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Agroecological Zones Simulator (AZS): A component based, open-access, transparent platform for climate change – Crop productivity impact assessment in Latin America

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Abstract: The Agro-ecological Zones Simulator (AZS) is a platform for data and models sharing for scientists and policy makers, facilitating the analysis of climate change impacts and the identification of possible response strategies through a comprehensive regional-level analysis comprised of: (i) Geo-referenced climate, soil and terrain data, combined into a land resources database; (ii) Crop suitability assessment and land productivity of cropping systems; (iii) Procedures for calculating the potential agronomically attainable yield; (iv) Procedures for computing actual yields as limited by water availability and management, biotic and abiotic factors; and (v) Selected agricultural production systems with defined input and management relationships, crop-specific environmental requirements and adaptability characteristics. The software core of the platform is given by an instance of the BioMA platform. The platform facilitates the evaluation of the impacts of projected changes in temperature, precipitation and evaporative demands on crop growth and function, including investigations of adaptation potentials by means of management optimization and use of available or improved crop varieties. Simulations are performed using modelling solutions based on extensible, multi-model components for crop growth and development, soil water dynamics, biotic (e.g., diseases) and abiotic (e.g., ozone concentration, frost events) stressors, hourly and daily weather variable generation, automatic management practices, and with a generic component implementing different approaches for crop suitability. The inclusion of biotic and abiotic factors in modelling solutions allows for explicit computations of changing pressures on crops under a changing climate, increasing the realism of the modeled systems. AZS is currently operational for Latin America and Caribe; it was recently used by the World Bank's Agriculture and Rural Development of Latin America for the analysis of climate change impacts on four major crops: wheat, maize, rice and soybean. The results of those simulations and analysis are presented as a first application of the AZS platform.

Keywords: adaptation strategies; diseases; abiotic damages; BioMA; rice.

1 INTRODUCTION

Climate change is expected to significantly affect ecosystem functions and human activity in coming decades [IPCC AR4 2007], with specific impacts on agro-ecosystems, including: changes in ecosystems composition, biome boundaries and area distribution shifts; increasing aridity and desertification; and increasing incidence and impacts of crop pests and disease. Agriculture is likely to suffer the largest and most direct impact of climate change among economic sectors in many

regions [de la Torre et al. 2009]. For Latin America, estimated total economic damage ranges from \$35 billion [Mendelsohn and Williams 2004] to over \$100 billion by 2100. These projected losses could be substantial already by 2050 under pronounced warming scenarios [de la Torre et al. 2009]. In addition to the impacts of climate change through changes in mean climatic variables, projected increases in the frequency and severity of extreme events pose serious threats to agricultural production systems [Tubiello et al. 2007].

In the face of projected changes in climate and impacts on land use systems, adaptation strategies – and robust and quantitative assessment tools for their identification – are needed to guarantee the long-term sustainability of food production and agro-ecosystems.

The aim of this study was the development of a climate change-crop productivity impact modelling platform (Agro-Ecozone Simulator, AZS), providing for an extensible, open-access tool, fully transparent with respect to both model components and data.

The rationale behind the development of the AZS modelling platform was to:

- Provide a user-friendly and accessible solution to data and model sharing among local and international stakeholders (including research institutions), enhancing their capacity of providing policy makers with clear and effective information;
- To avoid dependencies from spatial scales, specific modelling approaches, adaptation strategies, production levels, and data sources, in order to guarantee both global, exploratory assessments and context-specific, high-detail studies.

The AZS platform was derived from BioMA (<http://agsys.cra-cin.it/tools/bioma/help/>), an application for analyzing, parameterizing and running biophysical modelling solutions on spatially explicit units. The AZS, developed in collaboration with the World Bank's Agriculture and Rural Development of Latin America Department, is currently operational for Latin America and the Caribbean Region (LACR).

This paper describes the AZS platform and provides as example an application to assess climate change impacts in LACR on four major food crops (wheat, maize, rice and soybean) under different climate scenarios and time horizons, production levels and adaptation strategies.

