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). 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 part of the 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 costs the Sudan accumulatively (2018-2050) US$ 109.5 billion in total absorption and US$ 105.5 billion in GDP relative to no climate change scenario.

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

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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.

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 annual temperatures vary between 26ºC and 32ºC 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 growth of the country's Gross Domestic Product (GDP) 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, and 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 4, we present and discuss the results obtained from the modeling suit at the CGE front and finally, Section 5 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, namely, 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 agriculture predominantly employed poor households 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) into 83 different classes that are aggregated to 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 (MAF, 2017; World Bank Group, 2015). This can be observed 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 (Figure 1).

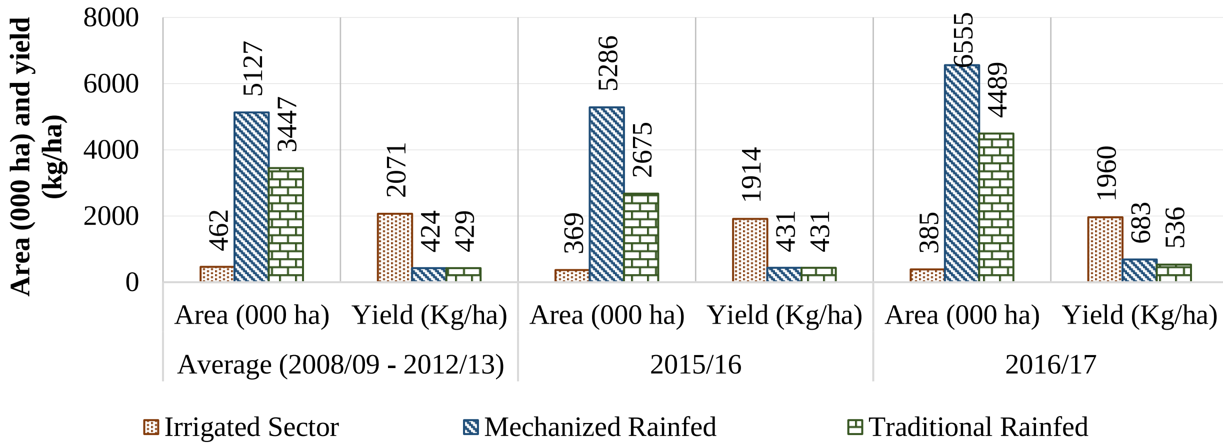

Figure 1: Area cultivated (000 Ha) and yield (Kg/Ha) for sorghum (2008/09 – 2016/17)

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) (World Bank Group, 2015). 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 the 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. Apart form rainfall variability, a common cause of this is the low usage of inputs. In addition, 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

Temperature increase is expected to affect all the Sudan, 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]

[4] Note that Figure 2 use colors to associate climate stressors to impacts and affected communities.

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 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).

