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# Modelling the impact of climate change on irrigation area demand in the Jordan River region

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**Abstract:** Changing climate conditions in the Jordan River Region are likely to have adverse effects on irrigated crop yields and, as a result, increase the demand for irrigation area. We apply a regional version of the dynamic land-use change model LandSHIFT to quantify the effect of climate change on the demand for irrigation area needed to maintain a constant production of irrigated crops. To evaluate uncertainties induced by climate projections, we use an ensemble of four regional climate datasets based on the IPCC emissions scenario A1B. In order to interpret the simulation results on additional irrigation area demands due to changing climate conditions, we compare them to the simulation results that were generated assuming socio-economic changes (increase in crop demand) under constant climate conditions. Our simulation results show that climate change may cause an expansion of irrigation area by about 25%, whereas different climate projections only lead to minor variability in the simulated irrigation area demands. By comparison, an increase in crop demand could result in an expansion of irrigation area by about 71%.

***Keywords**:* LandSHIFT; Middle East; land-use and land-cover change; climate change; uncertainty.

## 1 INTRODUCTION

With total renewable water resource values between 52 and 535 $m^3$ $cap^{-1}$ $y^{-1}$ [FAO 2003], ranging far below the threshold value of 1000 $m^3$ $cap^{-1}$ $y^{-1}$ for chronic water scarcity [Falkenmark and Rockström 2004], the Jordan River region (JRR) has one of the lowest per capita water availabilities worldwide. A large part of the regional renewable freshwater resources is used for irrigation purposes, making irrigation agriculture one of the major water users in the JRR. The 4th IPCC Assessment Report projects increased mean annual temperatures accompanied by decreased precipitation amounts for the Mediterranean region [Christensen et al. 2007]. Moreover, projections of future population development for the JRR indicate a strong population growth [UN 2009]. Hence, it is expected that irrigated agriculture will expand in the future in order to meet the increasing demand for agricultural production of a growing population under climate change [FAO 2002].

Given current conditions of water scarcity, it is considered uncertain whether there will be enough water to sustain or expand the existing irrigation area in the future, also because the demands of other water use sectors are similarly likely to increase [Döll and Siebert 2002]. Hence, there is an urgent need for simulations of future irrigation water requirements [Döll 2002], which are a function of the location and extent of irrigation area. Thus, spatially explicit projections of irrigation area are a prerequisite for the evaluation and assessment of the future water situation in the JRR.

Current approaches of land-use change modelling at the large scale do not explicitly consider changes in irrigation area that go beyond the distinction of rice and non-rice areas or do not have the appropriate spatial resolution to capture the natural heterogeneity of the JRR [Weiß et al. 2009, Verburg et al. 2002]. In this study we use a regional land-use change model that operates on a spatial resolution of 30 arc seconds and distinguishes between three different crop categories to examine and quantify the effect of climate change on the demand for irrigation area in the JRR. For this purpose, an ensemble of four different regional climate projections, all based on the IPCC emissions scenario A1B [IPCC 2000], is used as model input. This allows the analysis of uncertainties of the land-use simulations introduced by different climate projections. We furthermore compare the impact of climate change on land-use change to the corresponding impact of changes in socio-economic conditions. For this purpose, we use scenario assumptions on future increase in crop demand as input for one simulation run. Exemplarily, we compare the results on additional demand for irrigation area due to increasing crop demand to the simulation results based on climate change input.

## 2 STUDY REGION

The JRR consists of Israel, Jordan, and the Palestinian Authority (PA). The region is bordered by Lebanon and Syria in the north, by Iraq and Saudi Arabia in the east, by Egypt in the southwest and by the Mediterranean Sea in the west. The region covers about 115 thousand $km^2$ of land area and 1 thousand $km^2$ of inland water area. According to FAO Aquastat [2012a] about 3 thousand $km^2$ in the study region are equipped for irrigation, of which about two thirds are located in Israel.
The climate in the northern, central, and western part of the JRR is Mediterranean, characterized by hot, dry summers and cool, wet winters [EXACT 1998]. In the residual part of the JRR, a semi-arid to arid climate predominates. A key feature of the study region is the steep gradient of mean annual precipitation, ranging from 900 mm in the north to less than 50 mm in the desert areas located in the south of Israel and the south and southeast of Jordan.
In 2000, about 14 million people lived in the JRR, 43% in Israel, 34% in Jordan, and 23% in PA [FAO 2012b]. The largest cities in the study region are Amman, Jerusalem, Tel Aviv, and Gaza.

