FAO-MOSAICC: THE FAO MODELLING SYSTEM FOR AGRICULTURAL IMPACTS OF CLIMATE CHANGE TO SUPPORT DECISION-MAKING IN ADAPTATION

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ABSTRACT

The Food and Agriculture Organization of the United Nations (FAO) has developed in partnership with European research institutes an integrated package of models to carry out climate change impact assessment studies at the national level. This package, called FAO-MOSAICC (for Modelling System for Agricultural Impacts of Climate Change), allows for climate data downscaling, spatial interpolation, hydrological modelling, and crop and economic simulations, to be carried out sequentially. FAO-MOSAICC is designed to be distributed to national institutions in developing countries. While FAO-MOSAICC can be used for a wide range of analyses (climate change impacts on water resources, crop yields etc.), its ultimate

objective is to identify the most robust adaptation strategies to mitigate the potentially adverse effects of climate change on national food security. This paper describes the modelling system with a focus on the Dynamic Computable General Equilibrium (DCGE) model that simulates the effects of climate-change-induced changes in crop yields on national economies over time. To make the use of the model as cheap as possible for use by national institutions, it uses an open source programming language and free software to solve the model. The model can be implemented and solved on Windows and Linux platforms. Some features of the model will be illustrated by a test of the model on Moroccan data with projections over the period 2001-2030.

1. Introduction

Information on the impacts of climate change is fundamental for designing policies and making informed decisions in all areas. In agriculture, climate change will affect crop production by a combination of factors: changes in temperature and rainfall regimes, variation in growing season onset and length, the CO_2 fertilization effect, technological improvements and water availability for irrigation, among many others. In turn, changes in agricultural yields will affect food production and the economy through the inter-linkages with the other sectors of the economy. In this regard, a multi-disciplinary approach is useful to deal with these different aspects jointly.

The Food and Agriculture Organization of the United Nations (FAO) is currently developing an integrated software package to study climate change impacts on agriculture called "FAO-MOSAICC" (Modelling System for Agricultural Impacts of Climate Change) in partnership with specialized European research institutes. FAO-MOSAICC includes tools for climate data downscaling and spatial interpolation as well as hydrological, crop and economic models. The software package is designed to be distributed to national institutions (meteorological services, agriculture departments, universities etc.) having the capacity to host the server, to maintain the system and to coordinate country-wide climate change impact studies in agriculture. The system will be delivered with documentation and training programs for use by local researchers from relevant technical institutions. A comprehensive use case of FAO-MOSAICC will be undertaken in Morocco before implementing it in selected African and Asian countries.

While FAO-MOSAICC models can be used for a wide range of analyses (climate change impacts on water resources, crop yields etc.), its ultimate objective is to identify the most robust adaptation strategies to mitigate the potentially adverse effects of climate change on national food security. The aim is to deliver the system to relevant national institutions, accompanied with the necessary training.

This activity started at the end of the year 2009 and built upon FAO's experience with a study jointly conducted with the World Bank and the Government of Morocco in 2007 to assess the impacts of climate change on fifty crops in Morocco over the 21st century (Gommes et al., 2007).

This paper describes the methodology, the models and their integration into FAO-MOSAICC. Section 2 presents the overall methodology of the project and briefly describes the individual non-economic models. Section 3 presents the economic model that was specifically build for this project. Section 4 describes the test of the model on Moroccan data. It should be noted that the test is not much more than a technical test to check whether the model did indeed run on real data and whether the results were in the expected range. As yet, we make no claim to the validity of the results. Section 5 concludes and makes recommendations for further action.

2. Overall methodology

The construction of FAO-MOSAICC is based on a generic methodology defined to assess the impact of climate change on agriculture, covering crop yield projections, water resources estimations and economic modelling. The focus is on the country scale; however the system has some flexibility both in terms of spatial and temporal scale.

Like most climate change impact assessment methodologies, FAO-MOSAICC relies on low resolution projections for future climates, produced by General Circulation Models (GCMs) such as the ones that were used for the IPCC Assessment Reports. These projections are statistically downscaled onto the weather station network for the period of interest. The constructed weather station "observations" are spatially interpolated using various interpolation methods, to a convenient spatial resolution for subsequent crop and hydrology modelling.

Crop yield projections are derived from the interpolated climate projections as well as soil maps and crop parameters by means of crop models. The approach is based on crop forecasting, i.e. a multivariate regression model is fitted between model output and historical yield statistics to assess the contribution of weather conditions in the yield variability. This regression model is then applied to crop simulations achieved under future climate projections. Various scenarios of technological progress can be used for the projections. Both rainfed and irrigated crops can be simulated; for the latter the water requirements for a perfect irrigation are also computed. Crop projections are computed for a set of crops representative of the national agriculture.

Future water resources at the scale of an irrigation dam, a water basin or the entire country are also estimated on the basis of the interpolated climate projections. Simulations of river discharges are carried out using a spatially distributed precipitation runoff model. Estimations of water availability for irrigation are derived from the discharge time series using scenarios on the use of the water resources in the area considered.

Finally the effect of the yield projections on the national economy is assessed using a dynamic computable general equilibrium model (DCGE). Yield projections are used as exogenous variables and the national production for each crop is computed by the model under land and water availability constraints. Typical economic indicators such as GDP, employment, investments and prices are projected for the future under the different climate scenarios that were used to derive the crop projections. The economic effects of possible policy responses to cope with the adverse effects of climate change on agriculture can also be simulated.

The models were chosen for their robustness, their ability to work with minimal input data and their flexibility in terms of spatial and temporal resolutions and domain of applicability, in order to facilitate applications in different countries. Other criteria for the model selection were their previous use under various agro-climatic conditions, their licensing (free if not open source in order to avoid an expensive installation and maintenance in the target countries) and their ability to run on both Windows and Linux platforms.