2 THE AGRO-ECOZONE SIMULATOR (AZS) PLATFORM

The software core of the AZS platform (deployment model in Figure 1) is based on BioMA, the platform for running biophysical models of the European Commission. BioMA is an application designed and developed for analysing, parameterizing and running modelling solutions – chains of biophysical models developed for targeting specific objectives within specific contexts – against a database of spatially explicit units.

BioMA is based on independent components, for both its modelling solutions and graphical user's interface. Each component is provided with documentation of its algorithms and code included in a complete software development kit. This component-based structure allows BioMA to implement diverse modelling solutions (including any developed autonomously by third parties) targeted to specific modelling goals. The BioMA simulation environment includes integrated tools for Monte Carlo-based sensitivity analysis (LUISA), and a solver framework (Optimizer) to assist in parameters calibration. Both LUISA and the Optimizer can be used with any modelling solution made available in BioMA, and both can be extended, for sensitivity analysis engines and solvers/objective functions, respectively.

AZS is derived by adding specific datasets and modelling solutions to BioMA, to customize the latter for climate change impact studies in Latin America and the Caribbean regions. The datasets, described in the sections below, are linked to the software part of the platform via a “data layer” component, allowing BioMA to be interfaced with common database systems (e.g., Oracle, SQLServer).

AZS, currently operational for Latin America and the Caribbean, can be extended spatially, i.e., to other regions of the world, and for different levels of abstraction, i.e., the level of representation of specific agricultural production systems of interest. AZS facilitates such extensions through its modular and open structure. In addition, the AZS platform allows for powerful analyses of impacts and adaptation responses, via the following:

- selection of agricultural production systems with defined input and management relationships, crop-specific environmental requirements and adaptability characteristics;
- links to geo-referenced climate, soil, and terrain data, combined into a land resources database;
- procedures for calculating the potential agronomically attainable yield and for matching crop environmental and management requirements with the respective environmental characteristics contained in the land resources database, by grid cell;
- routines for computing water limited, biotic factors limited, abiotic factors limited, and actual crop yields, by grid cell;
- different approaches for assessing crop suitability and land productivity of cropping systems.

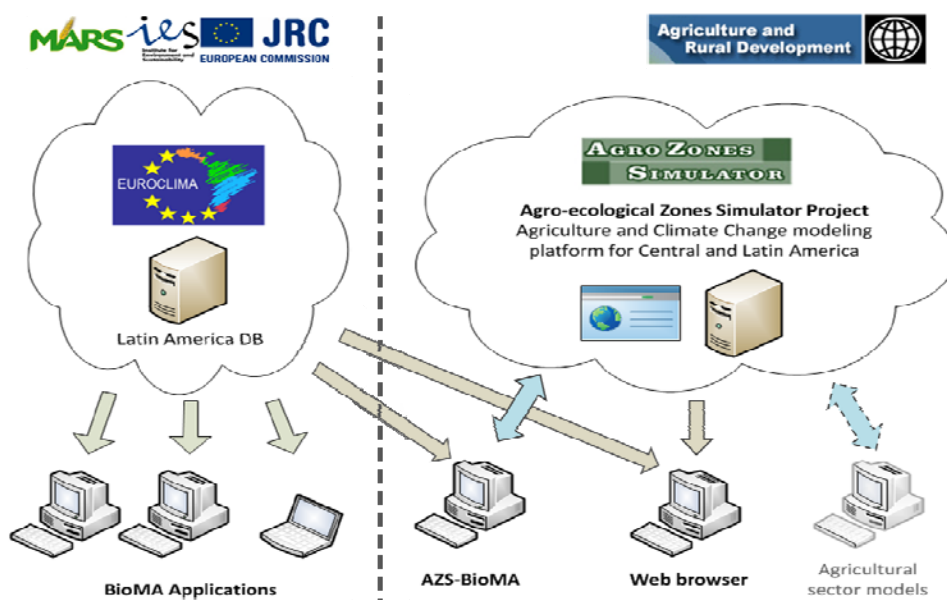


Figure 1 AZS-BioMA deployment model.