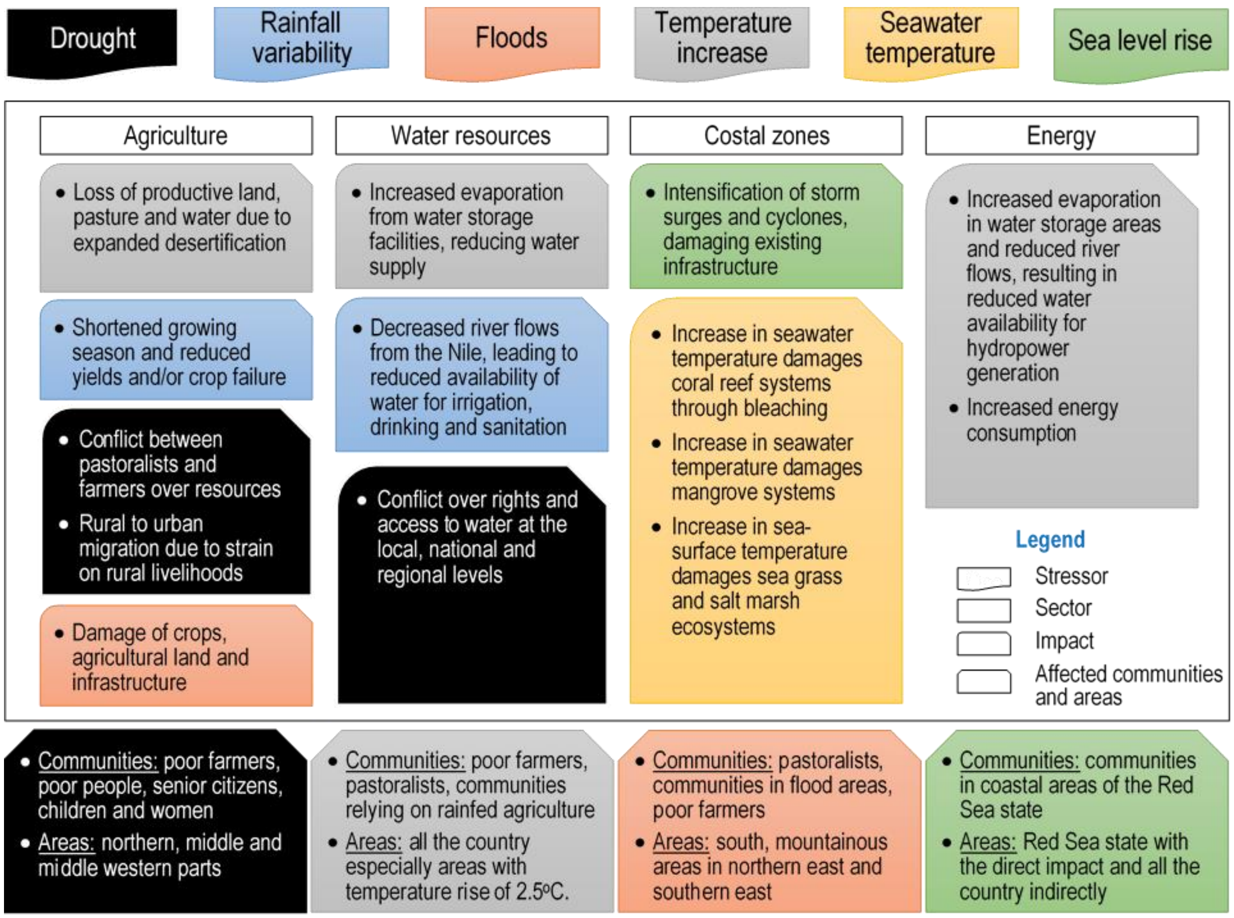

Figure 2: Climate stressors and their potential impact on sectors, areas and communities in the Sudan[5]

Source: Authors' elaboration.

[5] Note that Figure 2 use colors to associate climate stressors to impacts and affected communities.

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 researchers, identifies common environmental stressors, sectors and affected population groups and areas in the Sudan (Figure 2; FAO, 2017; USAID, 2016; FAO, 2015; Sayed and Abdala, 2013; Taha et al., 2013).[6] 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.

In a recent assessment of adaptation options for the Sudan, the report stress that adaptation measures should "focus on reducing sensitivity, improving resilience to variability and extremes, and improving heat tolerance and water efficiency in agricultural production" (WFP, 2017: pp 37). This implies that not only projected mean changes in climate that need preparedness, but variability and extremes.

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.

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

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 only at the policy and politics front. 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).

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 the Sudan in general, and more specifically the agriculture sector. to address this research question, the study implements a multiple modeling framework that while evaluating the impact of various climate scenarios on economic growth, food security and people's welfare, it implements policy interventions aiming at mitigating the negative consequences of climate challenges.

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 of Figure 3. The second component is the stochastic analysis that produces 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.

