Beyond mean rainfall and temperature changes: distributional effects of stochastic yield variability in the Sudan

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Abstract:

Several environmental changes have encountered the Sudan in the past; several are ongoing and others are projected to happen in the future. The Sudan has witnessed increases in temperature, various floods, rainfall variability and concurrent droughts (USAID, 2016). This study do not only look at the economy-wide impacts of climate change, but also consults national policy plans, strategies and various other environmental assessments to propose possible interventions. We feed the climate forcing as well as water demand and macro-socioeconomic trends into a modelling suite that includes models for global hydrology, river basin management, water stress and a DSSAT1 all connected to IMPACT2 model. The outcomes are annual crop yield (ton/hectare) and global food prices under various climate change scenarios until 2050. The distributional effects of such changes are assessed using a single country dynamic CGE3 model for the Sudan. Additionally, we introduce yield variability into the CGE model based on stochastic projections of crop yield until 2050. Results reveal that while the projected mean climate changes bring some good news for the Sudan, extreme negative variability cost the Sudan accumulatively (2018-2050) US$ 109.8 billion in total absorption and US$ 105.1 billion in GDP relative to no climate change scenario.

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Abstract

Several environmental changes have encountered the Sudan in the past; several are ongoing and others are projected to happen in the future. The Sudan has witnessed increases in temperature, various floods, rainfall variability and concurrent droughts (USAID, 2016). In a country where agriculture, which is mainly rainfed, is a major contributor the GDP, foreign exchange earnings and people's livelihood, these changes are especially important, necessitating comprehensively studying them and measuring their impact at all levels. This study do not only look at the economy-wide impacts of climate change, but also consults national policy plans, strategies and various other environmental assessments to propose possible interventions. We feed the climate forcing as well as water demand and macro-socioeconomic trends into a modelling suite that includes models for global hydrology, river basin management, water stress and a DSSAT[1] all connected to IMPACT[2] model. The outcomes of this modeling suite are annual crop yield (ton/hectare) and global food prices under various climate change scenarios until 2050. The distributional effects of such changes are assessed using a single country dynamic CGE[3] model for the Sudan. Additionally, we introduce yield variability into the CGE model based on stochastic projections of crop yield until 2050. Results reveal that while the projected mean climate changes bring some good news for the Sudan, extreme negative variability cost the Sudan accumulatively (2018-2050) US$ 109.8 billion in total absorption and US$ 105.1 billion in GDP relative to no climate change scenario.

Key words: global climate, local yield changes, the Sudan, climate variability, interventions.

1 Introduction

After the secession of South Sudan in 2011, the area of the Sudan became 1.8 million km^2, which makes it still a vast country with considerable diversity of ecology, topography and people. Mean

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[1] Decision Support System for Agrotechnology Transfer.

[2] International Model for Policy Analysis of Agricultural Commodities and Trade.

[3] Computable General Equilibrium.

annual temperatures vary between 26^oC and 32^oC across the country. Rainfall patterns ecologically divide the country into five vegetation zones from North to South: (1) desert with 0-75 millimeters of precipitation, (2) semi-desert with 75-300 mm, (3) low rainfall savannah on clay and sand with 300-800 mm, (4) high rainfall savannah with 800-1500 mm, and (5) mountain vegetation with 300-1000 mm of precipitation (MEPD, 2015).

According to UN (2015), the population of the Sudan will more than double by 2050, reaching 80 million inhabitants. The economy is projected to restore steady growth of an average of 3.6% in the next five years and a growth rate of 3.5% in 2022 (IMF, 2016). The secession of the South reduced the country's Gross Domestic Product (GDP) growth from 2.5% in 2010 to -1.2% and -3.0% in 2011 and 2012, respectively (IMF, 2016). It has also forced some structural changes on the economy including an increase in the agricultural share in GDP from 28.9% in 2011 to 30.4% in 2012 and a decline in the share of industry from 26.5% in 2011 to 24.5% in 2012. In the meantime, agriculture remained an important contributor to GDP, given the declining oil production and exports. It contributed 30.1% to GDP in 2016 with an annual growth rate of 5.5% from 2015 (CBoS, 2017).

The demand for food in the Sudan is projected to grow, due to a growing population and income. Staple foods, which consist of cereals and roots are projected to grow from 6.5 million tonnes in 2010 to 10.1 million tonnes in 2030, dairy products from 6.3 to 9.7 million tonnes and sugar from 0.9 in 2010 to 3.4 million tonnes in 2030 (OECD-FAO, 2017). From 2017 to 2030 demand for these three products is projected to increase by 35%, 56% and 157%, respectively. Moreover, demand for fats and meat products will increase by 100% and 22% between 2017 and 2030, respectively. On the production side, staple foods, dairy products, sugar, fats and meat products are projected to increase by 6.8%, 56%, 21%, 14% and 23%, respectively. Although the remaining gap can be filled with increasing imports, this adds to the pressures at the national level such as government budget and trade deficits as well as the international challenges of making adequate supplies of food available to a growing population worldwide.

Households in the Sudan are predominantly rural dwellers with 73% of the population living in rural areas while the remaining 27% are urban dwellers (MHRDL, 2013). Among rural households, more than every second rural household (58%) lives below the poverty line compared to only one in four urban households (27%). Rural households mainly rely on agriculture as the main livelihood, as 65.4% of rural population are employed in agriculture compared to only 8.9% in urban areas.

Besides population and economic growth, that together trigger increases in demand for food, water and energy, the Sudan is subjected to several environmental changes. (FAO, 2017; USAID, 2016; FAO, 2015; Sayed and Abdala, 2013; Taha et al., 2013). The Sudan is reliant on agriculture as it makes one third of the GDP, one-half of foreign exchange earnings and provides livelihoods to more than half of the Sudanese people (CBoS, 2016). Acknowledging that the absolute majority of annually cultivated land in the country is rainfed (93% in 2016), such environmental changes are especially important, creating rebill effects in the entire economy and affecting the livelihoods of the people everywhere in the Sudan directly or indirectly.

Therefore, the objectives of this study are to estimate the effects of changes in global and local climate on the Sudanese economy and people and propose policy interventions that mitigate the negative environmental implications and promote the positive ones.

We apply a modeling approach that builds on the interlinkages among food, water and energy in the economy and on the insight, that any environmental, economic or policy intervention in one of these three component will affect the others (Nielson et al., 2015). It is the first time ever that such a comprehensive approach is applied to address the complex issue of climate change in the Sudan. It includes models for global hydrology, river basin management, water stress and a DSSAT model connected to IMPACT model with the end-point impact on the Sudanese economy being depicted by a Computable General Equilibrium (CGE) model. This shows the changes at the macro-level as well as changes in different economic sectors (detailed representation of agriculture, industry and service sectors), incomes and expenditures of different household groups, incomes to and employment of different factors of production.

The findings of this study are expected to be useful to many stakeholders in the Sudan, especially policy makers who would be able to see climate change impact in a detailed way and assess the suitability of the various options of intervention. While aiming to contribute to scientific knowledge and filling in a research gap in a country where similar studies are lacking, the study tries to present the various national strategies and action plans that mainstream environmental recommendations in an implementable rather than prescriptive way.

The following section shows the nature and significance of the agricultural sector and reviews the environment-related national strategies and action plans in the Sudan as well as published research with the aim of extracting implementable policy interventions that reduce or mitigate the projected changes in global and local climate. Section 3 presents our methods with brief descriptions of the biophysical, stochastic and economic models. Here we also provide a detailed description of the climate projections as well as our suggested policy interventions. In Section 0, we present and discuss the results obtained from the modeling suit at the CGE front and finally, Section 0 provides conclusions and recommendations to policy makers and other stakeholders in and outside the Sudan.