3 THE LATIN AMERICA AND CARIBBEAN STUDY

3.1 Data, Modelling Solutions and assumptions of the study

We present herein, as a first well-developed example of AZS applicability, the results of a climate change impact study focused on the most relevant food crops in Latin America and the Caribbean Region. Such impacts, and possible adaptation responses, were analysed over two future 20-year time windows, centred on 2020 and 2050, chosen to investigate, respectively, immediate and medium-term impacts on Latin American agriculture.

Historical climate data were derived from the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA-Interim database (20 years, centred on 1998) (www.ecmwf.int/research/era/do/get/era-interim). Variables not available in the ERA-Interim database were derived using the CLIMA libraries [Donatelli et al. 2009, Bregaglio et al. 2011]. Two IPCC AR4 climate change scenarios (A1B and B1; IPCC 2007) were selected as input for two different GCMs: Hadley3 [Gordon et al. 2000] and NCAR [Collins et al. 2004]. In order to generate spatially distributed

weather data to be used for feeding biophysical models, the Climak weather generator [Danuso 2002, Confalonieri 2012] was used.

The used soil data set [Hoogenboom et al. 2009] was derived from the updated version of the “World Inventory of Soil Emission Potentials” (WISE version 1.1, Batjes 2002). WISE 1.1 database was created to provide a basic set of uniform soil data for a wide range of global and regional environmental studies (e.g., agro-ecological zoning and assessments of crop production).

Crop masks for maize, wheat, soybean and rice, together with related crop calendars, were derived from the SAGE Center for Sustainability and the Global Environment database (SAGE, <http://www.sage.wisc.edu/index.html>).

The general definition of adaptation tested via simulation in this project is given by changes in agricultural management that farmers may implement to alleviate negative impacts of the weather scenarios evaluated.

Adaptation tests were run considering three factors:

- genotype: the duration of the crop cycle evaluated is medium (with respect to the current climate) for the analysis of the baseline, whereas early and late maturity genotypes are also evaluated in the simulation of weather scenarios;
- planting time is explored by testing the shift in planting dates;
- water supply is implemented with the same rule-based model used for the baseline simulation, parameterized in order to provide a medium level of water availability (e.g., less than 300 mm/season of irrigation; less than 3 irrigations).

Water supply was always active in simulations for irrigated/potentially irrigated crops (i.e., maize and soybean in this study; rice is mainly paddy in the region; while wheat is largely rainfed), while all combinations related to genotype and planting time were explored.

The crop models used for this study were CropSyst [Stöckle et al. 2003] for soybean, maize and wheat, and WARM [Confalonieri et al. 2009, 2010] for rice. CropSyst has been successfully used worldwide for many crops [e.g., Donatelli et al. 1997] under a variety of agro-climatic conditions [e.g., Wang et al. 2006]. WARM is the model used by the European Commission for rice yield forecasts in Europe, China and India. The parameters of both models were calibrated by using field data retrieved from the literature, selecting – where available – papers and experiments with measurements referring to different state variables (e.g., aboveground biomass and LAI). The two crop models (implemented in the CropML library, Confalonieri et al. 2012) were included in dedicated modelling solutions able to perform simulations under the following production levels:

- potential production (P: crop growth solar radiation and temperature driven);
- water limited (WL: all factors of P and water limitation);
- abiotic stresses limited (AL: P and effects due to temperature-induced spikelet sterility in this study);
- disease limited (DL: P and impact from one crop-specific disease);
- multiple-factors limited (MFL: P, WL, AL, and DL limited).

The simulation of diseases limited production did not include agro-management needed to alleviate the impact of a possible increased pressure by plant pathogens due to climate change. In this study, basic food commodities-based production systems abstracted at the level of “crops”, and basic adaptation strategies, were evaluated following the work of previous crop assessment studies. However, our approach to the simulation of impacts of extreme events and of the crop-disease interactions provides a methodological advance compared to previous attempts.