## 3 MATERIALS AND METHODS

### 3.1 Modelling Framework

To simulate the effect of climate change on the demand for irrigation area, we utilized a regional version of LandSHIFT [Schaldach et al. 2011]. This model was successfully applied in a set of scenario studies on land use and livestock grazing in the Middle East [Koch et al. 2009, Koch et al. 2011]. Detailed descriptions of the regional version of LandSHIFT and of model testing and validation are given in Koch et al. [2008] and Koch [2010].
The model version applied in this study consists of three functional components: the Land-use change module (LUC-module), the Socio-economy module, and the Biophysic module (Figure 1). The rational of the LUC-module is to calculate changes in land use. It operates on two spatial scale levels: the macro-level and the micro-level. The Socio-economic module specifies macro-level (country-level) drivers of land-use change, e.g. crop demand, as well as planning measures and policies. On the micro-level, which is a grid with a spatial resolution of 30 arc seconds, the Biophysic module prepares crop yield data, calculated with GEPIC [Liu et al. 2007] as a function of climate conditions. Furthermore, the calculation of changes in land-use and land-cover by the LUC-module is carried out on the micro-level. For this purpose, demands for area intensive commodities are allocated to the most suitable micro-level grid cells. Landscape and land-use characteristics used for the suitability assessment are also specified on the micro-level. Since this study focuses

on irrigation area, only changes in irrigated crop production (AGRO IR) are calculated (Figure 1).

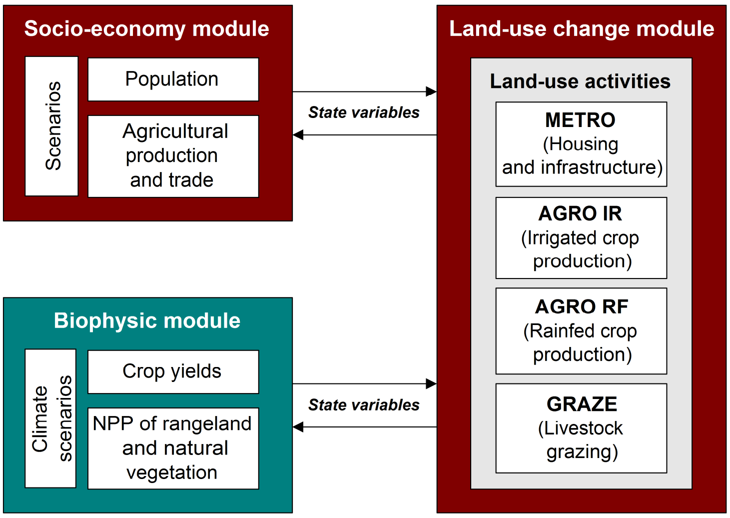


**Figure 1** Schematic representation of the modeling framework LandSHIFT.

The LUC-module carries out three process steps: (i) pre-processing, (ii) suitability assessment, and (iii) demand allocation. Pre-processing prepares the macro-level input for the other two process steps. Within the suitability assessment, a Multi Criteria Analysis method [Eastman et al. 1995] is applied to assess the suitability of the micro-level grid cells for the different land-use activities, in our case irrigated crop production:

$$suit_k = \sum_{i=1}^{n} w_i p_{i,k} \cdot \prod_{j=1}^{m} c_{j,k} \text{ with } \sum_i w_i = 1 \text{ and } p_{i,k}, c_{i,k} \in [0,1]. \quad (1)$$