2 Agriculture and climate change in national policies and action plans in the Sudan

2.1 Main characteristics of Sudanese agriculture

Agriculture in the Sudan is practiced under two major farming systems, namely rainfed (mechanized and traditional), which occupies more than 90% of the cultivated land, and irrigated farming, which makes up the remainder. Additionally, the sector is divided into three major subsectors cropping, livestock and forestry/fisheries, contributing 39%, 61% and 1%, respectively, to agricultural GDP in 2015/16 (CBoS, 2016). This highlights the importance of the livestock component, which is even more important when it comes to its contribution to foreign exchange earnings, especially after the shrinking contribution of oil exports.

Agriculture provides a livelihood to 65% of total population especially in rural areas and for poorer households. With respect to household income, 61% of households in the poorest income quintile rely on agriculture as their main livelihood compared to only 20% of households in the wealthiest quintile (World Bank Group, 2015; CBS, 2009). This implies that poor households are predominantly employed by agriculture in the Sudan, suggesting that the sector must be central to any poverty reduction policies and programs. Moreover, agriculture is the main employer in the country according to the latest labor force survey. It employed 47% of the labor force in 2011, including 41.4% of the male workers and 63.5% of female workers. These shares are even more prominent in rural areas, making 65.4% of total rural employment including 59.1% of male workers and 82.2% of female workers (MHRDL, 2013).

Land cover atlas of the Sudan (FAO, 2012) classifies total land area of the country (188 million hectares) 83 different classes that are aggregated seven major classes. Agriculture is mainly practiced in the first class (Agriculture in terrestrial and aquatic/regularly flooded land), which makes up 23.7 million hectares and represent 12.6% of the country's land area. A brief look at the distribution of the first land cover class across the states of the country shows that the majority of the agricultural land falls within predominantly rainfed states including northern Kordufan (19.3%), El Gadarif (14.6%), southern Darfur (9%), White Nile (8.7), and southern Kordufan (8.3%).

The agricultural sector in the Sudan operates below its productive potential. That is not only because arable land is far from being fully cultivated, but also and importantly, because it operates far below its productivity potential. This can be clearly seen in the main crops, namely sorghum, cotton, groundnuts, sesame, millet and wheat. Other agricultural subsectors such as sugar cane, gum Arabic and livestock, particularly live sheep and camels, and hides and skins are slightly different as far as productivity is concerned. A brief look at sorghum production during the last decade in the major farming systems of the country shows low productivity in the rainfed sectors that represent more than 95% of the total sorghum-cultivated land compared to the irrigated sector. Productivity in the rainfed sectors is one third of that of the irrigated sector (**Error! Reference source not found.**).

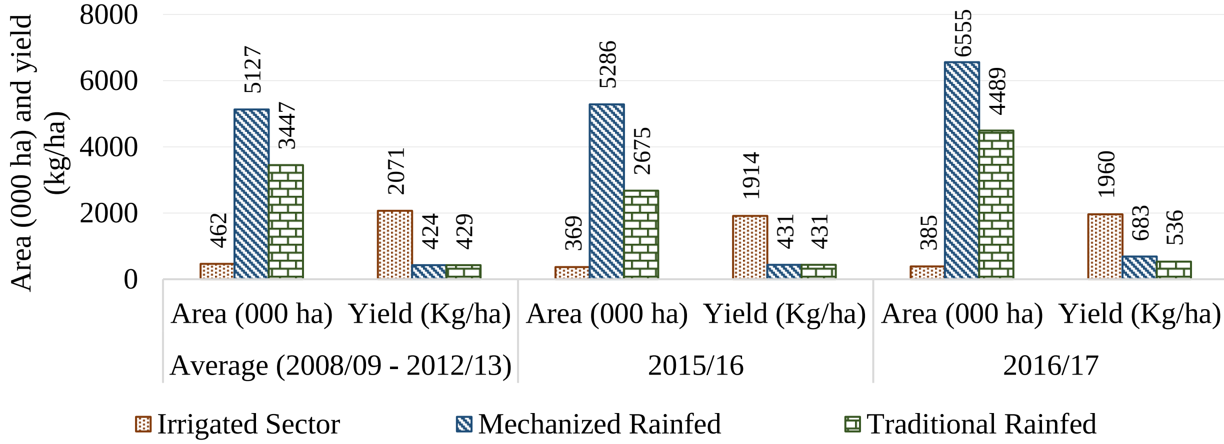

Figure 1: Area cultivated (000 Ha) and yield (Kg/Ha) for sorghum (2008/09 – 2016/17)

Data source: MAF (2017).

In addition, area and yields of crops are continuously fluctuating due to dependence on unpredictable rains, recurrent occurrences of droughts, pest infestation, and the general lack of application of fertilizer and other inputs (World Bank Group, 2015).

Millet, which is a main staple food in Western Sudan and produced in the traditional rainfed sector of Darfur and Kordofan, is also low yielding in the Sudan with an average productivity of less than 238 Kg/hectare per year. The low productivity is mainly due to low input use (usually, there are no purchased inputs used such as fertilizers). Besides, the amount and stability of rainfalls affect and eventually determine production. Sorghum, sesame, millet, and pasture species are primarily grown in the traditional rainfed sector that is generally characterized by low crop productivity, which is associated with the lowest usage rates of chemical fertilizers in the world.

In general, average fertilizer usage in the Sudan is half that of Ethiopia in which the peasant community is much poorer than in the Sudan. A comparison of the fertilizer usage in 155 countries in 2009 ranks the Sudan 129th with an average fertilizer usage of 7.3 kg/ha compared to 17 kg in Ethiopia (ranked 115th). This however is different than it was in the mid-1970s when 80 kg/ha were used and during the 1980s when 70 kg/ha were applied on average. As this partially explains the declining trends in the production of different crops in the Sudan, it shows the need for not only stimulating fertilizer usage, but also ensuring that adequate agricultural policies are in place.

The traditional rain-fed sector receives few credit, research, and extension services, while public investments in basic infrastructure for rural and agricultural development are generally negligible.

For wheat, the government encourages domestic production despite no comparative advantage for its production in Sudan. Average wheat yield in the Sudan is half of Chad's, one quarter that of Ethiopia, and 1/14 that of Egypt (World Bank Group, 2015). Wheat yields in the Sudan are among the lowest in the world, if not the lowest. Similar developments and characteristics are observed in groundnut and sesame production in the Sudan.

Low productivity is a denominator in Sudanese cropping with very few exceptions. A common cause of this is the low usage of inputs, but besides, distortive centralized marketing and distribution arrangements have also contributed to eroding producer incentives. Good news on the removal of these distortions are coming from the experiences of gum Arabic and cotton, which is expected to pave the way for further policy reforms.

2.2 Action plans and climate research in the Sudan

Several types of environmental changes have happened previously in the Sudan, are ongoing and expected to happen in the future. Temperature increase is expected to affect all the country, but will affect more the areas with temperature increase of 2.5^{o}C. Vulnerable sectors to rises in temperature in the Sudan are particularly rainfed agriculture, aquaculture, natural ecology systems and biodiversity, water resources and energy (production and consumption). This ultimately increase the vulnerability of certain communities such as poor farmers, pastoralists and generally communities that rely on rainfed agriculture (Figure 2).