The models have been grouped in four categories, corresponding to the four main steps of the methodology: Climate, Crops, Hydrology and Economics. A brief description of each model is given hereafter.

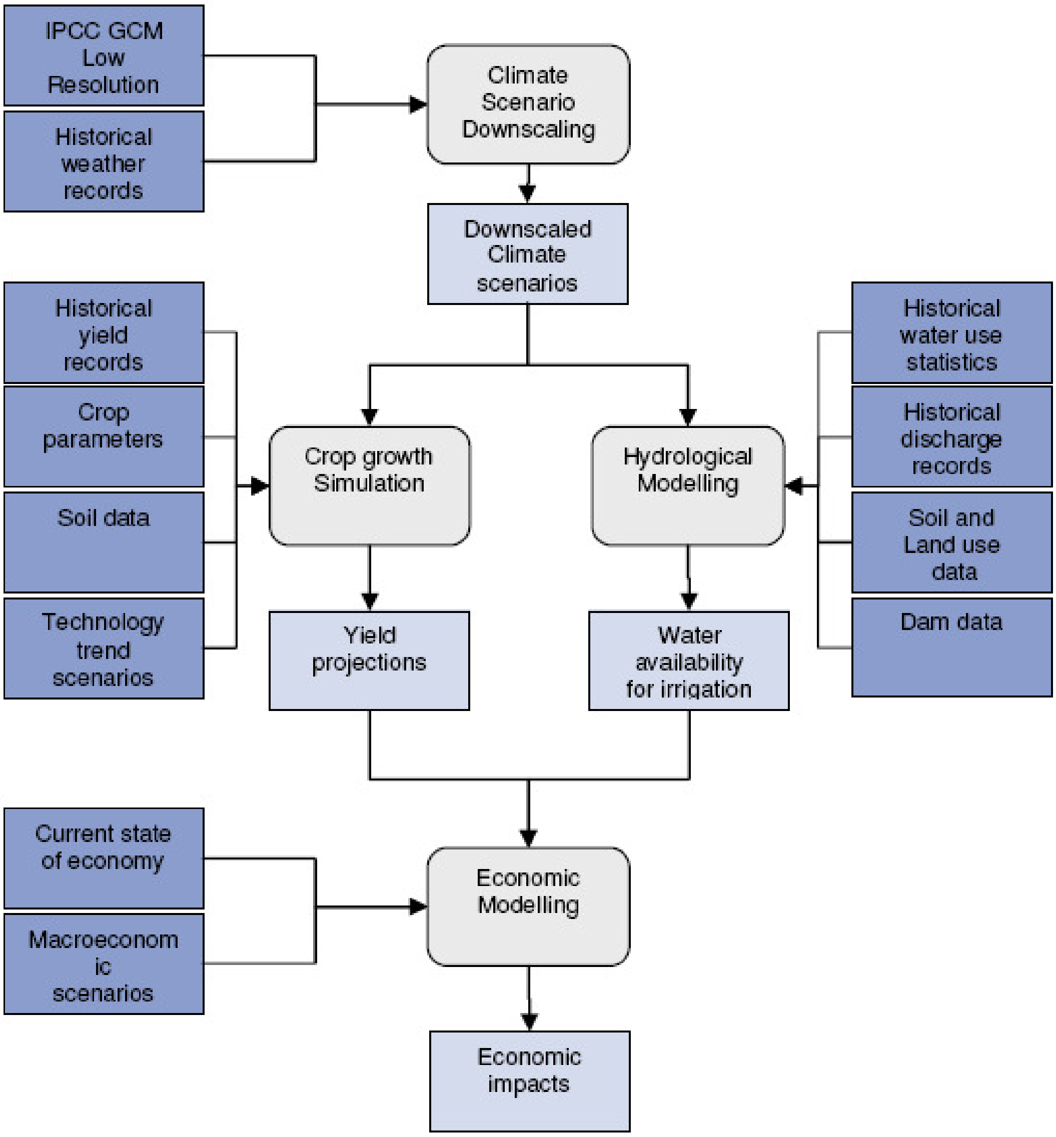

Figure 1. Overall flow of data with basic inputs in dark blue and produced data in light blue

CLIMATE

A statistical downscaling tool based on the DAD Portal (Data Access and Downscaling) has been developed by the Santander Meteorology Group of the University of Cantabria, Spain. This tool has been designed to perform statistical downscaling of coarse climate grids generated by GCMs. The data (precipitation, minimum and maximum temperature) can be downscaled simultaneously for a set of weather stations, provided that enough observation records are available for each of them. Several methods keeping spatial consistency are available, as for instance weather typing methods and regression methods. The tool also includes a weather generator to derive time series of the weather variables needed.

A second tool has been developed to interpolate the climate data over the study area using the method AURELHY (Benichou and Le Breton, 1986). AURELHY ("Analyse Utilisant le RElief pour l'Hydrométéorologie") is an interpolation method for meteorological and hydrological data based on the analysis of the topography. The tool consists in an R package, freely available on the R packages repositories.

In addition to the downscaling and interpolation tools, other utilities have been developed to calculate potential evapotranspiration (PET) and to estimate the beginning and the length of the growing seasons, respectively inspired by Hargreaves and Franquin's methods.

CROPS

In FAO-MOSAICC two models are available to produce crop yield projections. The first one is a crop-specific water balance model called WABAL. This model is designed to simulate the soil water balance at the level of the crop, using minimal input data: bioclimatic data (precipitation and reference evapotranspiration plus the starting date and the length of the growing season), soil data (soil water holding capacity) and crop parameters (crop factors and length of the crop growth stages). The results consist in the values of a number of crop water balance variables such as actual evapotranspiration water excess and deficit, and water satisfaction index for the growing season and the different growth stages. This model has been extracted from AgroMetShell, the FAO crop yield forecasting software and can be used for any type of crop.