The factor weights $w_i$ determine the importance of the suitability factors $p_i$; $c_j$ are constraining the change of the dominant land-use type of a grid cell. All $p_i$ are normalized by value functions, based on logistic regression analysis, which transform the factor values to a co-domain from 0 to 1. The CRITIC method [Diakoulaki et al. 1995] was applied to asses “objective weights” considering the spatial variability of the suitability factors, which are specified on the micro-level grid, and their intercorrelation. Suitability factors for irrigated crop production are: river network density, area equipped for irrigation, travel time to major cities, slope, crop yields, and population density. Land-use constraints include urban areas and conservation areas, both of which cannot be converted to cropland.
Demand allocation is also carried out on the micro-level. Within this process step, the macro-level demands for irrigated crop production are distributed to the grid cells with the highest suitability for the respective crop category. As a result, the land-use type of as many cells as required to fulfil the demand is changed. Crop categories considered in this study are fruits, vegetables, and field crops.
In LandSHIFT, changes in crop yields affect land-use changes in two ways: (i) crop yield is one of the factors that determine the suitability of a cell for crop production and as such affects the location where a demand is allocated, and (ii) crop yield is directly connected to the area required to produce a certain crop amount. If crop yields decrease, more area is needed to fulfil the same demand for crops and vice versa.
The initial land-use and land-cover map is derived from MODIS global remote sensing data for the year 2001 [Friedl et al. 2002]. In order to initialize the base year distribution for cropland, LandSHIFT distributes the demands and areas for the internal crop categories to the best suited micro-level grid cells, preferably to those categorized as “cropland” in the initial land-use and land-cover map (i.e. the MODIS map). At first, this is done for irrigated cropland. Thereafter, the demand for rain-fed cropland is distributed on the remaining “cropland” grid cells.

### 3.2 Simulation of Crop Yields

We applied GIS-based EPIC (GEPIC) [Liu et al. 2007], a combination of the crop growth model EPIC [Williams 1989] with a GIS, to simulate crop yields under current and future climate based upon four different regional climate modelling datasets [Smiatek et al. 2011]. EPIC has been used successfully to simulate crop yields under a wide range of weather conditions, soil properties, and management schemes [Liu et al. 2007]. We chose EPIC because it is public domain software and data requirements can be fulfilled with available large-scale datasets. EPIC works on a daily time step and considers the major processes in the soil-crop-atmosphere-management system [Williams 1989].
We used GEPIC to simulate potential yield under optimal irrigated conditions for wheat as a proxy crop type. The potential irrigated wheat yield simulation results were averaged over 30-year periods so as to derive values for the 2000s and 2050s. An additional step was required to transfer potential irrigated wheat yield values to actual irrigated yields for the crop categories fruits, vegetables, and field crops. We multiplied the grid cell values of potential irrigated wheat yield by the ratio of mean actual yield for the respective irrigated crop category to the mean potential yield on irrigated areas covered by this crop category. Therefore, we used actual yield values for the year 2000 – the simulation base year – calculated with the IMPACT model [Rosegrant et al. 2002]. The IMPACT simulation results were also used to provide the assumptions of future crop demands (cf. section 4). In this way, we ensure the consistency of yield values between the various model drivers and inputs. In addition, we are able to include spatial and temporal variability of the GEPIC crop yield simulations in our analysis.

