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An integrated interdisciplinary modelling system of climate change impacts on agriculture in support of adaptation planning: MOSAICC

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Abstract: Food and Agriculture Organization of the United Nations developed a server-based integrated system of tools and models called MOSAICC to evaluate climate change impacts on the agriculture sectors (crops, water resources, forests, and economy). MOSAICC is designed to respond to the needs of developing countries which may benefit from institutional and individual capacity development in producing relevant information for national climate change adaptation planning. This innovative system design facilitates a participatory environment where researchers with different expertise can work together efficiently. The utilization of the Web technologies avoids complex installations on the user's computer and makes maintenance and update of the system on the centralized server simple. MOSAICC is based on open-source technology and models thus it is transferrable to countries free-of-charge. The easy-to-use interface and data sharing/exchange through central database support interdisciplinary cooperation among local experts as the chain of simulations and data are transparent to users. Visualization and communication of the results in graphs and maps on the Web are integral parts of the system. The implementation strategy of MOSAICC in countries emphasizes stakeholder involvement in a technical working group throughout the study in order to produce information that is truly necessary in the country. National experts, who are members of the working group, design the study, perform simulations using MOSAICC, and publish the results to inform stakeholders. In the process, the experts learn the theory, methodology, and the use of models in a series of capacity development workshops.

Keywords*: climate change; agriculture; impacts; adaptation; food security*

1 INTRODUCTION

Climate change has been affecting agriculture and will continue to make impacts, potentially threatening food security, in the world with increasing population trends. The agriculture sector is highly diverse, consisting of sub-sectors such as crops, livestock, forestry, aquaculture, and fisheries. The climate impacts on agriculture are primarily biophysical, but vulnerability of the people to such impacts varies depending on socioeconomic conditions.

There are numerous climate change impact studies, but many of them are disconnected from decision-making processes of stakeholders (e.g. national ministries of agriculture, environment, and government agencies). On the other hand, many climate change adaptation policies / programmes / projects in developing countries lack a solid evidence-base about current and future climate impacts as well as vulnerabilities at different spatial and temporal scales. Little information that do exist were produced not by local researchers, due to insufficient technical capacities, but by international experts, in many cases with minimal engagement of local stakeholders (e.g. national research institutes and universities).

In order to fill this information and capacity gaps, Food and Agriculture Organization of the United Nations (FAO) developed the tool MOSAICC (Modelling System for Agricultural Impacts of Climate Change) and it has been implemented in several developing countries such as Morocco, the Philippines and Peru, and recently in Malawi and Zambia. MOSAICC employs an interdisciplinary assessment approach to addressing climate change impacts and adaptation planning in the agriculture and food security sectors. An innovative software design of MOSAICC supports participatory and integrated modelling environment in an interdisciplinary working group.

2 OBJECTIVES OF THE MODELLING SYSTEM

MOSAICC addresses common climate impacts on agriculture in an integrated way. Currently it combines five different components from diverse academic disciplines: statistical downscaling of climate change projections, yield simulation of crops, surface hydrology simulation, forest landscape model, and macroeconomic model. MOSAICC is a modular system and we keep exploring to add more components to simulate impacts in other sub-sectors.

MOSAICC supports an interdisciplinary approach that is essential in tackling a grand challenge of climate change and agriculture. All components run on a server and exchange data through a central geospatial database. This system design brings together very different models that are usually run independently by separate groups of researchers. MOSAICC facilitates and fosters collaboration of researchers from different disciplines who tend to work only in their own domains.

We designed MOSAICC so that it benefits national climate change adaptation policy processes, particularly in developing countries. In order to ensure the information produced by MOSAICC are put into use by stakeholders, we emphasize a country-driven process for implementing MOSAICC. The integrated and interdisciplinary design of the system supports participatory processes from designing a climate change impact assessment study to communication of the results. Section 3 discusses the MOSAICC system design, and section 4 discusses a typical country implementation of MOSAICC with examples from the Philippines and Peru.

3 SYSTEM DESIGN OF MOSAICC

3.1 Components and Models

MOSAICC is a system of models designed to carry out each step of climate change impact assessments from climate scenarios downscaling to economic impact analysis at national level in an integrated way. The development of MOSAICC originated from a study carried out by Morocco, the World Bank and FAO in 2008. Its basic design was determined to meet the requirements elaborated in a series of consultations with international scientists and economists, and government officials.