The second model AQUACROP is a water-driven crop model initially developed for irrigation scheduling and water management at field scale. AQUACROP distinguishes the soil evaporation and the crop transpiration, simulates the root development, the expansion of the canopy as well as the water stresses, and provides biomass production and yield estimates. Despite it does not comprise of a complete representation nutrient cycle, the effects of soil (in)fertility and increase in CO2 concentration in the atmosphere is taken into account as well. The following crops are already available: cotton, maize, potato, qinoa, rice, soybean, sugar beet, sunflower, tomato and wheat.

HYDROLOGY

The hydrological model is based on STREAM ("Spatial tools for river basins and environment and analysis of management options"), first described in Aerts et al. (1999). STREAM is a spatially distributed precipitation-runoff model aimed at simulating flow accumulation and discharge rate in large water catchments areas. It has been applied in various basins around the world, as for instance the Rhine, the Ganges/the Brahmaputra, the Yangtze and the Zambezi river basins. The new version of STREAM that is used in this project offers more flexibility in terms of inputs and integrates dams in the hydrological cycle. In this new version the model calibration has been automated.

ECONOMY

FAO-MOSAICC comprises a Dynamic Computable General Equilibrium Model that simulates the evolution of the economy of a given country and the changes induced by variations of crop yields projected under climate change scenarios.

3. A DYNAMIC CGE MODEL

The economic model that is developed in this study is inspired by the IFPRI dynamic CGE model (Lofgren et al 2002; Thurlow, 2004). Our economic model, like the IFPRI model, is designed to represent African agriculture and the wider African economy. IFPRI has applied its model on various occasions to assess the economy-wide effects of climate variability in African countries (Thurlow et al., 2009; Pauw et al., 2010). Specific features of both the IFPRI model and our economic model are their ability to account for the fact that a share of farm production is directly consumed at the farm and thus does not reach the market, and the division of demand between "subsistence" demand that is income-independent and "luxury" demand that grows with income. To account for spatial or other variations in yield effects of climate change, commodities, such as wheat, can be produced with several activities. Such activities could, for example, be "wheat produced in a favourable agro-ecological zone" and "wheat produced in an unfavourable agro-ecological zone". There could even be more "activities" producing one "commodity", so the economic model could distinguish between more agro-ecological zones (AEZ), if data were available. The economic model can also distinguish between different crops, to the extent allowed by the data.

The economic model is a dynamic computable general equilibrium model. The central concept of such a model is "equilibrium". In economics, equilibrium relates to the condition that supply equals demand in all markets; in equilibrium there is no excess demand – all markets clear. The equilibrium force is the price system. When the supply of a commodity goes down (e.g. the supply of wheat because of adverse weather conditions), its price tends to go up, thereby stimulating additional supply and depressing demand, until supply and demand are equal again. Note that this mechanism does not only operate on product markets, but also on factor markets (labor, capital), saving markets (value of savings equals the value of investments) and on the foreign exchange markets (value of imports equals value of exports). An additional equilibrium constrain is that there are no excess profits, i.e., the sales' revenues of a product are totally exhausted by competitive payments to the factors of production, expenditure for intermediate inputs, and, possibly, taxes paid to the government.

The diagram in Figure 2 presents a schematic overview of the links between production and consumption in the economic model. It is perhaps most illuminating to think of a small region with two farms and one village where consumers live. The farms both produce the same product; let's call it "food". The consumers in the village earn their income by renting out capital to the farms and spend this income on the consumption of food. A part of the produced food is exported to a neighboring village in exchange for, say, fertilizer.

At the bottom of Figure 2, both farms (Farm 1 and Farm 2) use a land/water composite, labor, capital and intermediate input (including fertilizer) to produce “food”. The land/water composite is an aggregation of land and irrigation water. Irrigation water is zero for rainfed crops. Part of the food is withheld at the farms for own (home) consumption. The remaining part is offered on the market and is labeled “aggregate quantity of domestic output” in the diagram in Figure 2. Part of this aggregate output is exported to the neighboring village in exchange for fertilizer (import). The other part is sold on the domestic market (“domestic supply to domestic market”). This domestic supply of food is combined with imported food (in our example the import of food is null) to form the “composite supply to the domestic market”. This composite supply is purchased by households for consumption and savings, and also possibly by the government who has no role in our example.

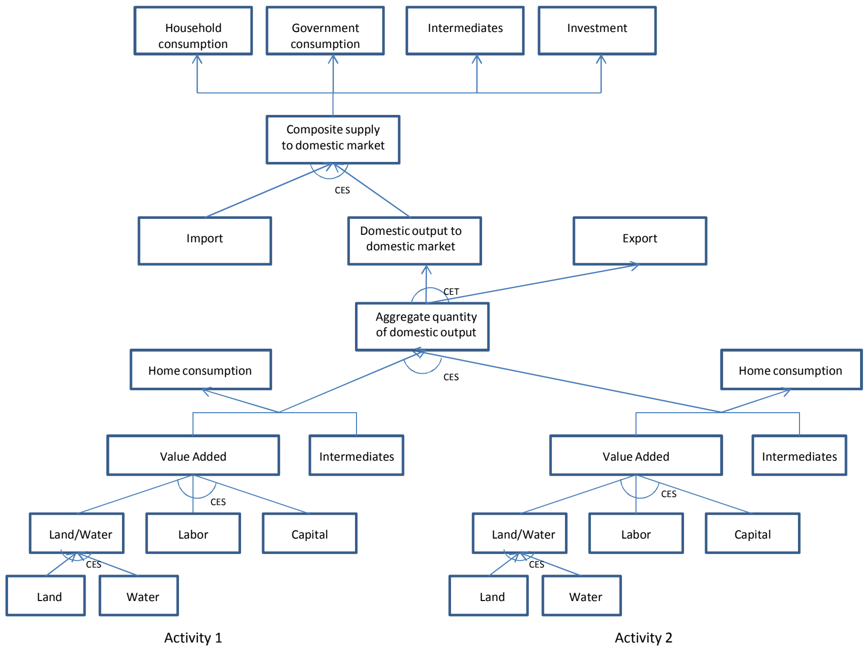

Figure 2 Simplified production and demand structure of the economic model with one commodity produced by two activities