Floods, flashfloods, and possibly landslide affects the southern and southeastern parts of the country as well as the mountainous areas in the northern east parts, while droughts affect more the northern parts and areas in middle and middle west of the Sudan. Communities that are mostly vulnerable to droughts and floods are pastoralists, poor farmers and generally poor families with senior members, children and women (Sayed and Abdala, 2013). Figure 2 summarizes the potential effects of climate stressors including drought, rainfall variability, floods, temperature increases, seawater temperature increases, and sea level rise on different sectors, areas and communities in the Sudan.[4]

It is important to notice that the summarized climate impact of Figure 2 points to the connection between climate change in the Sudan and agricultural productivity. It shows that four climate

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[4] Note that **Error! Reference source not found.** use colors to associate climate stressors to impacts and affected communities.

stressors, namely, temperature increase, rainfall variability, droughts and floods affect the agricultural sector and ultimately reduces its productivity. This implicate on the poor farmers, poor people, senior citizens, children and women particularly in northern, middle and middle-western parts of the country (Figure 2).

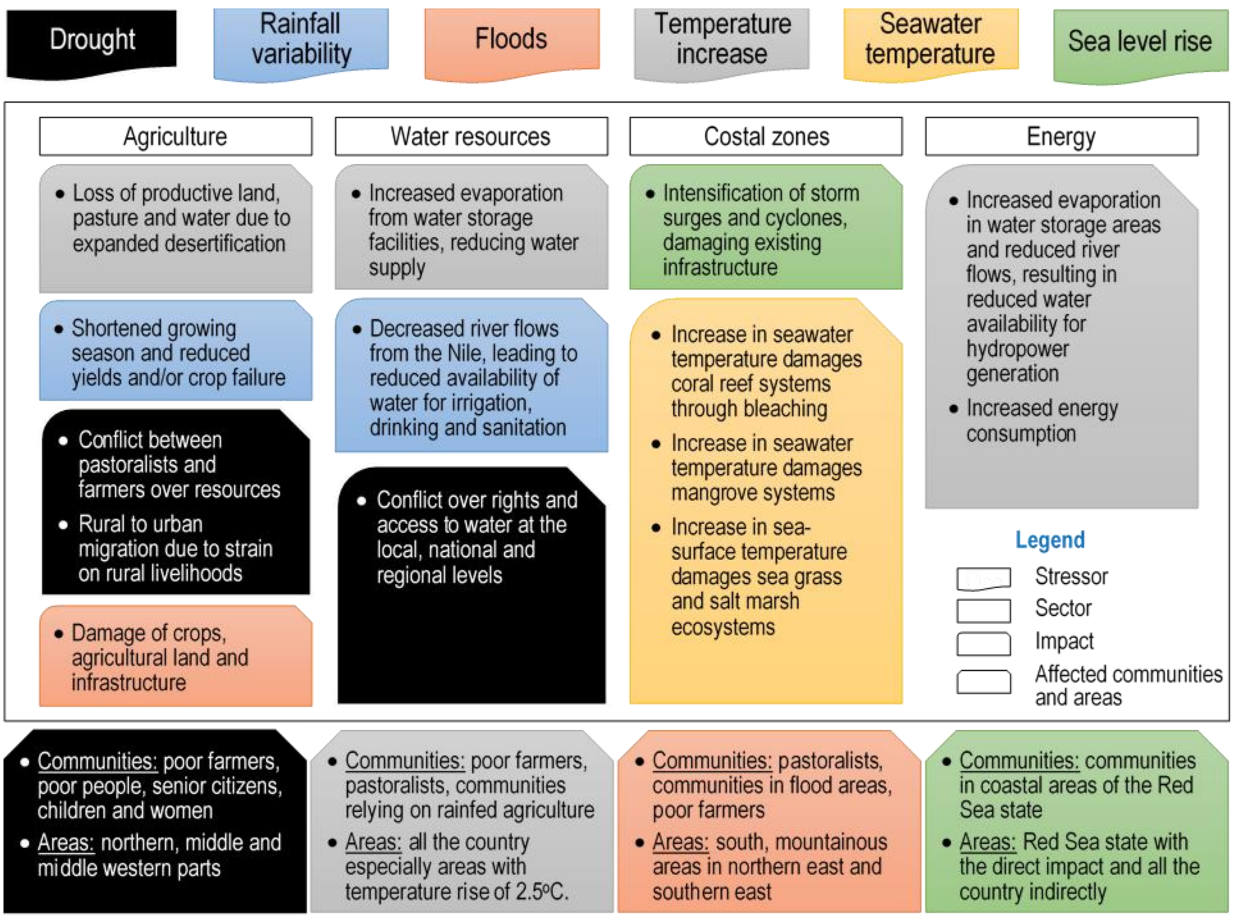

Figure 2: Climate stressors and their potential impact on sectors, areas and communities in the Sudan5

Source: Authors' elaboration.

2.3 Recommended interventions

After the mainstreaming of environmental and natural resource management issues in the national development plans, many climate-related recommendations featured in these plans. Additionally, these plans and several studies conducted by non-governmental institutions (NGOs) and other

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[5] Note that **Error! Reference source not found.** use colors to associate climate stressors to impacts and affected communities.

researchers, identifies common environmental stressors, sectors and affected population groups and areas in the Sudan (**Error! Reference source not found.**; FAO, 2017; USAID, 2016; FAO, 2015; Sayed and Abdala, 2013; Taha et al., 2013).[6]

However, from an operational perspective, the common approach seems to be too prescriptive rather than implementable. The plans and studies generally focused on responses to climate risk and climate change threats on the agricultural and rural development sector, not only because it is an important sector for the livelihood of the majority of the Sudanese population and the Sudanese economy, but also because it is the most affected sector in the economy by changes in climate.

The suggested interventions include: (1) *investing on infrastructure* to protect against flooding; (2) developing programs and projects for *mitigation and adaptation* within the agricultural and rural development sector; (3) enhancing *land ownership, especially for animal producers* to legally use land similar to crop producers and demarcating and mapping livestock routes and enforcing their use in order to increase access to natural productive assets; (4) addressing *water shortages* by encouraging water harvesting, full utilization of rainfall and seasonal streams outside the Nile Basin, using groundwater, and developing *drought resistant varieties*; and (5) treating water as scarce resource and enhancing its efficient use specially in irrigated agriculture to best utilize Sudan's share of water in the Nile.

3 Methods

Similar to most of the African countries, the Sudan is very vulnerable to climate change, as Africa is one of the most vulnerable regions in the world to climate change mainly due to poverty, lack of access to knowledge and a high dependence on natural resources and rainfed agriculture (MEPD, 2015). Economic growth in the Sudan is a desired goal that is recovering and becoming stable in recent years while population is growing fast similar to many African countries. Considering climate change, growth in the economy and population and policies and politics as the external factors affecting the integrated systems of food, water and energy, the space for intervention rests at the policy and politics dimension alone. Policies are required to determine what kind of economic and population growths are sustainable, while assuring that adequate environmental policies that help adaptation to and mitigation of the impact of changes in climate are in place (Mohtar and Daher, 2012).

[6] Refer to FAO (2015) for details on the different environmental plan and programs, especially those with involvement of the United Nations.

Due to the limited availability of natural resources, policies and politics need to take into account the synergies and tradeoffs between the interlinked components of our ecosystem. It is therefore almost impossible to address one dimension, e.g. food security, without adversely affecting progress towards desired outcomes in other areas, such as water security, energy and water uses or environmental sustainability. This makes incorporating key interlinkages among food, water and energy sectors inevitable.

Accordingly, this study answers the policy questions on what are the socioeconomic impacts of climate change challenges on the economy of Sudan in general and more specifically the agriculture sector. The study implements this research question a multiple modeling framework that while evaluating the impact of various climate scenarios on economic growth, food security and people's welfare, it implement policy interventions aiming at mitigating the negative consequences of climate change.