The five main components of the models (Figure 1) are:

- statistical methods for downscaling climate projections from General Circulation Models (GCMs)
- crop growth models to simulate future crop yields
- a hydrological model for estimating river water resources
- a forest model to simulate biomass and tree species distributions
- a CGE (Computable General Equilibrium) model to assess the effect of changing yields and water availability on national economies

Each component provides one or more models. There are also cross-component tools, such as spatial interpolation, grid area analysis, and cell statistics. The models chosen to be integrated into MOSAICC are relatively simple and robust, and can run with input data of limited quality and availability. Robust models can cope with errors in the inputs and with problems at run time. Simple but flexible models can be calibrated for use in different ecosystems. The participating models and tools are open source. As a result,

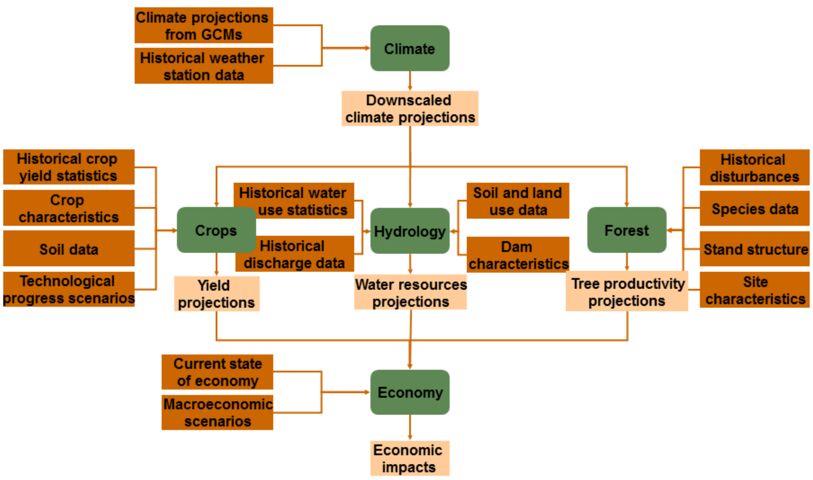

Figure 1. MOSAICC

MOSAICC is free and highly transferable to many different countries in diverse agroecological zones.

Climatologists first upload weather station locations and weather time series data, perform downscaling, perform spatial interpolation of the results, and share them with other users. The downscaling process is external to MOSAICC because it requires huge computation resources, but MOSAICC provides an interface to interact with it efficiently. There are several statistical methods available for climate downscaling (Gutiérrez et al., 2012).

The spatial interpolation operation address the problem of limited number and coverage of weather stations in developing countries. The optimized AURELHY (Analyse Utilisant le RELief pour les besoins de l'Hydrométéorologie) algorithm (Bénichou and Le Breton, 1987) facilitates subsequent model simulations by gridding climate data (and aggregating to administrative levels, as necessary).

Agronomists have several models and tools: the planting dekad model (PLD) (Franquin, 1973), the water balance model (WABAL) (Frère and Popov, 1986), and the crop water productivity model (AQUACROP) (Steduto et al., 2009). AQUACROP simulates crop yield and is used usually in specific locations because it requires a number of data collected in the field. WABAL is a simpler model with limited requirements of input data and produces crop-specific water balance variables as outputs. The variables are used to construct statistical models to simulate crop yield. The WABAL approach is more suitable for assessments at larger spatial scale. Many different crops can be simulated as long as necessary data are available.

Hydrologists work with a model called STREAM (Spatial Tools for River Basins and Environment and Analysis of Management Options) (Aerts et al., 1999). It is a rainfall runoff model that simulates discharges in river basins. The water availability is calculated at sub-basin level, depending on data availability.

For foresters, MOSAICC provides LANDIS (Landscape Disturbance and Succession) (Scheller and Mladenoff, 2004), which simulates forest succession, disturbance (including fire, wind, harvesting, insects), and seed dispersal across large landscapes. LANDIS requires a huge number of parameters. MOSAICC provides an interface to deal with all the details and re-arranges the information in required files. The results are post-processed to generate key variables: forest biomass, tree species distributions, biodiversity, establishments, forestry evolution, Leaf Area Index (LAI), and non-wood products.

Economists have the DCGE (Dynamic Computable General Equilibrium) model (Lofgren et al., 2002) to work with. It simulates the current and future economy under different climate projections. The model distinguishes the national economy and that of the rest of the world, between which goods and services are exchanged. The model uses crop yields and water availability generated by agronomists and hydrologists as shocks to the national economy. The main outputs are macro indicators (GDP), domestic market variables, external trade variables, and prices.