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

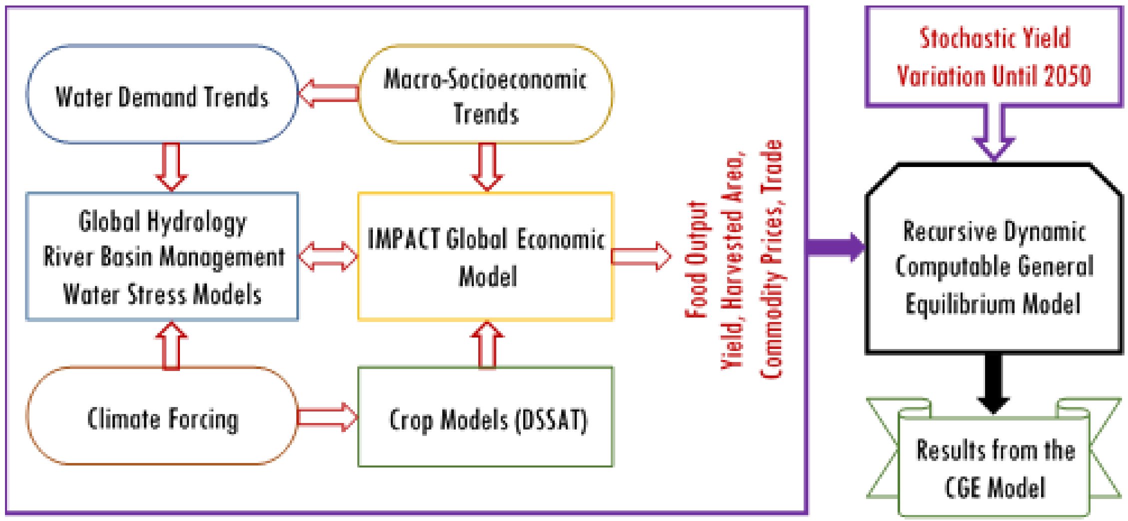

Figure 3: Models interaction within the modeling suite of the study

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 of 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˚ longitude by 0.5˚ 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. The river basin management model 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˚ grid to provide crop yield impacts of climate change to the IMPACT (Robertson et al., 2012). This allows analyzing 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

Because extreme weather shocks were among the main factors responsible for the food price spikes (Tangermann, 2011), this study aims to capture the impact of weather variability by conducting an uncertainty analysis. In recent years, many large-scale economic simulation models (ESIM, GTAP, FAPRI, Aglink-Cosimo)[8] that are used to study agricultural markets, have incorporated stochastic features in order to address market uncertainty and to engage in systematic sensitivity analysis.

A significant part of uncertainty around production and prices of crops based on historical data can be explained by variations in yields because they are mainly caused by weather fluctuations (Burrell & Nii-naate, 2013). Therefore, we use yield data for six major crops[9] 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), which calculate them as deviates from the estimated time trends.

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[8] ESIM = European Simulation Model; GTAP = Global Trade Analysis Project; FAPRI = Food and Agricultural Research Institute Models

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

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[10] 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 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 these tests 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 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

Climate change and climate variability affect agricultural world market prices and local agricultural productivities with direct implications for agriculture and indirect implications for processed food and the whole economy. We therefore use a multi-sector recursive-dynamic CGE model for the Sudan, which distinguishes several agricultural and agro-processing sectors as well as industrial and services sectors. A detailed description of the model structure and equations can be found in Diao and Thurlow (2012). The model is based on the post-separation Sudan Social Accounting Matrix for year 2012 (Siddig et al., 2016).

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[10] *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 these tests rejects the null hypothesis that the series is normally distributed, the assumption of normality is dismissed.*

The Sudanese economy is modelled as a competitive economy with flexible prices and market conditions. Agents represented in the model are consumers, who maximize utility; producers, who maximize profits; and the government. The Sudan is connected with the rest of the world via trade flows, remittances, and other transfers.

Producers in the model are price takers in output and input markets and maximize profits using constant returns to scale technologies. Primary factor demands are derived from constant elasticity of substitution (CES) value added functions, while intermediate input demand by commodity group is determined by a Leontief fixed-coefficient technology. The decision of producers between production for domestic and foreign markets is governed by constant elasticity of transformation (CET) functions that distinguish between exported and domestic goods in each traded commodity group in order to capture any quality-related differences between the two products. Under the small-country assumption, the Sudan faces perfectly elastic world demand curves for its exports at fixed world prices. On the demand side, imported and domestic goods are treated as imperfect substitutes in both final and intermediate demand under a CES Armington specification. Households use part of their incomes to consume commodities according to fixed budget shares.