The production, consumption and exchange decisions of the different agents in the model (farms, households, government) are governed by relative prices. Throughout the mode it is assumed that agents are price-takers (the prices are "given" to them; they cannot influence them) and that, given the prevailing market prices, they aim to maximise their utility or profit. In Figure 2, important decision nodes are labelled by CES, CET, and LES. These acronyms refer to functions that specify by how much the demanded or supplied quantity will change if the market price changes. For example, in the bottom of the diagram of Figure 2, a CES (Constant Elasticity of Substitution) function determines by how much the demand for labour will decrease by an activity when the price of labour increases relative to those of the land/water composite and capital. A CET (Constant Elasticity of Transformation) function determines the share of the aggregate quantity of domestic output that is exported, based on the export price relative to the domestic market price. A LES (Linear Expenditure System) function determines the household demand, based on income and relative prices of the products that are offered for sale.

Climate change can affect agricultural production in two ways. First, yield changes predicted by one of the crop models (WABAL or AQUACROP) are passed-on to the economic model through exogenous shocks to a technical shift parameter in the production function. In the benchmark this parameter is 1. A yield decrease of x% of a crop in a particular year reduces the shift parameter to (1-x/100). Second, changes in the availability of irrigation water predicted by the STREAM model are passed-on through an exogenous decrease of the water endowment.

The dynamics of the model are relatively simple. Population, labour, government spending and transfers, and total factor productivity grow at an exogenous rate. The income-independent share of demand grows at the same rate as population. In the standard closure, investments grow exogenously and savings adjust endogenously. We are working on more sophisticated dynamics in which prices, household expenditures and savings can adjust slowly to their long-run equilibrium values.

A requirement of the FAO-MOSAICC project was that the software used would be open source and multiplatform. The model is therefore programmed in the open source modelling language Dynare and can be solved with GNU Octave, a high-level language, primarily intended for numerical computations. GNU Octave provides a convenient command line interface for solving linear and nonlinear problems numerically, and for performing other numerical experiments using a language that is mostly compatible with Matlab. GNU Octave is freely redistributable software.

4. A TEST ON MOROCCAN DATA

This section describes an illustrative example of the application of the economic model to climate change induced yield changes in Morocco.

SETS AND BENCHMARK DATA OF VARIABLES

The Social Accounting Matrix (SAM) of Morocco was derived from the GTAP 6 database (Dimaranan, 2006), combined with GTAP Land Use Data (Huey-Lin et al., 2009). Our SAM of the Moroccan economy contains 41 accounts. The sets of production activities, traded goods, production factors and institutions are shown in Table 1 below.

Table 1: Sets in the Moroccan SAM

Set	No. of elements	Elements
Traded goods (import and domestic)	8	Barley, Wheat, Olives, Tomatoes, Sugar, Other Agriculture, Food, Mining & Manufactures & Services
Production activities	12	Barley_Fav, Barley_Def, Wheat_Fav, Wheat_Def, Olivies_Fav, Olives_Dev, Tomatoes_Fav, Tomatoes_Dev, Sugar, Other Agriculture, Food, Mining & Manufactures & Services
Production factors	3	Labor, Capital, Land
Institutions	3	Private Household, Government, Rest-of-World

In four crop-growing activities (barley, wheat, olives and tomatoes) a distinction is made between activities in favourable agro-ecological zones (FAV) and unfavourable agro-ecological (DEF) zones of Morocco. Hence, there are twelve production activities and eight traded goods.

CLIMATE CHANGE SHOCKS

The yield shocks are taken from the FAO-World Bank study (Gommes et al., 2007). Specifically we applied the shocks "*Percent change in average yield (WITHOUT tech trend; CO2 fertilization)*" for the year 2030 under climate scenario A2. Table 2 provides an overview of the estimated yield shocks, for different regions in Morocco. Figure 3 below presents a map of Morocco with the spatial distribution of the regions.

Table 2: Yield shocks (%, 2030, scenario A2)

	Favorable	Inter-mediaire	Montag-ne	Devaf Oriental	Devaf Sud	Sahara
Barley	-1	-4	-7	-13	-5	-6
Durum Wheat	-5	-4	-8	-6	-6	-2
Soft wheat irrigated	2	1	0	-1	2	2
Soft wheat rainfed	-5	-4	-3	-7	0	-11
Olive irrigated	-10	-5	2	-999	-999	3
Olive rainfed	-7	-6	-5	12	2	-999
Tomato	4	2	3	3	3	4
Sugar beet irrigated	3	0	0	-1	0	0
Sugar beet rainfed	0	0	-16	0	0	0
Sugar cane	3	-999	2	-999	-999	-999

n.b. -999 means no data.