Key outputs of MOSAICC simulations are future projected values of these different variables simulated by each model. All the models can use the data generated from other models through a central geospatial database. The user works on MOSAICC with a web browser to connect to the MOSAICC server over the Internet. Data, models and results are all on the server. Nothing is required on the user's computer. The systems installed in countries can be easily upgraded remotely by MOSAICC developers.

3.2 Architecture

MOSAICC is a complex server-based system designed to provide a centralized environment where experts work, focusing on data and experiments, without the need for spending energy on details of model executions because they are handled from the user interface.

The MOSAICC system is based on a server-class computer, running an enterprise level Linux distribution, e.g. CentOS 6.x. A typical hardware configuration is a rack server with Intel Xeon CPU E5-2650 with 32 GB RAM and 3 TB of disk in RAID 5 mode.

MOSAICC has heterogeneous components, developed in different environments and programming languages. It is possible to choose and activate any specific components, depending on the interests of the user country. OpenVZ (Kolyshkin, 2006; Furman, 2014) allows creation of an isolated environment for installing and running a component without affecting any other components. A local firewall implements the security from the network to the WEB interface and among the five virtual machines that run the core and the components.

The Web-GIS interface is based on Apache as Web server, PostgreSQL as DBMS, PHP as programming language, Drupal as CMS, MapServer as map builder, and OpenLayers as map displayer. Several custom modules have been developed to customize Drupal to the MOSAICC user interface, which connects the users to the models, managing the data and the parameters that they require and generate. MOSAICC is based on three concepts: user-profile, data-type and model execution. User-profile and data-type are the keys to the security model defined in MOSAICC.

3.3 User profiles

Considering the data flow required to perform climate change impact assessments, five user profiles are defined: climatologist, agronomist, hydrologist, forester and economist. Each user profile allows accessing a number of user functions. Each user function corresponds to a model type, as MOSAICC allows defining multiple models of the same type (e.g. potential evapotranspiration calculations (Hargreaves and Penman-Monteith methods); two versions of a model: AQUACROP 3.1 and 4.0). Each model type requires certain parameters and data types. MOSAICC uses the relationship between data types and model types to link together user profiles, user functions and data types.

3.4 Data types

MOSAICC implements a geodatabase based on the open-source DBMS PostgreSQL 9.x and its GIS extension PostGIS 2.x. to handle about 60 data types, most of which are georeferenced. Data types can be rasters or vectors. Some data vary in time. The user can upload the definition of the objects (e.g. weather stations) and then the time-dependent data (e.g. weather observation) as tables. Some models require configuration files. For example, crop files for AQUACROP must be uploaded.

3.5 Model execution

The models are executed following the sequence of climate change impact assessments:

1. Climatologists perform downscaling of climate projections, create derived variables (e.g. PET), and spatially interpolate the data.
2. Experts use crop, hydrology and forest models to assess climate change impacts in respective disciplines, using data from climate downscaling. These models can be run in parallel.
3. Economists use all the data generated by the other experts to assess climate change impacts from the economic point of view.

MOSAICC guarantees the coherence of input data for the models at several levels:

- spatial coherence, i.e. all used data types are for the same area and spatial resolution.
- temporal coherence, i.e. all used data types are for the same period and temporal resolution.
- logical coherence, i.e. all used data types are for the same time period (historical, reference time or future) and climate change scenario and GCM.

The model execution is organized in three phases: the wizard-based model configuration, the model execution, and the result visualization and analysis. The wizard method is the easiest way to perform the model configuration. It checks and sets up the model to run smoothly, avoiding common errors. MOSAICC looks after all the details and leads the user from the input data to the results. Advanced users can access the logs for detailed analysis and check. A model execution sometimes requires hours to run, but it happens on the server and the users have tools to check what is happening anytime.

3.6 Visualization and communication

The outputs of the models are usually complex - many files with a lot of information, often coded. MOSAICC facilitates the result analysis and visualization by post-processing the generated files and displaying them in a convenient way. Sometimes the results consist of thousands of grid points that MOSAICC helps to analyse by performing statistical analyses, such as grid area analysis against a selected vector data (usually the administrative division) or cell statistics.

MOSAICC provides some visualization tools to display the data and the results of experiments as tables, graphs or maps. It has a Web-GIS interface to display all the geographic data and to perform common GIS queries. In addition, it can display time-dependent data as graphs and tables. Data aggregation functions are available as well. The user can access the raw model outputs and the post-processed files. The results can also be downloaded as they are or in formats such as CSV or XLS.