Simulations were run at 25 × 25 km spatial resolution. Results were aggregated at national level using the crop mask information derived by the SAGE database.

3.2 Climate Change Impacts Assessment

The simulations performed in this study indicate that the impacts of climate change on agriculture in Latin America and Caribbean are expected to be significant, with severe risk to maize, soybean and wheat production in most countries, whereas an increase in rice productivity is expected.

For Maize (Fig. 2 and 3), without adaptation, negative impacts of climate change were simulated throughout the continent, mainly because of the reduction in the grain filling period due to higher thermal time accumulation rates, not compensated by the increase in daily biomass accumulation under elevated CO₂, generally leading to increased growth rates (albeit lower in C4 species like maize compared to C3 like wheat soybean and rice). The countries most affected were Brazil, Ecuador, Mexico and the Caribbean countries, where maize is a major staple food. Generally, the Hadley GCM led to the highest losses except for Brazil and Ecuador (and for the latter, only for the B1 scenario). Considering the heterogeneity of the responses in the area, country-level adaptations strategies will be critical to mitigate productivity declines. Especially in the 2020 time frame, adaptation significantly reduced the climate change impacts simulated in most countries – although yield decreases were still significant in major maize producing countries like Mexico. In general however throughout the region of study, adaptation strategies positively contributed to limit climate change damage to maize production, even in the countries where grey leaf spot disease was the most limiting factor.

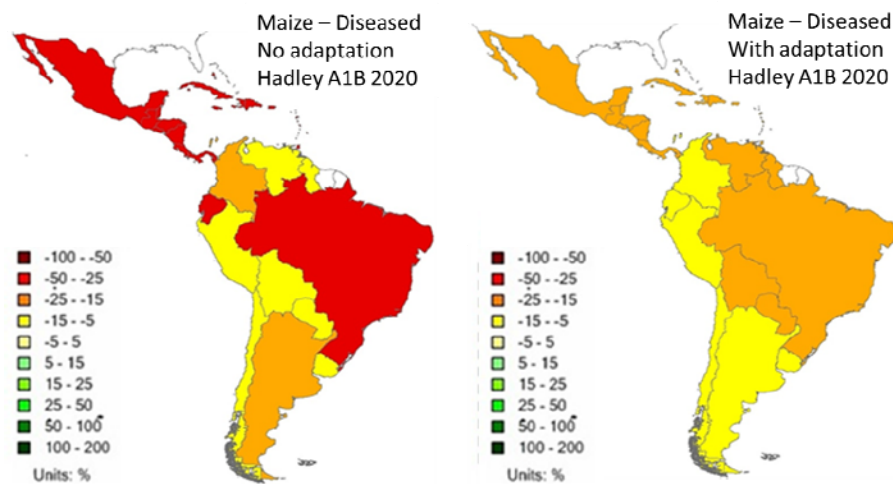


Figure 2 Percentage yield decrease simulated for maize with and without adaptation for 2020 (Hadley - A1B). Grey leaf spots (*Cercospora zeae-maydis*) impact is simulated.