Source: FAO-World Bank study (Gommes et al., 2007)

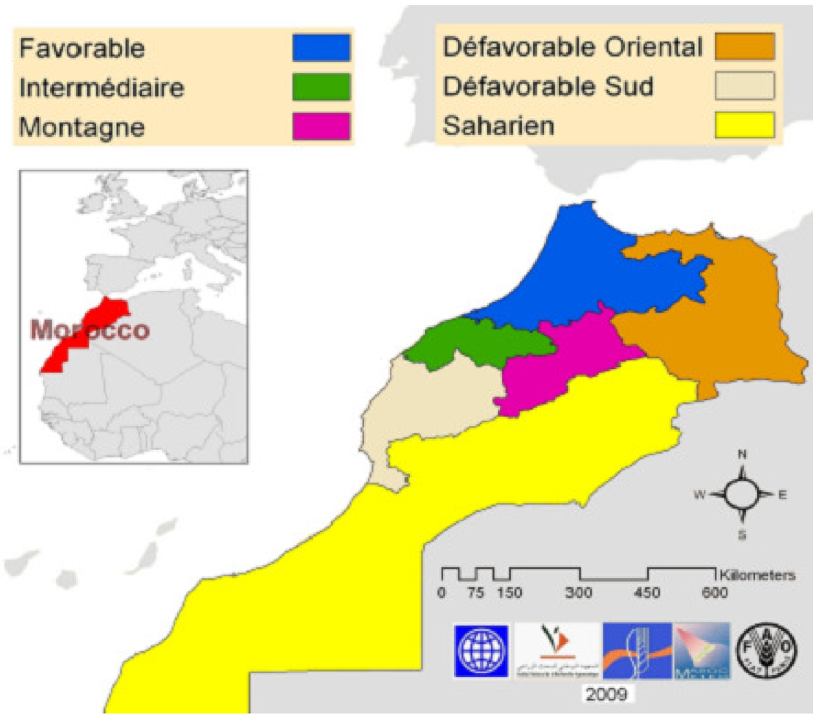

Figure 3: Regions in the FAO-World Bank study (Gommes et al., 2007)

To use the given yield impacts as shocks to our economic model some transformation was necessary:

1. Transformation of the given crops to the crops in the available SAM;
2. Transformation of the given regional distribution to the regional distribution in the available SAM.

The regional distribution of AEZs in our base data is shown in Fig. 4. A comparison of the maps in Fig. 3 and Fig. 4 suggests that an exact mapping of the regions of Fig. 3 to the AEZs of Fig. 4 is difficult or impossible. We have crudely differentiated between Favourable (Favorable and Intermédiair in Fig. 3) and Unfavourable zones (the other zones in Fig. 3), where Favourable (FAV) is made up of the AEZs 3,4,9 and 10 (the wetter regions) and Unfavourable (DEF) is made up of AEZs 1,2,7 and 8 (the dryer regions).

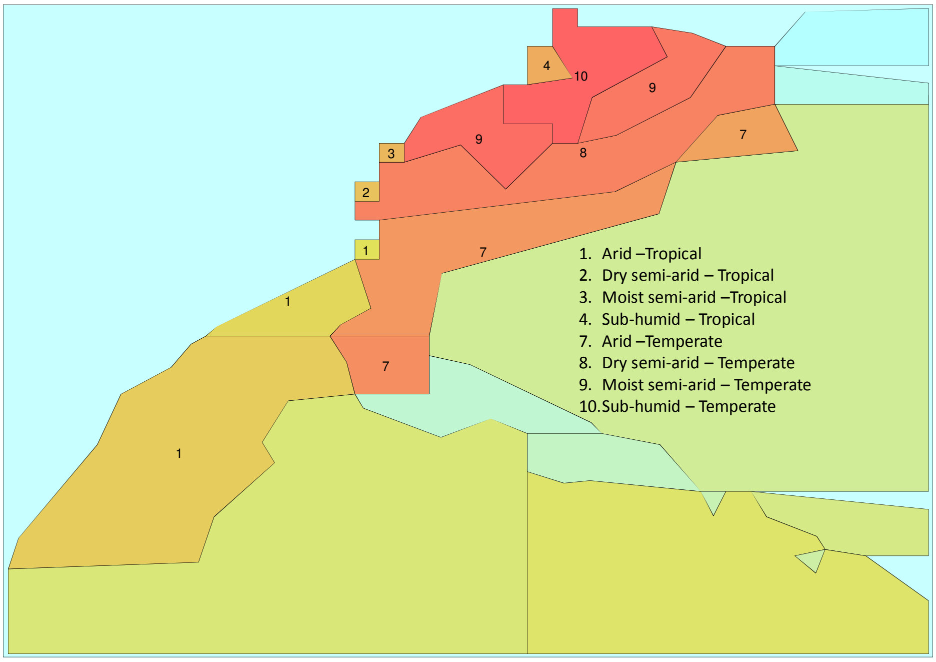

Figure 4: Agro-ecological zones in Morocco (source: GTAP 6 database and GTAP land use data)

Mapping between and aggregating over crops and regions produced aggregated yield shocks for the favourable (FAV) and unfavourable (DEF) regions of Morocco, as shown in Table 3.

Table 3: Aggregated yield shocks

	FAV	DEF
BARLEY	-1	-6
WHEAT	-5	-4
OLIVE	-7	2
TOMATO	4	3
SUGAR	1	0

The yield shocks were fed into the economic model as changes to the technical shift parameter in the activity production functions for barley, wheat, olives and tomatoes in both the favourable and unfavourable regions and for sugar in the favourable region alone (in our SAM there was no production of sugar cane or beet in the unfavourable region). Note that the yield shocks are negative for barley and wheat, they are negative or positive for olives depending on the region, and they are (slightly) positive for tomatoes and sugar. For barley there is a marked difference in the magnitude of the negative yield shock between the favourable and unfavourable region.

In this simulation we have not simulated an irrigation water constraint. This is both because we have no estimates of water stress from the FAO-World Bank study and because the GTAP data have no data for the value of irrigation water in the benchmark.

In the simulation all exogenous variables remain constant over the projection period: their growth rates are zero. This is a simplifying assumption for testing purposes; we do of course not claim that this is a realistic assumption.

RESULTS

In our simulation, climate change negatively affects the productivity of barley and wheat production. Hence, the marginal costs of the cultivation of barley and wheat in the FAV and DEF regions of Morocco increase as shown in Figure 5. The highest cost increase is for barley in the unfavourable, dry, regions where marginal costs increase by 31%. The marginal costs of producing barley in the favourable region increases by less than 3%. The difference of cost increase of wheat between the favourable and unfavourable region is small. The marginal cost of wheat production increases by 17-19%.