The modeling suite of the study consists of three major components as shown in Figure 3. The first component, which produces the indicators reflecting the impact of local and global climates through the IMPACT[7] modeling system, is presented in the left panel in Figure 3. The second component is the stochastic analysis that is producing the indicators reflecting the climate variability is presented in the top-right corner of Figure 3, while the third component is the dynamic CGE model in which the simulations are defined and the results are produced. Descriptions of each modeling component is provided in the following subsections.

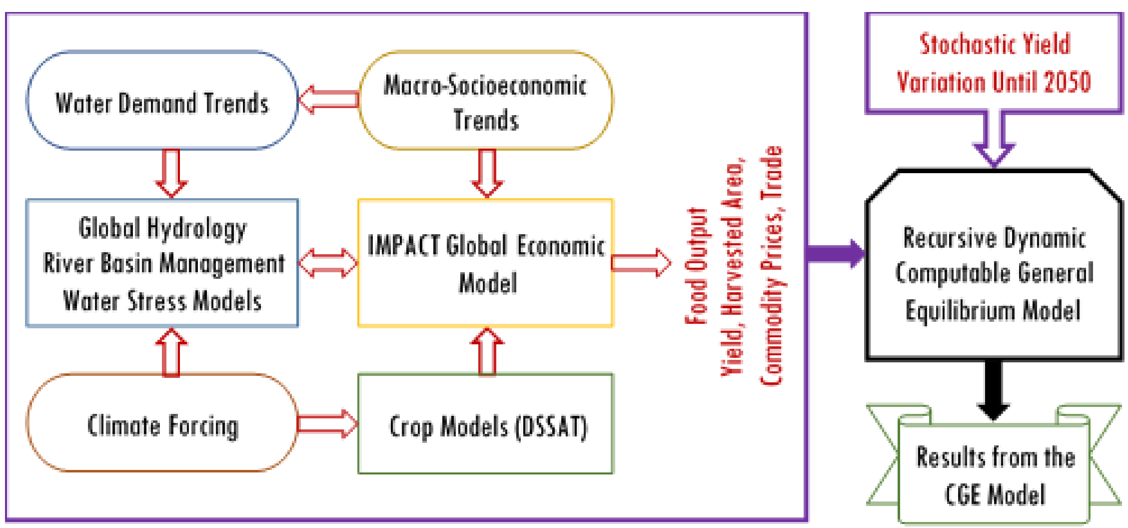

Figure 3: Models interaction within the modeling suite of the study

[7] International Model for Policy Analysis of Agricultural Commodities and Trade.

Source: Author compilation and Robinson et al. (2015).

3.1 The biophysical analysis component

Four climate models are used in this study to project changes in climate for the Sudan, namely, HadGEM2-ES, NorESM1-M, GFDL-ESM2M, and MIROC-ESM-CHEM. HadGEM2-ES is used with Representative Concentration Pathway (RCP) of 8.5, NorESM1-M with RCP 4.5 and RCP 8.5, GFDL-ESM2M with RCP 4.5, while MIROC-ESM-CHEM is with RCP 4.5 and RCP 8.5. This makes the total number of climate scenarios six in additional to a no-climate change scenario.

The IMPACT Model System is at the center of this biophysical component as shown in the left panel if Figure 3. It is a system of linked models around a core multimarket economic model of global production, trade, demand, and prices for agricultural commodities (Robinson et al 2015). As shown in Figure 3, the core model is linked to biophysical modules, including hydrology, river basin management, crop water stress and crop simulation models. The hydrological and crop simulation modules have a spatial resolution of 0.5-degree longitude by 0.5-degree latitude, whereas the core multimarket model and the river basin management module operates at the level of Food Producing Units (FPUs). There are 320 FPUs globally, created by intersecting 159 world economic regions with 154 river basins.

The multimarket core model specifies supply and demand behavior and simulates the operation of national and international markets. It solves for production, demand, and prices that equate supply and demand across the globe, providing a consistent framework for analyzing baseline and alternative scenarios.

The global hydrological module simulates monthly soil moisture balance, evapotranspiration and runoff generation on each 0.5˚ latitude by 0.5˚ longitude grid cell. Simulated hydrological outputs are spatially aggregated to the FPUs and are used as input for the river basin management model, which simulates reservoir regulation of river flow and abstraction of surface water and groundwater at monthly interval to meet projected water demands in each FPU, by minimizing water supply shortages subject to available water and water infrastructure capacity (Zhu and Ringler 2012).

The Decision Support System for Agrotechnology Transfer (DSSAT) family of crop models (Jones et al 2003) is used to shift the supply functions for the various crops in each FPU in a manner consistent with the effect of climate change for the particular model/scenario under consideration. The DSSAT crop models have been adapted to a global 0.5-degree grid to provide crop yield impacts of climate change to the IMPACT (Robertson et al 2012). This allows for analysis of the combined biophysical and economic effects of crop yield changes due to climate change and the consequent effects on production, consumption, trade, and prices of agricultural commodities.

3.2 The stochastic analysis

Extreme weather shocks were one of the main factors responsible for the price spikes (Tangermann, 2011). Therefore, this study aims to capture the impact of weather variability through an uncertainty analysis. In recent years, many large-scale economic simulation models (ESIM, GTAP, FAPRI, Aglink-Cosimo) that are used to study agricultural markets, have incorporated stochastic features in order to address market uncertainty and to engage in systematic sensitivity analysis.

Since a significant part of uncertainty around crop production and prices based on historical data can be explained by variations in yields, mainly caused by weather fluctuations (Burrell & Nii-naate, 2013), we have used the yield data of six major crops[8] grown in both irrigated and rainfed agriculture in the Sudan for the period between 1984 and 2014 to conduct the stochastic analysis.

In order to separate the stochastic part of the yield time series, we have followed the procedure explained by Artavia et al. (2015), by calculating them as deviates from the estimated time trends. For example, if $y_{i,j}$ is the observed yield of crop i in year j and $\hat{y}_{i,j}$ is the estimated trend value of the same crop in the same year, then the observed deviate is captured as $z_{i,j} = y_{i,j} / \hat{y}_{i,j} - 1$. However, if the historical time series are stationary, the stochastics are captured as deviates from the mean. This implies that the expected values of the stochastic variables (yield deviates) are zero. The standard deviations of the yield deviates, are in the range of 0.1 to 0.3. According to the Dickey-Fuller tests for stationarity, all the deviates are stationary at 5% level, and the normality tests[9] show that all variables except irrigated groundnut yield are normally distributed at 5% level.

In order to account for correlation between stochastic variables, we generated a multivariate normal distribution based on their means and the covariance matrix. Then we simulated 10,000 random values for each stochastic variable in each simulated time period from the multivariate normal distribution using the Latin Hypercube Sampling (LHS) technique. This method divides the distribution into equal intervals and from each interval randomly draws one value, thus making

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[8] The variables that are treated as stochastic in the analysis are cotton (irrigated), groundnuts (irrigated, rainfed), millet (rainfed), sesame (rainfed), sorghum (irrigated, rainfed), and wheat (irrigated).

[9] *The following tests for normal distribution of the deviates have been performed: Shapiro-Wilks, Anderson-Darling, Cramer-von Mises, Kolmogorov-Smirnoff, Chi-Squared. If one of those tests rejects the null hypothesis that the series is normally distributed the assumption of normality is dismissed.*

sure that the randomly selected points are evenly distributed across the sampling space. To validate that the random values are correctly simulated from the original dataset we applied the following non-parametric tests: Two-Sample Hotelling 2 T-Test, Box's M Test, and Complete Homogeneity Test. All of those tests have failed to reject that the simulated matrix and the matrix of historical deviates have the same means and equivalent correlation matrices at 5% level.