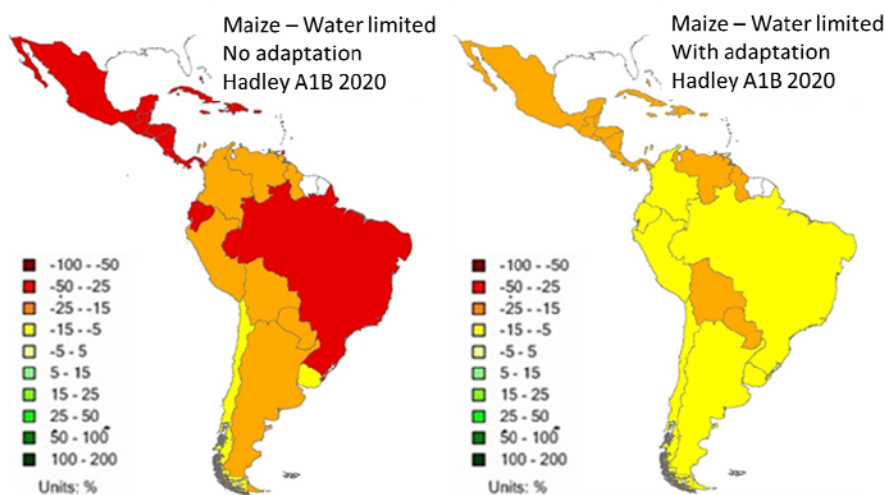


Figure 3 Percentage yield decrease simulated for maize with and without adaptation for 2020 (Hadley - A1B). Water limitation to crop growth and development are simulated.

For Rice, the simulations showed, on average, productivity increases. The fact that rice is a wetland/irrigated crop contributed significantly to these results, particularly, the high crop thermal requirements and the high sensitivity of rice to elevated CO₂. Considering potential conditions (Fig. 4) (not limited by water, diseases and abiotic damages), without adaptation, only Mexico and Brazil had yield losses exceeding 15% by 2050, whereas increases in yields were simulated for Colombia, Peru and Uruguay for all time horizons. These results were explained by the modulation of the interacting effects of increased temperature regimes and CO₂ fertilization. Adaptation strategies allowed an almost complete recovery of losses, with slight losses expected only for Mexico by 2050.

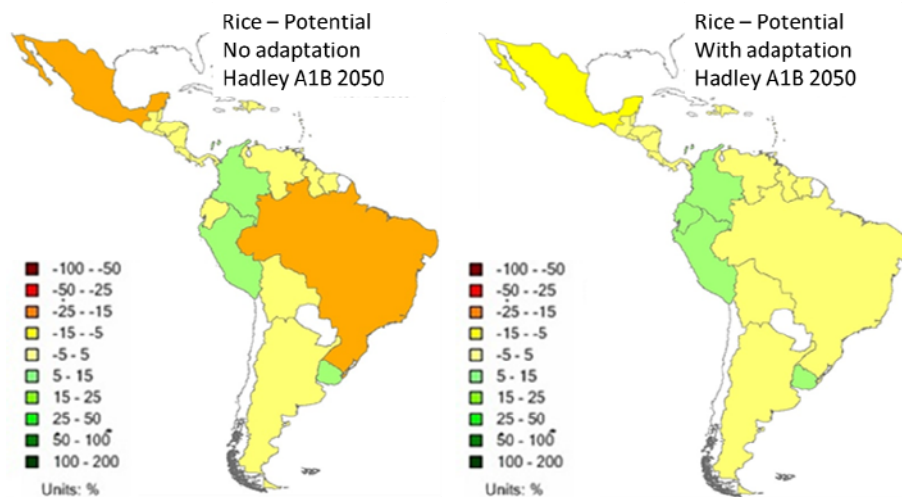


Figure 4 Percentage yield decrease simulated for paddy rice with and without adaptation for 2050 (Hadley - A1B). Crop growth and development under potential conditions are simulated.

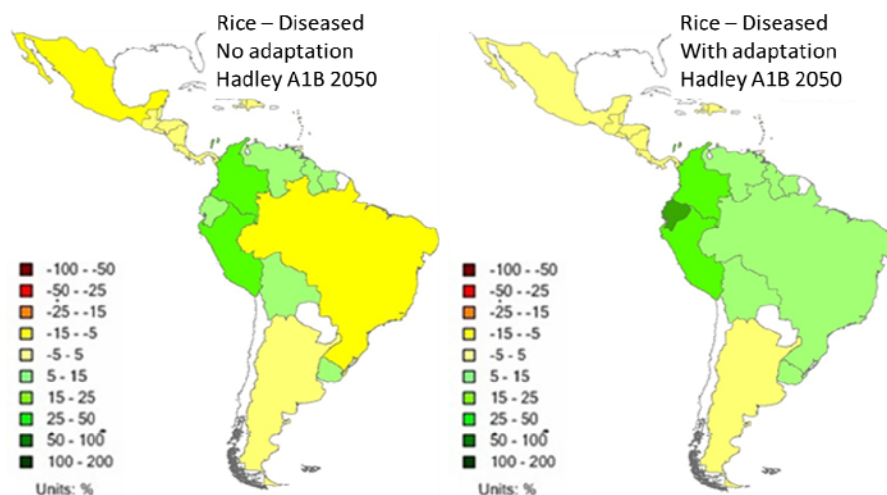


Figure 5 Percentage yield decrease simulated for paddy rice with and without adaptation for 2050 (Hadley - A1B). Blast disease (*Pyricularia oryzae*) impact is simulated.

