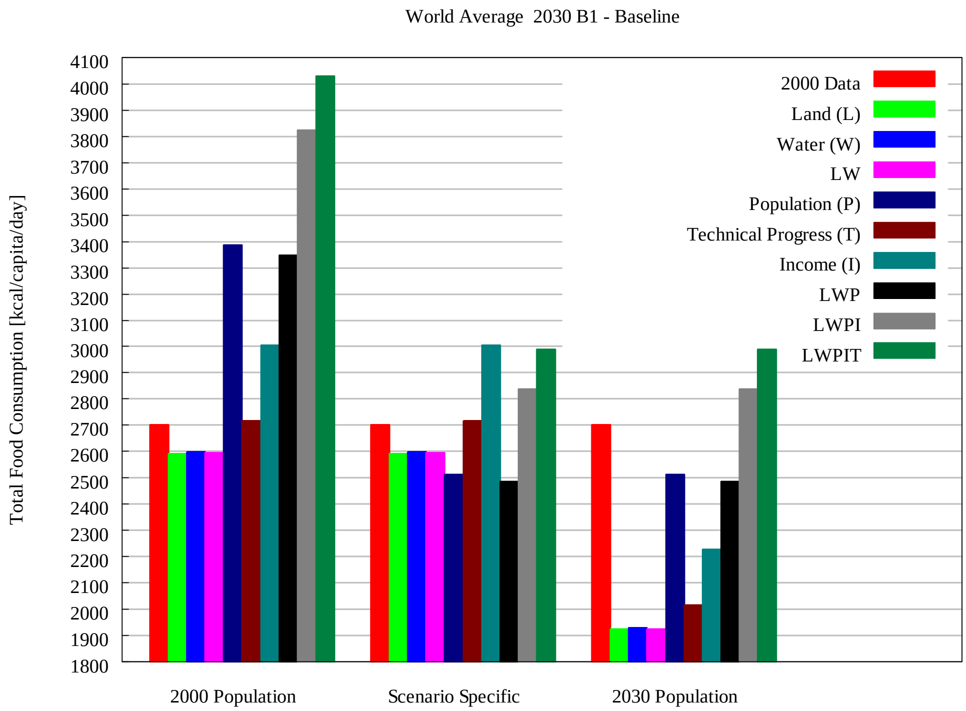

Figure 4 Panel A: Global average total food energy consumption in 2030 for the revised SRES B1 and different scopes of impact implementation.

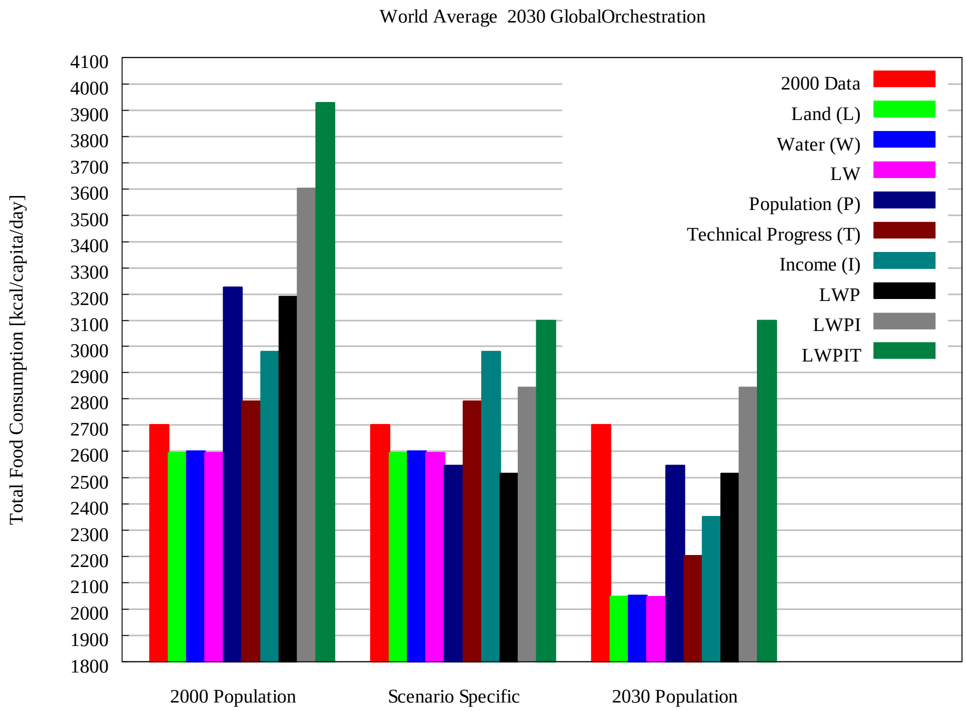

Figure 2 Panel B: Global average total food energy consumption in 2030 for the Global Orchestration scenario and different scopes of impact implementation.