After obtaining the simulated random variables we have generated three scenarios to be analyzed: best case, average and worst case corresponding to 95% quantile, mean, and 5% quantile values, respectively for each crop. In this particular study, we only consider the worst case scenario as an indicator for worst climate variability.

3.3 The CGE analysis

The third component of the modeling suite is an economy-wide recursive dynamic CGE model (Diao and Thurlow, 2012). The evolution of the economy within dynamic modeling framework (DCGE) is captured through two connected components. The within-period component, which is standard static CGE model solving to achieve the equilibrium of the economy in one period where the number of these equilibriums correspond the number of years for which the dynamic model is solved. The second component is the between-period component, which is the mean by which the individual static solutions (static CGE) are connected to one another to produce a chain of equilibriums reflecting the economy evolution through the time. This component adjusts selected variables in the model such as accumulation of capital, supply of labor, availability of agricultural land, and the technical progress of each sector in order to imitate the likeliest trend of economic development and sectoral growth.

Similar to standard static CGE models, the DCGE specifies production by sector that after deduction of commodity exports and the addition of commodity imports makes up the supply of goods and services within the domestic economy. The decision of the producer to sell in the domestic or export markets depends on the relative prices of each commodity domestically and abroad. The transformation between these two markets is depicted using a Constant Elasticity of Transformation (CET) function.

Despite the freedom of choosing to sell domestically or abroad, the model assumes that the Sudanese producers are price takers in output and input markets. Therefore, their profit maximization is subject to constant returns to scale technologies. However, producers also seek maximizing their profits via minimizing the cost of production. They determine their demand for aggregate primary factors (value added) against the demand for aggregate intermediate input mix following a Constant Elasticity of Substitution (CES) function. Within the value added nest, they employ different primary factors based on a CES function, while determining intermediate input demand by commodity using a Leontief fixed-coefficient technology. The SAM for the Sudan (Siddig et al., 2016), which injects Sudan's data in the model, includes 14 primary factors including capital, land and natural resources and 12 labor categories. Labor are categorized by residence location to rural and urban, by sex and by skill level to highly skilled, semi-skilled and unskilled workers. Capital accumulation is modeled assuming a "putty-clay" formulation whereby new investment is allocated across sectors in response to rate of return differentials, but once installed, equipment remains immobile (Diao and Thurlow, 2012). The model assumes that primary factors of production are fully employed and mobile across sectors except capital, which is although fully employed, is factor specific. This is to limit the possibility of moving activity specific capital (machinery) to other sectors.

The Sudan is small country in the world economy, hence it faces perfectly elastic world demand curves for its exports at fixed world prices and an infinitely elastic world supply at fixed world prices for its imports. Imported good are considered imperfect substitutes to domestically produced goods in both final and intermediate demand. The model is calibrated to a SAM for the Sudan (Siddig et al., 2016) that includes 10 household groups comprising households residing in rural and urban areas, while each group is categorized by income into five quintiles. After receiving their factor and transfer incomes, households pay for consumption of good and services, which is distributed across commodities according to a linear expenditure system (LES) specification, they pay taxes and save according to their respective saving propensities.

Government income consist of revenue from taxes and net transfers from the rest of the world. This income is spent on government consumption expenditure and transfers to households and state-owned-enterprises, which together leave the government budget in a deficit. National savings in the model consist of savings from the four different institutions, namely, households, enterprises, government, and the rest of the world. These total savings are used to finance investment in the model.

The economic environment chosen for the model of Sudan consist of three major balances, namely, the internal balance, the saving-investment balance and the external balance. For the internal balance, government savings (deficit in the base year) are assumed flexible while direct tax rate is fixed to avoid increasing taxes on domestic institutions. A fixed absolute share of investment in total absorption and uniform changes in the saving rates as depicted by marginal propensity to save characterize the saving-investment balance. Savings rates would therefore adjust to assure financing investments. The external balance assumes that the exchange rate is flexible while the foreign savings are fixed.[10]

[10] Driven by the limited access to foreign exchange and the resulting exchange rationing in the Sudan, the entire private sector has virtually moved its transactions to the parallel market (black market). The gap between the commercial banks and parallel market exchange rates reached a peak of 48.5% in May 2012, which forced a 66% devaluation of the official rate in June 2012 (Jenkins et al., 2013; Ebaidalla, 2017). However, in June 2012, the central bank

3.4 Simulation scenarios and major findings

3.4.1 The baseline scenario

Prior to the implementation of the effects of global and local climate change scenarios in the CGE model, we established a way in which the economy of the Sudan evolves starting from the initial year, which is the year for which the model data is provided (SAM) until 2050. In order to establish it we applied the likeliest paths of growth for the external variables including GDP, population, labor force and Government consumption spending with data from different sources.

We obtained data on GDP growth rates until 2022 IMF-WEO (2017). From 2022 and one we preserved the final year's growth rate, which is projected to become stable. We depicted national GDP growth rates using total factor productivity (TFP) of the individual sectors in the SAM, while preserving the structure of the economy with respect to aggregated shares of agriculture, industry and services in the national GDP until 2016. From 2016 to the end of the simulation period, we sustained 2016's TFP growth by sector.

For population and labor force growth, we used the UN (2015) data, which shows the population of the Sudan growing by 2.2% in 2013, 2.1% in 2030 and 1.8% in 2050. For government consumption spending, we used data from IMF-WEO (2017), which suggest a growth rate of 39% in 2015 declining to 16% in 2022. Afterwards, we preserved the 15% until the final simulation period. Figure 4 shows the resulting real GDP for the Sudan until 2050.

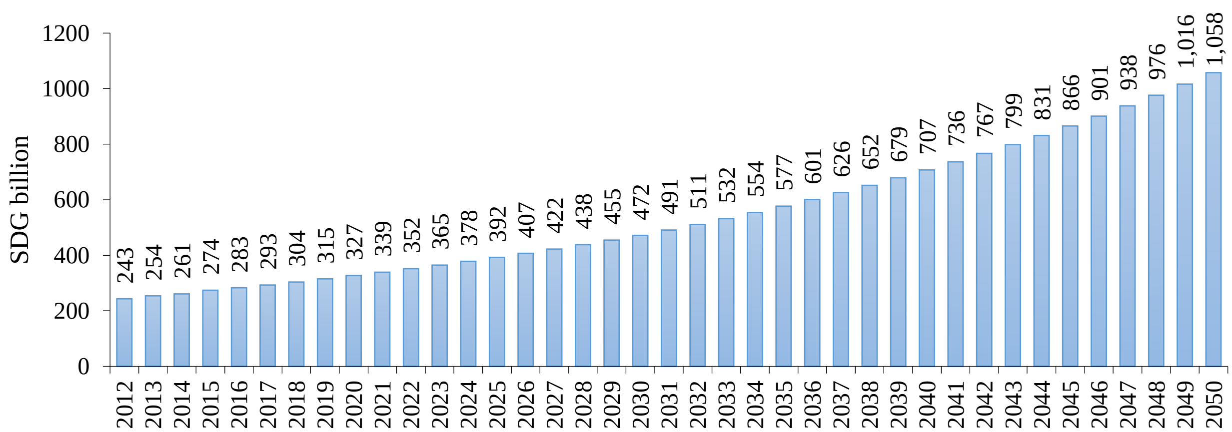

Figure 4: GDP for the Sudan in the baseline (2012-2015) in SDG billion.