## 4 Simulation Experiment

We set up a simulation experiment consisting of an ensemble of five simulation runs, referred to as scenarios. Four of the scenarios are based on different climate projections and a constant crop demand (NoDemC) on year-2000 level. The fifth scenario combines constant climate (i.e. current climate conditions for the entire simulation period) with an increase in crop demand. It was set up to allow a comparison of climate change impacts on irrigation area demand (derived from the first four scenarios) with the impact of changes in socio-economic conditions on irrigation area demand. All five scenarios apply a 5-year time step for a simulation period of 50 years (2000-2050). Since the focus of the study is on irrigation area, changes in urban area, rain-fed cropland, and grazing area were not calculated, i.e., only the AGRO IR module of LandSHIFT, responsible for the allocation of irrigated crop production, was utilized (Figure 1).
For the four scenarios with changing climate conditions, we used climate datasets for current and future conditions resulting from a dynamical downscaling of the output of general circulation models (GCMs) with a regional climate model (RCM) driven by the IPCC emissions scenario A1B [Smiatek et al. 2011]. These climate projections comprise the four combinations of the GCMs ECHAM5 (EC) and HadCM3 (HAD) and the RCM MM5 in the versions v3.5 and v3.7. Using an ensemble of climate projections for the same emission scenario allows us to analyse the uncertainty in crop yield calculations and, as a result, the uncertainty in calculations of irrigation area demand, introduced by different combinations of GCMs and RCM versions. The projections of future climate in the JRR show an ensemble mean increase of 2.1 K (1.8 to 2.3 K) in mean annual temperature until the 2050s. Mean annual precipitation is projected to decrease by -11.5% (-13% to -9%) in the same period [Smiatek et al. 2011].
We applied the fifth scenario to assess the relative importance of climate change impacts in comparison to the impact of socio-economic changes on the demand for irrigation area. As a rough estimate of the impact of socio-economic changes, we drive LandSHIFT with projections of crop demands (DemJRR) under current climate conditions (NoCC). These projections of future crop demands were generated

in the context of a participatory scenario exercise for the JRR ["Modest Hopes" scenario, cf. Anonymous 2011]. In this scenario exercise, crop demand for Israel was calculated with VALUE [Kan et al. 2007] whereas demands for Jordan and PA are based on IMPACT [Rosegrant et al. 2002] simulation results.
We refer to the various combinations of climate conditions and crop demand with identifiers according to the scheme "climate assumption"-"demand assumption" (e.g. HADv3.7-NoDemC for HADCM3 with MM5 v3.7 combined with no change in crop demand).

## 5 RESULTS

The simulation results for the base year 2000 show an initial irrigation area of about 2 950 km² (Table 1). Small differences between the different scenarios are due to numerical inaccuracies of LandSHIFT.

**Table 1.** Summary of input data on irrigated crop yield and crop demands as well as simulation results on irrigation area for the five scenarios.

| Scenario | Mean change in irrigated crop yields through 2050 (%) | Change in crop demands through 2050 (%) | | | Irrigation area 2000 [km$^2$] | Irrigation area 2050 [km$^2$] |
|---|---|---|---|---|---|---|
| | | Israel | Jordan | PA | | |
| ECv3.5-NoDemC | -23.86 | 0 | 0 | 0 | 2 951 | 3 721 |
| ECv3.7-NoDemC | -23.96 | 0 | 0 | 0 | 2 953 | 3 765 |
| HADv3.5-NoDemC | -23.25 | 0 | 0 | 0 | 2 951 | 3 568 |
| HADv3.7-NoDemC | -23.53 | 0 | 0 | 0 | 2 952 | 3 689 |
| NoCC-DemJRR | 0.00 | 201 | 221 | 167 | 2 953 | 5 043 |

All five scenarios show an increase in irrigation area demand (Table 1). For the four scenarios considering climate change, the increase accounts for approximately 25 % (Ø 734 km²) by 2050. The lowest increase, with 617 km$^2$ (+21%), is calculated for HADv3.5-NoDemC; the highest increase, with 812 km$^2$ (+27%), is calculated for ECv3.7-NoDemC. These results can be directly related to the mean change in irrigated crop yields. The strongest decrease in crop yields results in the strongest increase in irrigation area demand (ECv3.7-NoDemC) and vice versa (HADv3.5-NoDemC).