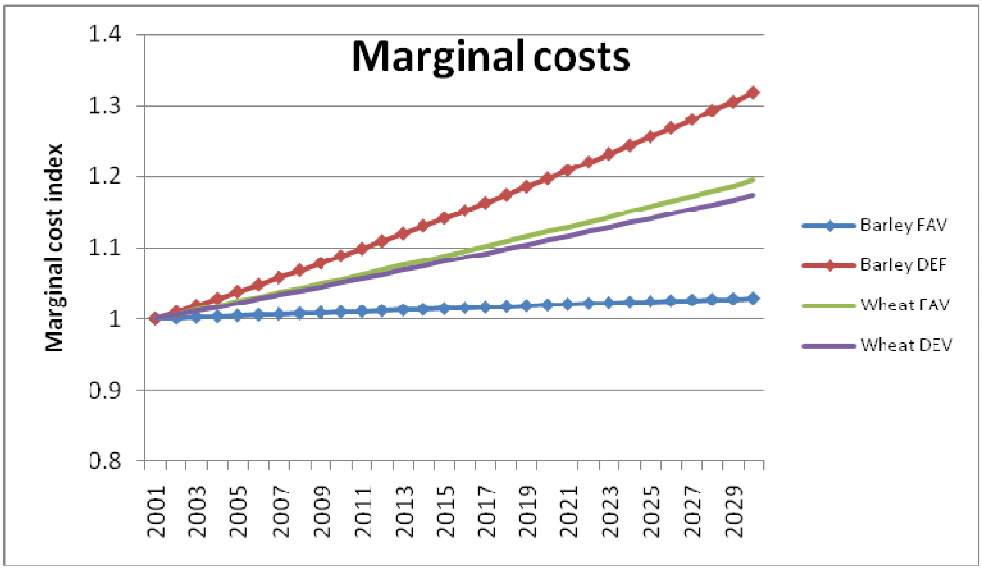

Figure 5: Marginal cost index of cultivation of barley and wheat in FAV, DEV.

If there were no changes in management and land use, the yield changes could be directly translated into changes in the harvests of crops. However, due to the changes in marginal cost and profitability, farmers adjust their cropping pattern and management. Figure 6 shows that the harvest (output) of barley in the DEF region decreases relatively more than yield. The productivity losses in barley induce farmers to switch to other crops.

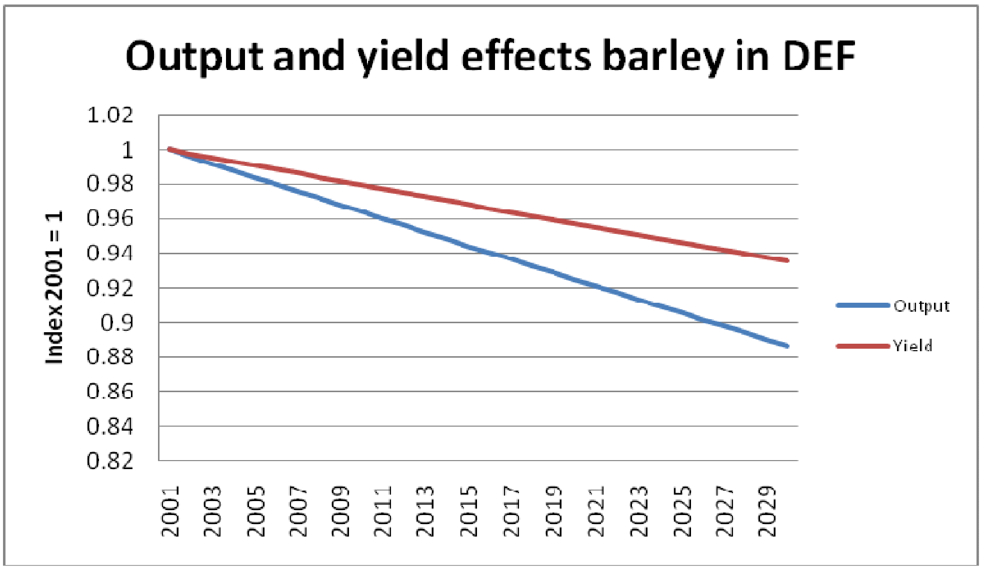

Figure 6: Harvest and yield effects of barley in DEF

The overall effect of climate change on the market prices of all agricultural commodities in 2030 is shown in Figure 7. Note that the price changes are relative to the business-as-usual (BAU) scenario. As explained above, in our very simple simulation the BAU scenario is a no-change scenario: all variables remain at their 2001 levels over the entire simulation period.

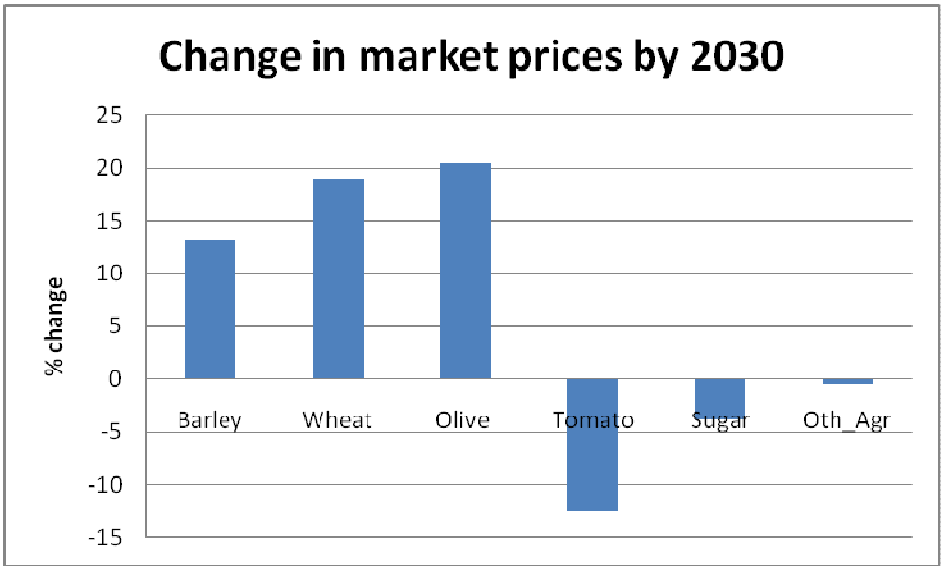

Figure 7: Changes in market prices of all agricultural commodities in 2030 relative to BAU.