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introduced measures aiming at increasing exchange rate flexibility. Within this arrangement, the central bank only intervene if the exchange rate exceeds a band of + or -3% around the closing rate of the previous day (Jenkins et al., 2013). Accordingly, a flexible exchange rate regime is applied in the model.

Source: Study's CGE model.

3.4.2 Local and global climate scenarios

Beside the baseline scenario, we implement several non-base scenarios to capture the effects of climate change. These include the depiction of local climate change, global climate change and climate variability. The local and global climate scenarios are based on outputs of biophysical modeling components, namely, local yield changes in a form of TFP shifters for the local climate scenarios and world price changes in the case of global climate scenarios. In order to have a common ground for comparison, the biophysical component also developed a non-climate-change scenario. Accordingly, using the six climate models, the biophysical component provides the CGE model with six local and six global climate scenarios in addition to the non-climate-change scenario, hence 7 simulation scenarios.

Average yield changes of selected agricultural sectors[11] in the Sudan for the period between 2013 and 2050 under the 7 scenarios show yield improvements throughout the period. Out the six climate change scenarios, models project positive average yield change for the period of the study (2013-2050). The positive changes in local yield is confirmed by the aggregated results from the DCGE as shown in Figure 5. The resulting average annual growth in GDP at factor cost as well as agricultural and crops GDP at factor cost under the six local climate scenario are higher than those of the NoCC scenario are. Within the six local climate projections, LocCC1 can be described as the driest scenario, while scenario LocCC6 is the wettest scenario measured by the average annual GDP growth (national, agriculture and crops).

[11] These sectors represent the activities included in the SAM fort the Sudan (Siddig et al., 2016).

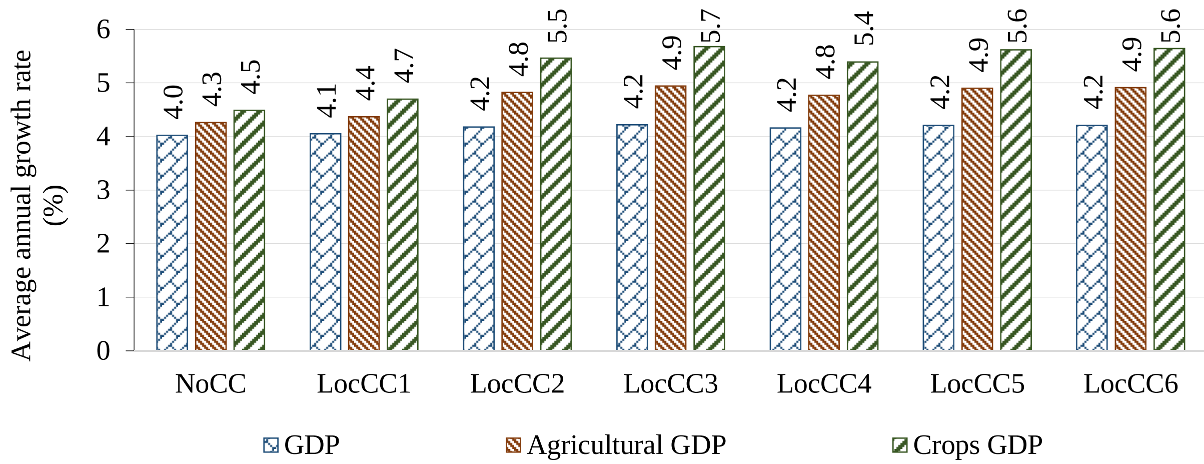

Figure 5: Average annual growth of GDP, agricultural GDP and crops GDP at factor cost (due to local yield change)

Source: Study's CGE model.

Turning to the global climate scenarios, which are depicted by changes in world prices of commodities for the same period until 2050, average annual changes in GDP (national, agriculture and crops) are depicted in Figure 6. The changes in the global climate trigger these changes in world prices and therefore their impact is not limited to particular country but to the entire world. The severity of their impact on each country depend on the degree of trade openness of each country and the detailed structure of the traded commodities as well as their significance in the economy. Briefly, world price changes of the agricultural commodities in the Sudan are higher under the dryer scenario (GlobCC1) while they are lower under the wetter scenario (GlobCC6). This is reflected in higher average annual growth rates under the wetter climate projection as compared to both the drier climate projection and the NoCC scenarios.

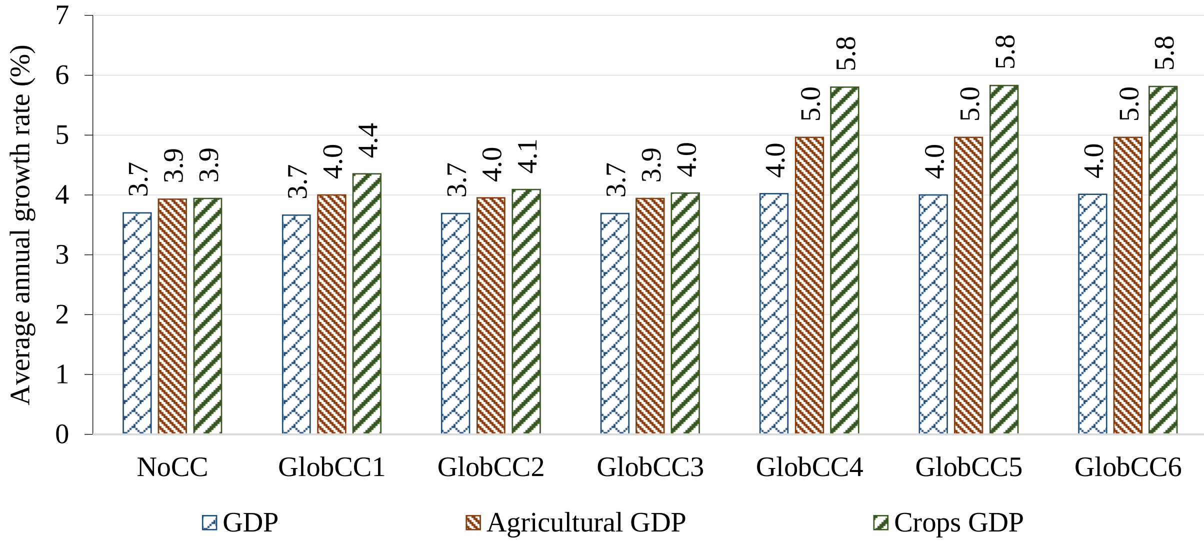

Figure 6: Average annual growth of GDP, agricultural GDP and crops GDP at factor cost (due to global climate change)

Source: Study's CGE model.

Of course, the aggregated results as exemplified by the annual growth rates in the GDP are too stenographic and may be misleading, therefore, we will come back to a detailed presentation of the results of the different scenarios later in the results section. Now, acknowledging the negative climate incidence in the region recently, specially the waves of drought, it is hardly acceptable by the ordinary Sudanese to conclude that climate projections for the present and the future of the Sudan are promising. This implies that climate variability, which is not depicted biophysical models; need to be brought in too in order to assess its impact.

3.4.3 Stochastic yield variation scenario

Average annual changes in GDP, agricultural GDP and crop GDP caused by four counterfactual simulations besides the NoCC scenario are presented in Figure 7. The counterfactual scenarios presented are the driest global climate scenario (GlobCC1), the driest local climate scenario (LocCC1), a combination of the two driest global and local climate scenarios (ComCC1), and the stochastic variability scenario (VarCom1).[12]

[12] The stochastic yield projections are implemented on the top of the combined climate scenario.

Results of Figure 7 indicate that annual growth rates will be lower under variable climate projections, especially the crops component of agriculture, which grows by only 2.5% on overage compared to 4.4% under no climate variability and 4.0% under no climate change.