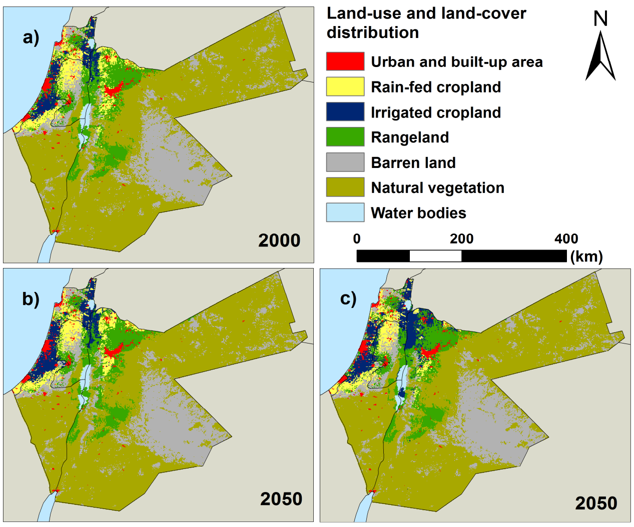


**Figure 2.** Land-use and land-cover distribution in a) the base year (2000) and the year 2050 for b) one example (ECv3.5-NoDemC) with constant demands and climate change, and c) NoCC-DemJRR.

As compared to the scenarios considering climate change, the NoCC-DemJRR scenario shows with 2 090 km$^2$ (+71 %) a much stronger increase in irrigation area. Since this scenario does not include climate change, the increase in irrigation area demand can be directly related to changes in socio-economic conditions, such as change in crop demand (Table 1).
Figure 2 shows the spatial simulation results in form of land-use and land-cover maps. As compared to the initial land-use and land-cover distribution for the year 2000 (Figure 2a), the scenarios with climate change show only moderate differences (Figure 2b). The spatial evaluation of the scenarios with climate change shows the highest increase in irrigated area and, hence, the strongest negative impact of climate on crop yields for

Israel. This is found consistently for all four scenarios with climate change (Figure 3). New irrigation area in Israel is preferably allocated in the coastal plain (Figure 2b), indicating that this region has the most suitable conditions for irrigated crop production.

The simulation results for NoCC-DemJRR (Figure 2c) show a considerable increase in irrigation area for Jordan (1 535 km²) and a moderate expansion of irrigation area in PA (330 km²) and Israel (224 km²). This corresponds well with the change in crop demands for the different states (Table 1), driving the land-use changes in this scenario. New irrigation area in Jordan is preferably allocated in the north-western part of the country, close to the Jordan River.

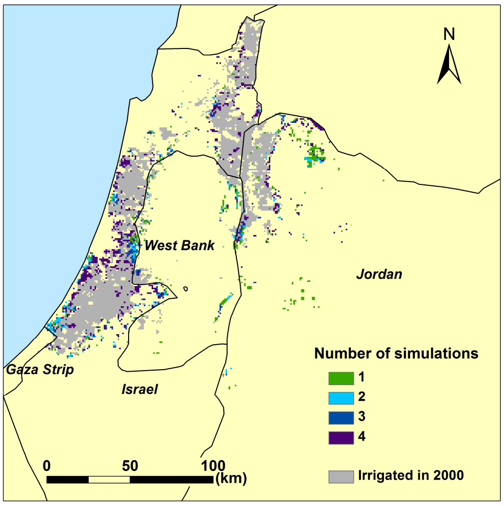


**Figure 3.** Number of simulations with climate change projecting a conversion to irrigated cropland through 2050.

## 6 DISCUSSION

The simulation results show that under all five scenarios additional irrigation area is required. For the four scenarios with climate change, this directly reflects the decreasing crop yields. Since the crop yield calculations were carried out assuming optimal irrigation, the decrease in crop yields is induced by increasing temperature stress. This means decreasing precipitation does not lead to a decline in irrigated crop yields but increases the demand for irrigation water. Even though the different climate projections for the A1B scenario introduce some uncertainty to the simulation results (6 % difference in irrigation area expansion between the highest and the lowest scenario), they show the same general trend in changes in crop yields (Table 1). However, the different climate projections were generated with the same RCM (MM5), though in different versions. The application of a larger ensemble of climate projections, utilizing additional RCMs, may result in stronger variations of the simulation results on irrigation area demand. As compared to the scenarios with climate change, the scenario assuming constant climate conditions and socio-economic changes shows with 71 % a higher increase in irrigation area demand. Since the underlying “Modest Hopes” scenario is a rather extreme scenario characterised by strong increases in crop demands [Anonymous 2011], the results for this scenario likely show the upper limit of the range for future increase in irrigation area demand. Although the growing demand for agricultural products could have stronger impact on the demand for irrigation area than the projected climate change, the simulation results show that the effect of climate change in the JRR cannot be neglected.