There are 12 labor categories in the model, differentiated by regional affiliation (rural and urban), gender status (male and female), and skill category (unskilled, semi-skilled, skilled), with all types assumed to be fully employed and mobile across sectors. The assumption of full employment is consistent with widespread evidence that, while relatively few people have formal sector jobs, the large majority of working-age people engage in activities that contribute to gross domestic product (GDP). Capital accumulation is modeled assuming a "putty-clay" formulation whereby new investment is allocated across sectors between periods in response to rate of return differentials, but once installed, equipment remains immobile within periods (Diao and Thurlow, 2012). In agriculture, cultivated land, which is differentiated into rainfed and irrigated land, is assumed to be fully employed and mobile across agricultural uses.

The Sudan dynamic CGE model is based on a 2012 social accounting matrix built by Siddig et la. (2016). It is specifically built to capture the economic and distributional effects of climate change and climate variability in the Sudan. Given the importance of agriculture for income generation and the satisfaction of consumption needs, the model captures the sector of crop production and its linkages to other sectors such as food processing, other manufacturing and services. The model includes 71 production sectors and 58 commodities, 14 factors of production, and 10 household types, distinguished by their regional affiliation and income level. The 35 agricultural production activities are split into livestock (7), forestry and rubber (2), and 13 crop production activities, most of them differentiated by irrigated and mechanized and traditional rainfed production modes (26). The household groups are separated into rural and urban, each differentiated by income quintiles. This differentiation of household groups allows us to capture the distinctive patterns of income generation and consumption as well as the distributional impacts of climate change and climate variability.

The model distinguishes between various institutions, including enterprises, the government, and different household groups. Households and enterprises receive income in payment for the producers' use of their factors of production. Institutions pay direct taxes and save according to their respective marginal savings propensities. Enterprises pay their remaining incomes to households in the form of dividends. Households use their incomes to consume commodities according to fixed budget shares as derived from a Cobb-Douglas utility function. The government receives revenue from activity taxes, sales taxes, direct taxes, and import tariffs and then makes transfers to households, enterprises and the rest of the world. The government also purchases commodities (actually remuneration for the provision of public goods) in the form of government consumption expenditures, and the government saves the remaining income (with recurrent budget deficits representing negative savings). All savings from households, enterprises, government, and the rest of the worl (foreign savings) are collected in a savings pool from which investment is financed.

The model includes three macroeconomic accounts: government balance, a current account balance, and a savings-investment account. To balance the macro accounts, it is necessary to specify a set of macro-closure rules, which provide a mechanism through which balance is achieved. In the government account, the fiscal balance and therefore public savings are endogenous, with government demand fixed and all tax rates held constant, so that government savings or dis-savings depend on the level of economic activity. For the savings-investment identity, an investment-driven balanced closure rule is assumed that fixes the share of investment in total absorption, while uniform changes in household savings rates adjust to generate the necessary funds. Finally, external balance assumes that voluntary external capital inflows are exogenously determined, while the exchange rate adjusts.[11]

3.4 Simulation scenarios and major findings

3.4.1 The baseline scenario: No climate change

In order to use the model to estimate costs imposed on the Sudan by global warming, we start by specifying a hypothetical dynamic baseline path to 2050 that reflects development trends, policies,

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[11] 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, since June 2012, the central bank 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.

and priorities in the absence of climate change. The baseline is not a forecast, but instead provides a counter-factual – a reasonable trajectory for growth and structural change of the economy in the absence of climate change that is used as a basis for comparison with the various climate change scenarios.

We obtained data on GDP growth rates until 2022 from IMF-WEO (2017). From 2022 and on, 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 16% until the final simulation period. Figure 4 shows the resulting real GDP for the Sudan until 2050.