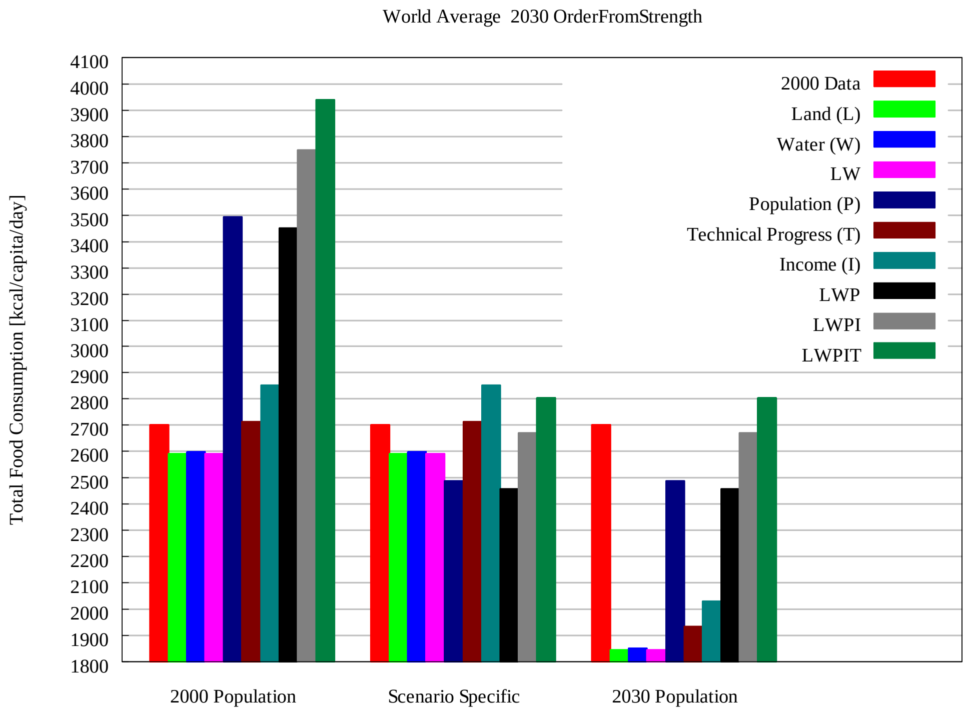

Figure 2 Panel C: Global average total food energy consumption in 2030 for the Order from Strength scenario and different scopes of impact implementation.

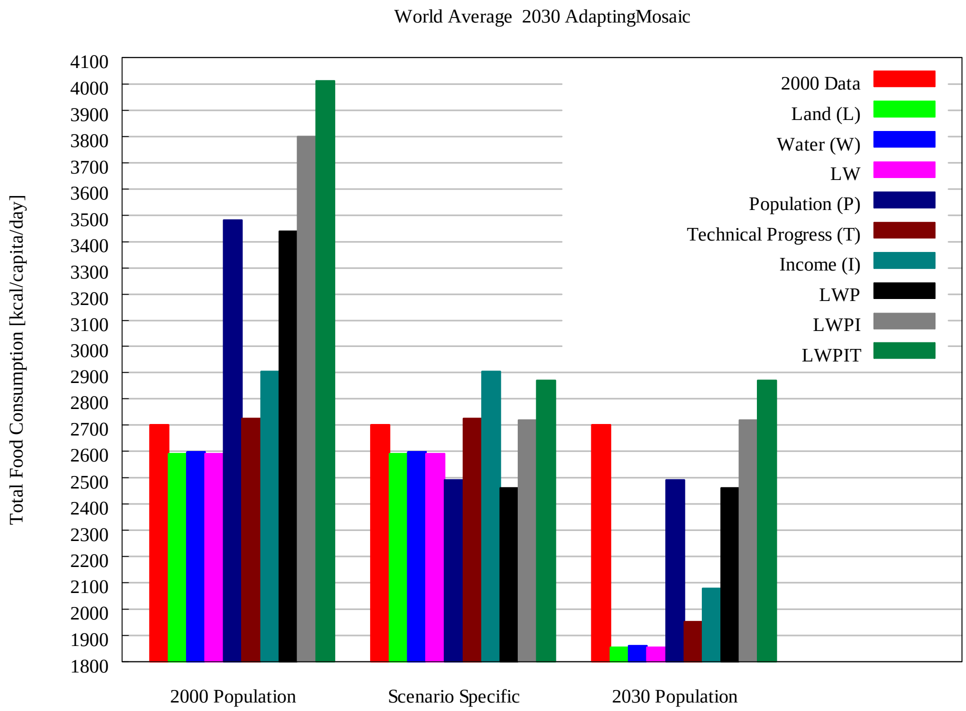

Figure 2 Panel D: Global average total food energy consumption in 2030 for the Adapting Mosaic scenario and different scopes of impact implementation.



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