New irrigation areas are allocated to regions with a typical Mediterranean climate, where there are the most favourable climatic conditions for agricultural activities. Furthermore, the results show that the expansion mainly occurs at the edges of existing irrigation area and in regions where irrigation infrastructure is available: in Jordan, these are the north-western parts of the state, which are located near the King Abdullah Canal and in Israel this is the coastal plain close to the National Water Carrier. These simulation results make good economic sense since irrigation agriculture highly depends on the availability of irrigation infrastructure.

The simulations of changes in irrigation area demand in this study are calculated separately for the three crop categories fruits, vegetables, and field crops with a spatial resolution of 30 arc seconds (approx. 1 km at the equator). The crop yield calculations underlying these simulations of land-use change were carried out with a spatial resolution of 0.02 decimal degree (approx. 2.2 km at the equator), applying high-resolution climate change simulations for the JRR [Smiatek et al. 2011]. This high level of detail reduces the uncertainty in spatial simulations of irrigation area demand and as a result facilitates a better evaluation of irrigation water requirements. However, because simulated wheat yields are used as a proxy for all crop types, the modelling approach does not consider differences among the three crop types regarding the spatial variations of yield and irrigation water requirements. Hence, incorporating additional GEPIC simulations of crop yields and water requirements for vegetables and fruits in future modelling exercises would improve the model results.

## 7 CONCLUSIONS

In this study, we show that the likely impact of climate change on irrigation area demand is considerable and that there is an urgent need for scenario analyses for the JRR that combine both the impacts of climate change and demand change. Since only minor uncertainty is introduced by different GCM-RCM combinations, it does not seem necessary to include several of these combinations in future scenario analyses for the JRR. Instead, additional emission scenarios and socio-economic scenarios should be considered and further sensitivity analyses should be carried out in order to examine the relative importance of changes in climate and socio-economy. In our simulation experiment, different crop categories as well as high-resolution regional climate projections, crop yield calculations, and land-use simulations were utilized. This allows for a spatially explicit analysis of the impact of climate change and socio-economy on future demand for irrigation area. This facilitates more detailed analyses of the corresponding future irrigation water requirements. Besides the agricultural sector, a comprehensive analysis of the future freshwater balance in the JRR should include other water intensive sectors such as industry and municipalities. This would allow to consider limitations for the expansion of irrigated agriculture, resulting from water scarcity and trade-offs between water use sectors, in order to assess its potential to increase food security in the region.

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## REFERENCES

Anonymous, Future management of the Jordan River basin's water and land resources under climate change - A scenario analysis, Summary report, Center for Environmental Systems Research, Kassel, Germany and Israel/Palestine Center for Research and Information, Jerusalem, Israel, 2011.

Christensen, J.H., B. Hewitson, A. Busuioc, and others, Regional Climate Projections, in Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller (Eds.), Climate change 2007: the physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK and New York, NY, USA, 2007.

Diakoulaki, D., G. Mavrotas, and L. Papayannakis, Determining objective weights in multiple criteria problems: the CRITIC method, *Computers & Operations Research, 22(7)*, 763-770, 1995.

Döll, P., Impact of climate change and variability on irrigation requirements: a global perspective, *Climatic Change, 54*(3), 269-293, 2002.

Döll, P., and S. Siebert, Global modeling of irrigation water requirements, *Water Resources Research, 38*(4), 1037, 2002.

Eastman, J.R., W. Jin, P.A.K. Kyem, and J. Toledano, Raster procedures for multi-criteria/multi-objective decisions, *Photogrammetric Engineering & Remote Sensing, 61(5)*, 539-547, 1995.

EXACT, Overview of Middle East water resources – water resources of Palestinian, Jordanian, and Israeli interest, Executive Action Team, Middle East Water Data Banks Project, URL: http://www.exact-me.org/overview/index.htm, 1998.