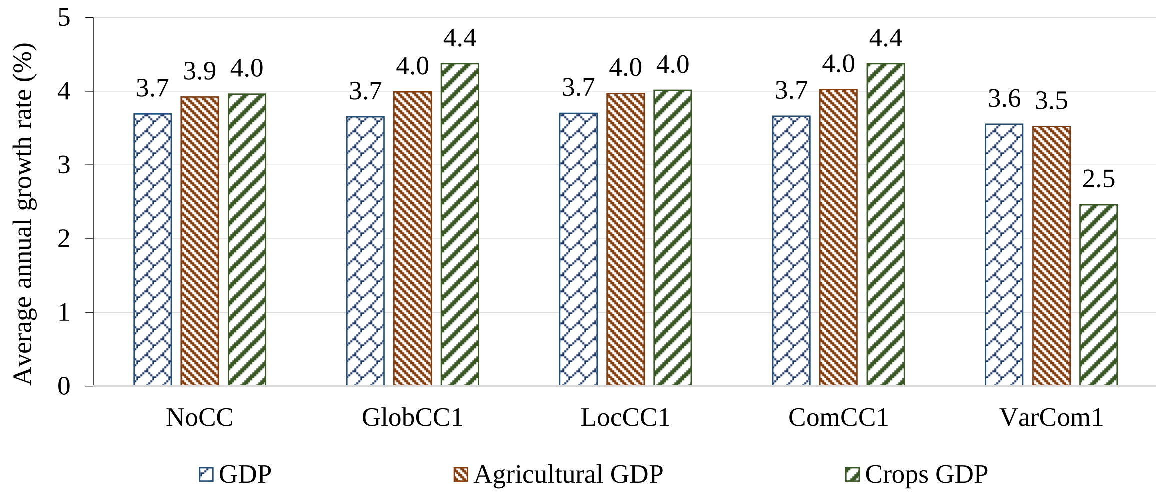

Figure 7: Average annual growth rate in GDP at factor cost (2013-2050) including variability scenario

Source: Study's CGE model.

3.4.4 An intervention scenario

Besides the counterfactual scenarios that reflect the projected climate changes, this study proposes interventions that are meant to help the Sudanese economy mitigating negative climate change effects at the sectoral level. The interventions are based on suggested development of drought-tolerant varieties of crops especially in rainfed agriculture and investing in extension services with the objectives of reducing and encountering the negative consequences of climate variability. For encountering the reduction in annual growth rates, the modeling suite suggested improving the productivity of rainfed crops by 3% annually in the first three years (2018-2020) and 2% annually afterwards until 2050 and for irrigated crops by 2% annually in the first three years and 1% annually afterwards until 2050. Enhancing the productivity of irrigated agriculture is based on the recommendation of increasing the level of input use specially fertilizer and pesticides, which is found to be almost the lowest in the world (World Bank Group, 2015).

Figure 8 presents the results of the intervention scenario (CropProd) in comparison to other scenarios. The implemented increases in crop productivity in rainfed and irrigated crops restored average annual growth rates of the national and agricultural GDP to their NoCC level, while increasing the crops GDP only from 2.4% under the variability scenario to 3.1%, which is still lower than the 3.9% under the NoCC scenario.

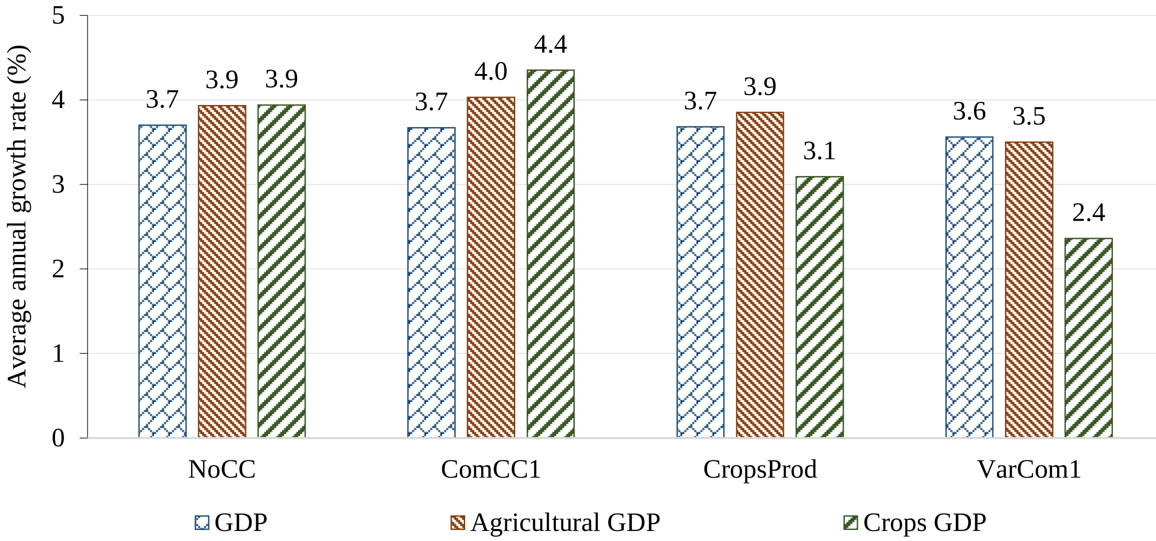

Figure 8: Average annual growth rate in GDP at factor cost (2013-2050) including intervention scenario

Source: Study's CGE model.

Further detail on the impact of the different simulation scenarios on other variables in the economy are to be presented in the result section.

4 Results and discussion

To present meaningful long-term (2013-2050) results in a country like the Sudan where the macroeconomic environment is relatively unstable with considerable exchange rate variations and growing inflation, we apply the following measures to the real macroeconomic indicators. First, we calculate the present values of indicators by applying a 5% annual discount rate from 2013 to 2050 to the Local currency (SDG) values, and second, we convert the discounted annual values (present values) to US$ by applying the 2012 official exchange rate (CBoS, 2017). In addition, we focus our presentation of results on the three most important simulations in order to reduce the amount of indicators. These scenarios include: 1) no climate change for comparison, 2) combined local and global climates, 3) climate variability, and 4) productivity enhancement as a policy intervention to encounter climate variability.

Results obtained for total absorption discounted and converted into US$ are presented in Table 1. They indicate that mean precipitation and temperature projections transmitted via our biophysical modeling component to the dynamic CGE model makes the Sudan better off by US$ 137.2 billion as compared to no climate change accumulatively for the period between 2018 and 2050 (Table 1). However, considering the variability in climate variables and particularly the concurrent drought incidences, which are known to happen rotationally, the accumulated loss in absorption relative to no climate change, will be US$ 109.8 billion.

Table 1: Accumulated discounted total absorption (2018-50) in SGD, US$ $ (2012 prices) and percentage

Simulations	Accumulated values (2018-50)		Deviation from No CC	
	SDG billions	US$ billions	US$ billions	%
No climate change	18961.9	4309.5	0.0	0.0
Global climate change	19350.1	4397.8	88.2	2.1
Local yield changes	19164.3	4355.5	46.0	1.1
Combined climate changes	19565.7	4446.8	137.2	3.2
Climate variability	18478.8	4199.7	-109.8	-2.6
Productivity intervention	18923.7	4300.8	-8.7	-0.2

Source: Model results and authors calculations.