The results needs to be presented and communicated in a suitable way in order to reach the widest audience, which can be decision makers or experts of different sectors. MOSAICC processes the finalized experiments selected by the modellers to provide a simple and optimized visualization of the results in terms of changes (absolute or in percentage) brought by climate change, with respect to the reference time. Those data are displayed as maps at different aggregation levels, such as regions, provinces, communes, agro-climatic zones, basins, and so on. Formatted PDF documents are generated to provide organized printer-ready information to the user. The responsive web design allows users to access the portal with a wide range of devices, from desktop computers to mobile phones.

4 COUNTRY-DRIVEN IMPLEMENTATIONS THAT SUPPORT POLICY PROCESSES

4.1 Institutional assessments

In order to ensure that local researchers use MOSAICC to produce information that are useful for stakeholders, we emphasize a country-driven process for implementing MOSAICC. A typical implementation of MOSAICC in a new country starts with a stocktaking exercise of existing information in the country about climate change impacts on agriculture. Once gaps in information availability become clear, national ministries are consulted as main stakeholders. They provide their views about needs for information about climate impacts in the sector for adaptation policies and programmes. In many cases, ministry of agriculture and its climate change office are the main stakeholders. They have responsibility for developing climate change adaptation policies and programmes. Information on potential climate change impacts support their work. For example, in Peru, the Ministry of Agriculture and Irrigation (MINAGRI) was identified as the main stakeholder and its Vice-minister chaired the steering committee of the project that implemented MOSAICC. Other ministries such as the Ministry of Environment were also consulted.

In parallel with information needs assessment, country's technical and institutional capacities in filling the gaps are assessed, across national research institutes and universities. In Peru, the National Meteorological and Hydrological Services, the National Agrarian University in La Molina, the Office of Economic and Statistical Studies in MINAGRI, were found to possess relevant knowledge and skills.

4.2 Technical working group

There are abundant climate impact studies at the global and continental scales. Also available are plot-scale information. MOSAICC is designed to fill information gaps that are most useful for national decision-making processes. Some examples of national policy processes that MOSAICC can inform include National Adaptation Plans and Climate Smart Agriculture programmes.

If MOSAICC appears to address country's information and capacity gaps, we start forming an interdisciplinary technical working group that is composed typically of ministries, national research institutes, and universities, and the group is supervised by the project steering committee. The main members of the group are subject experts that will be responsible for running simulations with each component of MOSAICC. Climatologists in national weather service often take responsibility for climate component. National agricultural research institutes may take on crop simulations. The group also includes policy makers as a main stakeholder (section 4.1). They guide a climate change study as a member of the working group from study design to communication of the results. Other technical offices of the government can also provide necessary data and expertise as a member of the group. The agencies mentioned in section 4.1 constituted the Peruvian technical working group. In the Philippines, the Department of Agriculture, Philippine Atmospheric, Geophysical and Astronomical Services Administration, Philippine Rice Research Institute, University of the Philippines – National Institute of Geological Sciences were the main members of the technical working group.

Data collection is a time-consuming process. MOSAICC requires relatively small amount of data as inputs to models, but data are often scattered across different offices, and not in a format suitable for computer processing. We also make sure that the data providers agree on sharing the data with all members of the technical working group so that a truly collaborative research is possible. Digital elevation model (DEM), land use, soil properties, weather stations, weather data, hydrological stations, hydrological data, crop files are examples of data that are necessary for MOSAICC simulations.

As a next step, the technical working group agrees on the study objectives, study design (including time periods, target crops, study areas, basins, etc.), taking account of stakeholder needs and data availability. In the process, the group members have an opportunity to reflect on country's context, and to build a common understanding about what would constitute a successful adaptation to climate change in the agriculture sector, and what kind of information MOSAICC should produce in support of achieving the goal.

The Philippines decided to examine climate change impacts up to mid-21st century. The climate statistical downscaling work is considered to complement dynamical downscaling work conducted in the past, and to provide up-to-date information with a new set of climate projections (CMIP5). Their MOSAICC crop and hydrology work were designed to highlight differentiated impacts of climate change in different locations across the whole country with a focus on rice and corn at the province level, and 24 river basins. Peru was interested in extending the projections up to the end of the 21st century, with a set of 29 crops at the region level, and 16 river basins that represent different agroecological systems.