The projected rice yield changes in the region of study continued to be positive even when the impact of diseases was simulated (Fig. 5). In fact, the climatic conditions explored in the future were found to be less favourable for the main rice pathogen, so that simulations indicated a lower disease pressure on the crop. Even without adaptation, yield increases were simulated (with biotic stresses) for 2050 in all countries, with exception of Brazil and Mexico, where a slight decrease

in production was computed. Adaptation strategies allowed to completely recover the yield gaps also in these countries, leading to a generalized optimistic situation for this crop in coming decades despite climate change.

For wheat, simulations indicated that yields were significantly affected by climate change, because of shortened crop cycles and regardless of the emission scenario or GCM considered. Percentage yield decreases were more pronounced in Mexico, in the Caribbean region, and in the North-eastern parts of the continent (Colombia and Brazil). Projected water-limited productions for 2020 and 2050 were always lower than in the baseline, with South-Western countries less affected. The projected yield decrease due to diseases in 2020 and 2050 was also significant. Frost damages were expected to affect wheat yields less seriously in Chile, where shortened cycles would also reduce the crop exposure to leaf rust. With few exceptions (e.g., Chile), insufficient water availability affected wheat productivity more than all other factors considered, thus suggesting the development of varieties with characteristics able to assure higher resistance to water shortages. With adaptation strategies, projected impacts were decidedly less pronounced for all the production levels and scenarios considered. Water availability still played a key role in limiting wheat productivity, with the use of genotypes with longer cycles compensating the shortening of crop cycles despite increased transpiration demands. Insufficient water availability played a major role in Brazil and Chile; disease pressure specifically affected productions in Argentina.

For soybean, without adaptation, negative impacts of climate change were simulated across the continent in 2020 and, increasingly, in 2050 – although with different magnitudes throughout Latin America. Yield losses were larger in Brazil and in the Northern countries (>-30% with respect to baseline yields), whereas in Argentina, Uruguay, Bolivia and Colombia the simulated yield decreases were less pronounced. By considering projected water-limited production level, yield losses were reduced in Argentina and Uruguay, whereas in Brazil, Central America and Caribbean regions they suffered reductions. This could be explained by the greater impact of climate change in Brazil, where the reduction of crop cycle length was more pronounced than in other parts of Latin America (higher temperature increase). Our simulated adaptation strategies reduced the magnitude of impacts across all scenarios and time windows considered. In Argentina, the use of varieties with longer cycle effectively compensated the climate change negative effects tending to shorten crop cycles.

4 CONCLUSIONS

The simulation results of the study carried out in Latin America and the Caribbean Region evidenced a negative impact of climate change on maize, soybean and wheat productivity, with impacts partly alleviated by adaptation strategies. Simulations by contrast suggested increases in future paddy rice yields, because of its high thermal requirements in the absence of water stress, its high sensitivity to CO₂ fertilization, and a reduced pressure of the blast disease agent.

Through the case study discussed, the AZS-BioMA platform proved its effectiveness in estimating climate change impacts and in identifying adaptation strategies on large areas. Moreover, (i) the possibility of easily extending the platform to new data layers and modelling solutions, (ii) the independence from spatial and/or temporal scales, and (iii) the availability of different approaches for each simulated process make AZS-BioMA a tool able to work at different levels of crop abstraction. This has direct implications both in the typology of production system considered (cropping system, farming system, etc.) and, consequently, in the spectrum of adaptation strategies evaluated.

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