Discounted values for the GDP under the different simulation scenarios are presented in Table 2. Results for GDP indicate that global climate alone will cost the country US$ 71.6 billion throughout the entire period until 2050 as imports grow faster than exports in response to change in world prices of food especially in the last ten years between 2040 and 2050. This leads the combined climate impact to be US$ 27.9 billion throughout the same period despite an accumulated benefit of US$ 40.0 billion under the local climate change scenario.

Table 2: Accumulated discounted GDP (2018-50) in SGD, US$ (2012 prices) and percentage

Simulations	Accumulated values (2018-50)		Deviation from No CC	
	SDG billions	US$ billions	US$ billions	%
No climate change	16849.2	3829.4	0.0	0.0
Global climate change	16534.3	3757.8	-71.6	-1.9
Local yield changes	17025.3	3869.4	40.0	1.0
Combined climate changes	16726.6	3801.5	-27.9	-0.7
Climate variability	16386.6	3724.2	-105.1	-2.7
Productivity intervention	16867.8	3833.6	4.2	0.1

Source: Model results and authors calculations.

The climate variability scenario reduces the accumulated GDP by US$ 105.1 billion throughout the period, while reducing total absorption by US$ 109.8 billion relative to the no climate change baseline. These huge losses are therefore genuine justification for investing in drought tolerant varieties and extension programs oriented towards increasing farmers' resilience to climate variability and coping mechanisms. Results of the productivity scenario support the benefits that can accrue from such intervention, leading to an accumulated benefit of US$ 4.2 billion relative to the no climate change baseline.

Table 3 presents aggregate results focusing on the agricultural sector. They include the accumulated (2018-50) present values of agricultural GDP in US$ as well as the present values of deviations from the no climate change scenario for each ten years. Results indicate that the agricultural GDP loses US$ 92.7 billion during the entire simulation period under the variability scenario compared to no climate change scenario despite a gain of US$ 86.1 billion under the combined climate change scenario over no climate change scenario.

Considering the time dimension, results of the four right-hand columns of Table 3 show that the majority of the loss under the climate variability scenario occurs in the last years as the absolute size of the economy and hence the agricultural sector become larger.

Table 3: Accumulated present values of agricultural GDP and changes (2018-50) in US$ (2012 prices)

Simulations	Value (US$ billion)	Deviation from No CC (US$ billion)				
	2018-50	2018-50	2018-20	2020-30	2030-40	2040-50
No CC	1141.9	0.0	0.0	0.0	0.0	0.0
Global CC	1172.9	31.0	0.3	5.8	12.7	12.4
Local CC	1200.2	58.3	1.0	11.9	27.4	18.4
Combined CC	1228.0	86.1	1.3	18.9	38.9	27.7
Variability	1049.1	-92.7	-1.3	-6.3	-26.5	-59.0
Productivity	1140.6	-1.3	-0.5	3.6	1.6	-6.0

Source: Model results and authors calculations.

The impact of the four scenarios on the individual household group is represented by the average annual changes in equivalent variation (EV), which is shown in Figure 9. It shows the ten household groups included in this study classified by location to rural and urban, while household in each location is further divided to five income quintiles. Starting with the combined climate change scenario, effects on the different household groups are similar to, if not better than, the no climate change scenario. However, the climate variability scenario shows different results forcing the annual change in EV to be lower than the no climate change scenario for all households groups, especially in rural areas and for poorer households.

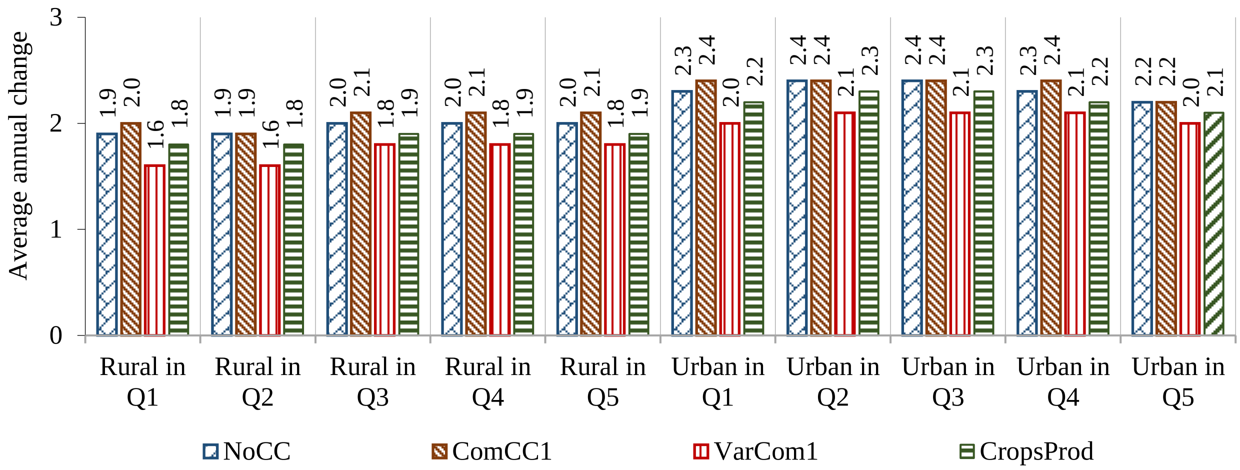

Figure 9: Average annual change in equivalent variation (percentage 2013-2050)

Source: Model results and authors calculations.

5 Conclusions and policy recommendations

In the Sudan, agriculture is mainly rainfed based on the annually cultivated land and it is a major contributor to GDP making up more than a third. It is also an important contributor the foreign exchange earnings and people's livelihood. Being mainly rainfed, agriculture in the Sudan is vulnerable to changes in rainfall amounts, time, and intensity. In this study, we combine various models to assess the impact of changes and variability of climate on the Sudanese economy until 2050.

We feed data representing climate indicators, water demand and macro-socioeconomic trends into a modelling suite that includes models for global hydrology, river basin management, water stress and a DSSAT all connected to the IMPACT model. Results of these modeling components, which include annual crop yield (ton/hectare) and global food prices under various climate change scenarios until 2050, are combined with stochastic projections of yield variation. All these indicators are then fed in a single country dynamic CGE model for the Sudan, which simulates different climate change scenarios and assesses their impact on the economy.

Results reveal that the projected mean yield changes after discounting it annually by 5% and converting it to US$ will accumulatively (2018-2050) make the country's GDP better off by US$ 40.01 billion compared to no climate change scenario, while global price changes create an adverse effect on the GDP causing a loss of US$ 71.57 billion compared to no climate change scenario. These two effects combined create a loss of US$ 27.88 billion compared to the no climate change scenario.

Accounting for extreme climate variability as obtained from historical yield changes to be added on the top of the combined climate change scenario worsens the situation further for the Sudan. They accumulatively (2018-2050) cause a loss of US$ 109.8 billion in total absorption and US$ 105.1 billion in GDP relative to the no climate change scenario. Similar effects are observed at the household level with the climate variability scenario hitting poor rural households more than urban or rich households.

Based on the recommendations of reviewed studies (see section 2), the negative effects of climate extremes on the Sudanese agriculture need to be encountered by additional investments in research that promotes the production and use of drought tolerant varieties. This can also be accompanied by targeted agricultural extension, education and investments. In this study, we implemented a scenario that depicts these measures and found that the negative consequences of climate variability can be compensated at the macroeconomic level my productivity improvement. The suggested productivity enhancement for crops in the rainfed sector is 3% annually in the first three years (2018-2020) and 2% annually afterwards until 2050 and for crops in the irrigated agriculture it is 2% annually in the first three years and 1% annually afterwards until 2050. At the household level, the negative consequences of extreme climate variability will be considerably reduced (fully recovered for some household groups) by the introduction of drought tolerant varieties that improve crop productivity.

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