Usually at least two Representative Concentration Pathways are examined (e.g. RCP 4.5 and RCP 8.5). Also at least three climatic models are evaluated in order to account for uncertainties from GCMs. The spatial scale for MOSAICC simulations is flexible, but the system design and model choices are most appropriate for national-level studies with sub-national dis-aggregation. MOSAICC primarily deals with medium- to long-term climate change time scale, beyond 10 years. The downscaled climate projections are daily data so aggregation to any temporal scales (10-day, month, season, year, etc.) is possible, and changes in frequency and intensity of extreme events, for example, can also be studied.

In parallel with formation of the technical working group, a server for installing MOSAICC is purchased and configured. The server initialization process consists of two actions: creation of management user(s) who can create other users, and definition of the geographic region of interest. In addition, country's own collected data sets are uploaded to MOSAICC.

4.3 Capacity development and simulations

Capacity development is another important focus in our MOSAICC implementation strategy. Climate change adaptation planning is a long and iterative process that should be periodically reviewed with new evidences, science, and outcomes from adaptation interventions. The capacities of country experts to carry out science work that forms an evidence-base about climate impacts and adaptation are key to a sustainable policy planning process. We provide extensive training programs to the identified local experts for use of each component of MOSAICC. At least one week of training per component is usually provided. The sustainability of strengthened technical capacities of individual experts is ensured by commitment of all stakeholders represented in the interdisciplinary technical working group.

The idea is that country experts can perform simulations using their country's own data in support of national planning. The trainers, who are original developers of participating MOSAICC models, continue to provide technical support to make sure the experts can accomplish simulation studies, after training. It takes about three months (per component) for experts to perform simulations provided dedicated researchers are assigned to the task.

4.4 Communication of results

Running simulations is only part of climate impact studies. The simulation results need to be analysed, interpreted, and visualized for stakeholders. They would inform policy makers of which areas / sub-sectors / crops / basins / forest species are more vulnerable than others are. The information would strengthen evidence-bases that support adaptation planning and allow strategic resource allocations, investment programmes, research and development, and prioritization of adaptation interventions.

The technical working group is tasked to make sure that the modellers can communicate the implications of model outputs to aid policy processes. Communication of the results can take a number of other forms: presentation in conferences, paper and electronic publications, and web site. MOSAICC is designed to publish results from the simulation server in a seamless manner as graphs/maps to the web server.

The technical working groups in the Philippines and Peru recently finished the simulation work. The work in the Philippines was presented in a national project conference hosted by the Department of Agriculture, with wide participation from other Departments, Climate Change Commission, research institutes, universities, international development agencies, NGOs, and media. The nation-wide assessment work was highly appreciated and will be a basis for National Adaptation Plans in the agriculture sector and other policy processes. In both countries, policy briefs and summary reports for wider audience are being prepared while the technical reports will be published soon. Some of the work are prepared for publication in international journals or were already published (e.g., Manzanas et al., 2015; Basconcillo et al., 2016).

5 CONCLUSIONS

MOSAICC was developed as a capacity development tool that enables researchers in developing countries to conduct climate change impact assessment studies in the agriculture and food security sectors that are highly diverse and interdisciplinary. An innovative system design facilitates a participatory environment where researchers with different expertise can work together efficiently.

MOSAICC is a server-based integrated system of tools and models to evaluate climatic impacts on crops, water resources, forests, and economy. The system provides a coherent approach (spatial, temporal, and logical) to the data exchanged among all the components through a Web-GIS interface. The utilization of the Web technologies avoids complex installations on the user's computer and makes maintenance and update of the system on the centralized server simple. MOSAICC is based on open-source technology and models thus it is transferrable to countries free-of-charge. The easy-to-use interface and data sharing/exchange through central database support cooperation among local experts as the chain of simulations and data are transparent to users. Visualization and communication of the results in graphs and maps on the Web are integral parts of the system.

The implementation strategy of MOSAICC emphasizes stakeholder involvement in a technical working group throughout the study in order to produce information that are truly necessary in the country. In each country of implementation, we facilitated collaboration among different ministries and institutions to make an interdisciplinary study possible. The software design of MOSAICC is catalytic in successful collaborations. Local experts in the group design the study, perform simulations using MOSAICC, and publish the results to inform stakeholders. In the process, the experts learn the theory, methodology, and the use of models in a series of training workshops.

MOSAICC was successfully implemented in several countries in support of national climate change adaptation policies and programmes, as briefly illustrated by the cases in the Philippines and Peru. We plan to continue to develop MOSAICC by adding components to simulate other sub-sectors, and to implement it in more countries as part of climate change projects.

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