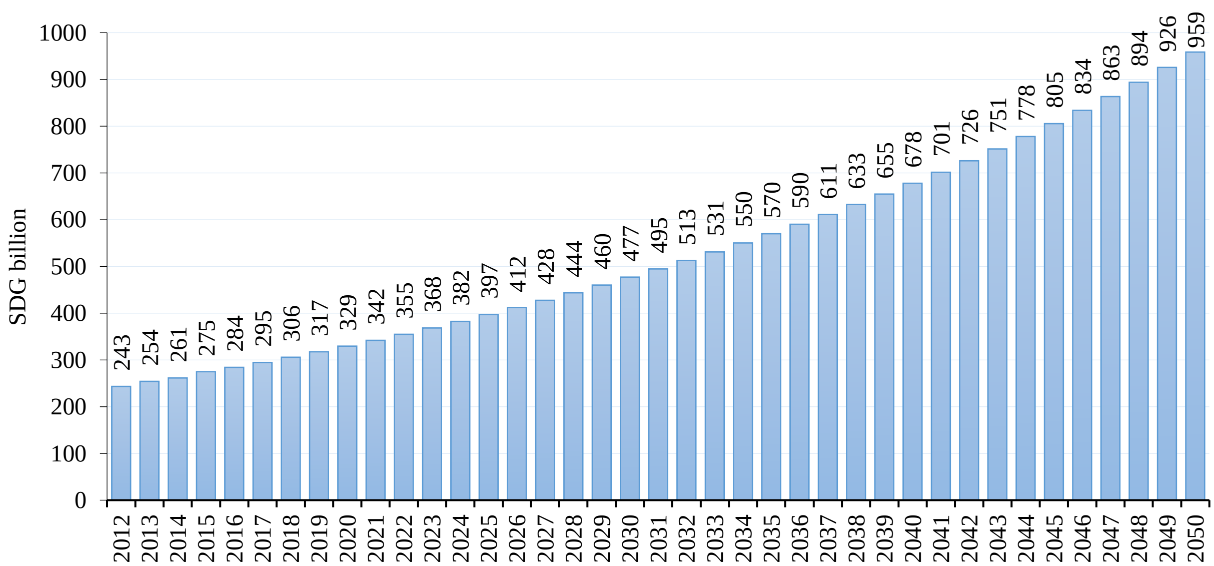

Figure 4: GDP for the Sudan in the baseline (2012-2050) in SDG billion.

Source: The Sudan DCGE 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 the biophysical modeling component. 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[12] in the Sudan for the period between 2013 and 2050 under the 7 scenarios show yield improvements throughout the period. For all 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 scenarios 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 as measured by the average annual GDP growth (national, agriculture and crops). These findings are in line with a recent WFP's (2017) projections for the Sudan in which the average change in rainfall across three different climate models under three different climate change scenarios indicating an increase.