Figure 7 shows that the marginal costs of the cultivation of barley, wheat and olives increase, while those of tomatoes, sugar and other agricultural commodities decrease.

Figure 8 shows the effects on imports and exports. For the interpretation of the effects, two things are important. First, in this simple simulation it is assumed that world prices remain constant. Second, the Moroccan exchange rate decreases by 3.4% over the course of the simulation period, so that imports become relatively more expensive, while exports become more competitive on the world market. The results of our simulation suggest that changes in imports will be relatively minor, while the bulk of the adjustment to climate change is in exports.

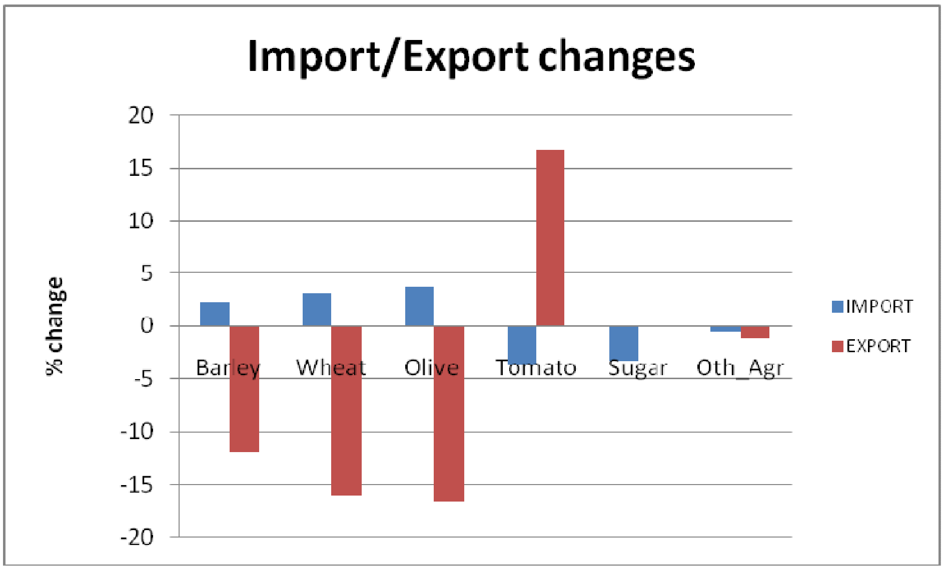

Figure 8: Effects on imports and exports in 2030, relative to BAU.

Figure 9 below shows the final effect of climate-change induced yield effects on household demand of agricultural commodities and processed food. The simulation results suggest a 5-7% decrease in the household demand for barley, wheat en olives in 2030 relative to BAU. The demand for tomatoes increases by 8.5%. In this simulation, we have assumed a subsistence share of 50% in the demand for food products. A higher share would lower the changes in household demand.

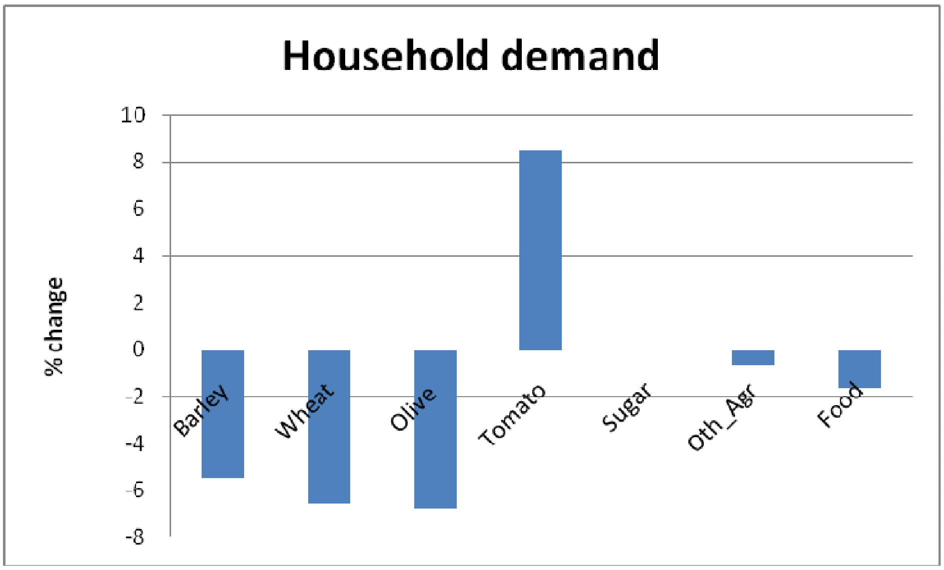

Figure 9: Household demand for agricultural commodities and food in 2030, relative to BAU.

The overall effect of climate-change induced yield effects on Gross Domestic Product (GDP) is presented in Figure 10 below. In 2030 GDP (in constant prices) is 0.5% below BAU.