Falkenmark, M., and J. Rockström, *Balancing water for humans and nature: the new approach in ecohydrology,* Earthscan, 247 pp., London, 2004.

FAO, Crops and drops - making the best use of water for agriculture, Food and Agriculture Organization of the United Nations, Rome, 2002.

FAO, Review of world water resources by country, Water Reports 23, Food and Agriculture Organization of the United Nations, Rome, 2003.

FAO, FAO Aquastat, Food and Agriculture Organization of the United Nations, URL:http://www.fao.org/nr/water/aquastat/main/index.stm, 2012a.

FAO, FAO Statistical Database, Food and Agriculture Organization of the United Nations, URL: http://faostat.fao.org/, 2012b.

Friedl, M.A., D.K. McIver, J.C.F. Hodges, X.Y. Zhang, and others, Global land cover mapping from MODIS: algorithms and early results, *Remote Sensing of Environment, 83(1-2)*, 287-302, 2002.

IPCC, *Special Report on Emissions Scenarios*, Intergovernmental Panel on Climate Change, Cambridge University Press, 612pp., Cambridge, 2000.

Kan, I., M. Rapaport-Rom, and M. Shechter, Economic analysis of climate-change impacts on agricultural profitability and land use: the case of Israel, paper presented at 15th Annual Conference of the European Association of Environmental and Resource Economists (EAERE), Thessaloniki, Greece, June 27-30, 2007.

Koch, J., R. Schaldach, and M. Köchy, Modeling the impacts of grazing land management on land-use change for the Jordan River region, *Global and Planetary Change, 64(3-4)*, 177-187, 2008.

Koch, J., R. Schaldach, and C. Kölking, Modelling the impact of rangeland management strategies on (semi-)natural vegetation in Jordan, in Anderssen, R.S., R.D. Braddock, and L.T.H. Newham (Eds.), 18th World IMACS Congress and MODSIM09 International Congress on Modelling and Simulation, Modelling and Simulation Society of Australia and New Zealand and International Association for Mathematics and Computers in Simulation, Cairns, Australia, July 13-17, 2009.

Koch, J., Modeling the impacts of land-use change on ecosystems at the regional and continental scale, thesis, kassel university press, Kassel, 2010.

Koch, J., J. Onigkeit, R. Schaldach, J. Alcamo, M. Köchy, H.-P. Wolff, and I. Kan, Land-use change scenarios for the Jordan River region, *International Journal of Sustainable Water and Environmental Systems, 3*(1), 25-31, 2011.

Liu, J., J.R. Williams, A.J.B. Zehnder, and H. Yang, GEPIC – modelling wheat yield and crop water productivity with high resolution on a global scale, *Agricultural Systems, 94(2)*, 478-493, 2007.

Rosegrant, M.W., S. Meijer, and S.A. Cline, International model for policy analysis of agricultural commodities and trade (IMPACT): model description, International Food and Policy Research Institute, Washington DC, 2002.

Schaldach, R., J. Alcamo, J. Koch, C. Kölking, D.M. Lapola, J. Schüngel, and J.A. Priess, An integrated approach to modelling land-use change on continental and global scales, *Environmental Modelling & Software, 26(8)*, 1041-1051, 2011.

Smiatek, G., H. Kunstmann, and A. Heckl, High-resolution climate change simulations for the Jordan River area, *Journal of Geophysical Research, 116*, D24123, 2011.

UN, World population prospects: The 2008 revision, United Nations, New York, 2009.

Verburg, P.H., W. Soepboer, A. Veldkamp, R. Limpiada, V. Espaldon, and S.S.A. Mastura, Modeling the spatial dynamics of regional land use: the CLUE-S model, *Environmental Management, 30(3)*, 391-405, 2002.

Weiß, M., R. Schaldach, J. Alcamo, and M. Flörke, Quantifying the human appropriation of fresh water by African agriculture, *Ecology and Society, 14*(2), 25, 2009.

Williams, J.R., C.A. Jones, J.R. Kiniry, and D.A. Spanel, The EPIC crop growth model, *Transactions of the American Society of Agricultural Engineers, 32(2)*, 497-511, 1989.