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

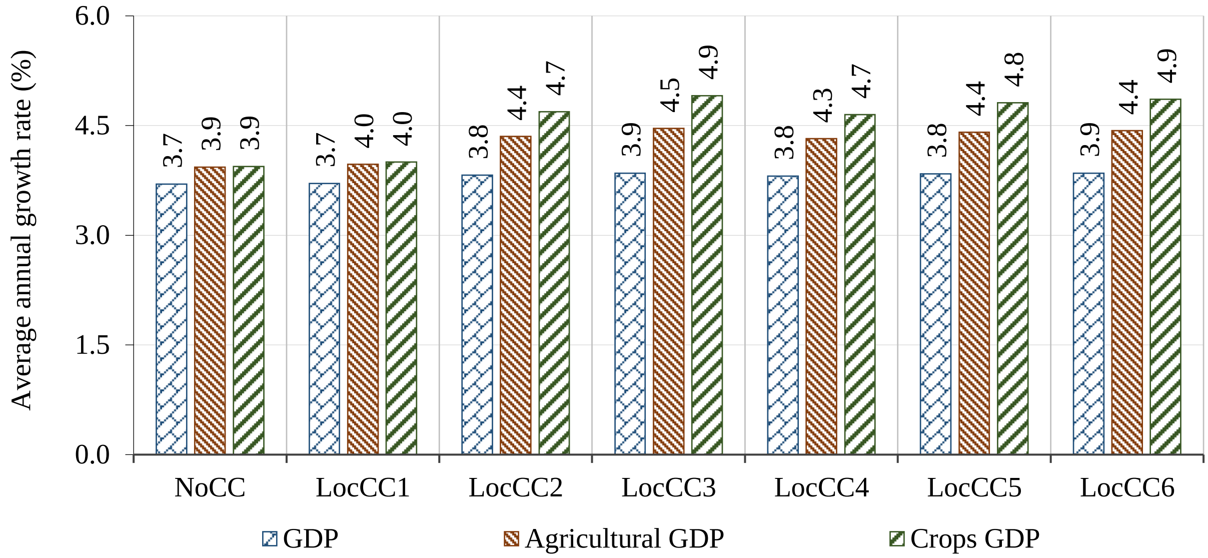

Figure 5: Average annual growth of GDP, agricultural GDP and crops GDP at factor cost (due to local yield change)

Source: Study's CGE model.

Turning to the global climate scenarios, which are depicted by changes in world prices of commodities throughout the same period (2013-2050). The changes in the global climate trigger changes in world prices and therefore, their impact is not limited to a particular country but to the entire world. The severity of their impact on each country depends on the degree of trade openness of the country and the detailed structure of the traded commodities as well as their significance in the economy. Average annual changes in the Sudanese GDP (national, agriculture and crops) are depicted in Figure 6. As expected, 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.

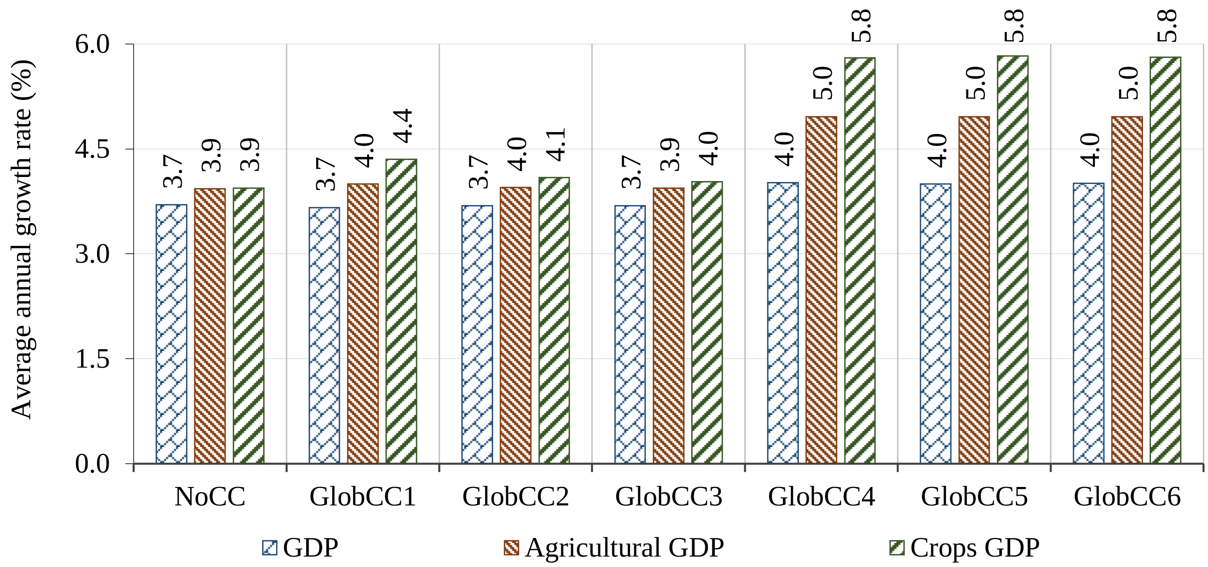

Figure 6: Average annual growth of GDP, agricultural GDP and crops GDP at factor cost (due to global climate change)