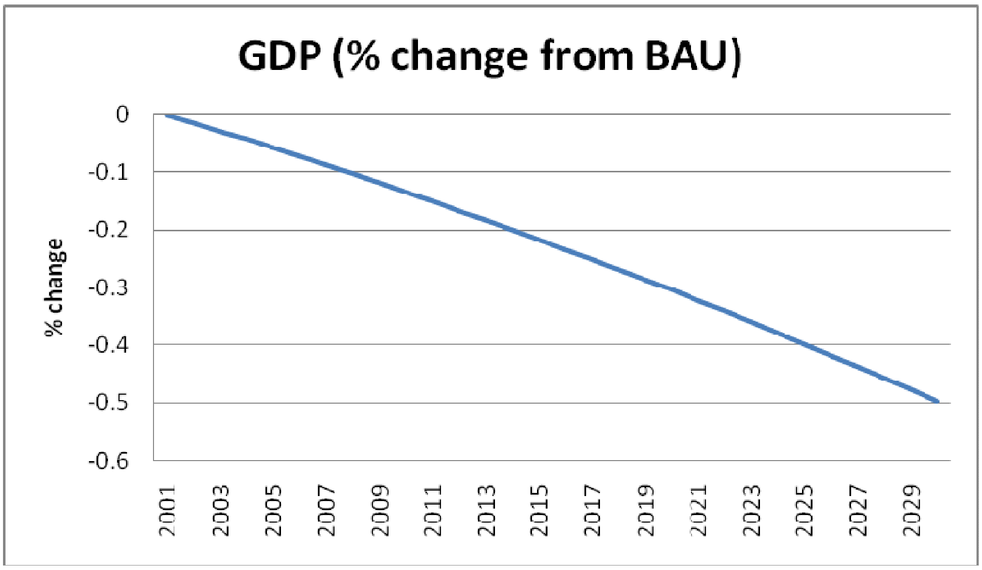

Figure 10: Evolution of GDP (% change from BAU)

One indicator of food security is the ratio of domestic self-sufficiency in food, as the ratio between domestic production and (apparent) domestic consumption (domestic production plus imports minus exports). Figure 11 shows that the self-sufficiency ratios for barley, wheat and olives slightly decrease between 2001 and 2030, the ratio for tomatoes increases, and those for sugar and other agricultural commodities are basically unaffected.

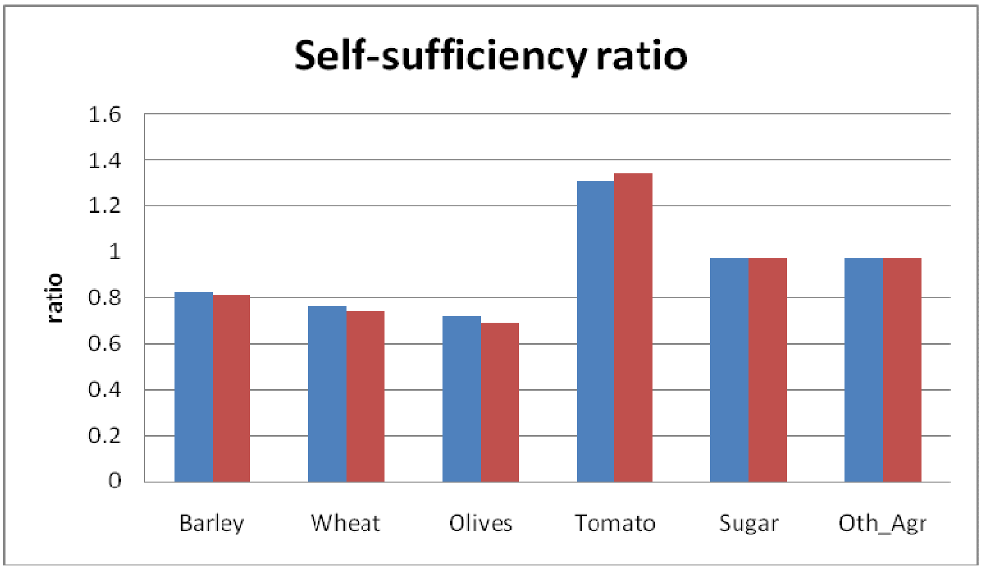

Figure 11: Self-sufficiency ratios

5. DISCUSSION

Combining various mathematical models, FAO-MOSAICC sets a framework to carry out multidisciplinary studies to assess climate change impacts on agriculture and provide support for planning and adaptation policies. The system is meant to be installed by national institutions and managed by a working group bringing together experts from each institution and each discipline. The system is delivered with complete documentation and training programs. A full test of the system will be undertaken in Morocco in 2011 before distributing the system to other countries.

The DCGE model of FAO-MOSAICC can simulate sector-level and macroeconomic effects of climate change impacts on agriculture. The simulation above is for illustrative purposes. We used GTAP data to construct the SAM on which the simulation was run. GTAP data provide a useful default dataset for simulations, but they contain little country-specific detail. We paid little attention to the magnitudes of the parameters of the model in production and consumption. Local experts are needed to expand the dataset and to advise on country-specific parameter values to increase the realism of the simulations.

Because of lack of data, some of the features of the DCGE model have not been utilised in the simulation. For example, in the simulation all private households were aggregated into one 'representative' household. To examine climate change impacts on food security, it would be interesting to distinguish between different types of households: e.g., poor rural, rich urban, and perhaps also between households from different regions. Given appropriate data, the DCGE model can handle this distinction. Another pending issue is the potential irrigation water constraint. For this to implement, we need data on the economic value of irrigation water and predictions on future water stress by the SREAM model

The effects on the composition of final demand in the simulations would perhaps be considered too large by country experts (too many tomatoes, to little wheat). A finer aggregation of crops would perhaps show interesting effects on food security that are now 'hidden' in broad commodity classes. Again, we would need local data to make this finer aggregation possible.

We think we have created a robust and flexible economic model that can potentially address a large number of questions regarding the economic dimensions of the impact of climate change on food security. We do need country expertise and data, however, to fully utilise the model's capabilities.

ADDITIONAL INFORMATION

For more information on the FAO-MOSAICC project, its models and its implementation, see http://www.fao.org/climatechange/mosaicc/en/.

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