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 by the biophysical models; need to be brought in too in order to assess its impact. Though limited, findings from studies investigating future climates of the Sudan stress that it is not mean changes in temperature and precipitation that would negatively affect the Sudanese agriculture and livelihoods, however, it is rainfall variability (WFP, 2017; Rhodes, 2012). The following section highlights the findings on climate variability 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).[13]

Results of Figure 7 indicate that annual growth rates will be lower under variable climate projections, especially the crops component of agriculture, which grows on overage by only 2.5% compared to 4.4% under no climate variability and 4.0% under no climate change. This confirm the conclusions of previous researches by WFP (2017), Siam and Eltahir (2017), and Rhodes (2012) on that climates variability generate more negative impact in the Sudan relative to mean changes in precipitation. Detailed valuation of the costs of the projected climate variability in the Sudan are presented in the following results section.

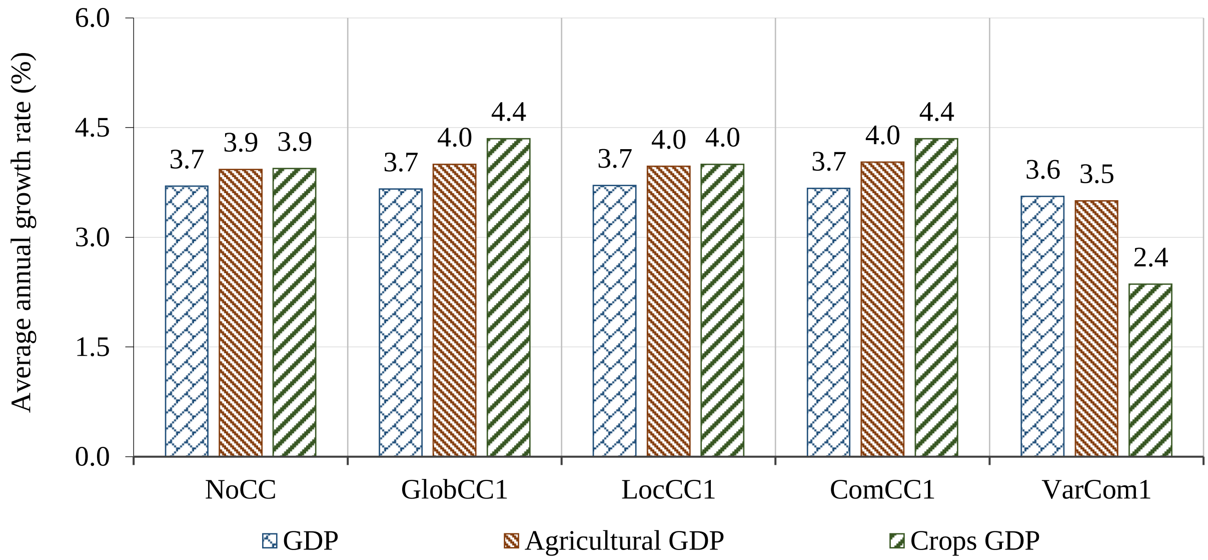

Figure 7: Average annual growth rate in GDP at factor cost (2013-2050) including variability scenario

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 challenges at the sectoral level. The interventions are based on the recommendations of previous studies and assessments. These include developing drought-tolerant varieties of crops especially in rainfed

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

agriculture and investing in extension services with the objectives of reducing and encountering the negative consequences of climate variability.

The advantage of this scenario over previous assessments conducted in various researches is that it provides simulated findings that show the monetary outcomes of such intervention at the sectoral as well as the national levels. For encountering the reduction in annual growth rates, the modeling suite suggested improving the productivity of rainfed crops by 4% annually in the first three years (2018-2020) and 2.5% annually afterwards until 2050. For irrigated crops the suggested increase in productivity is 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 GDP, agricultural GDP and crops GDP to their NoCC levels.

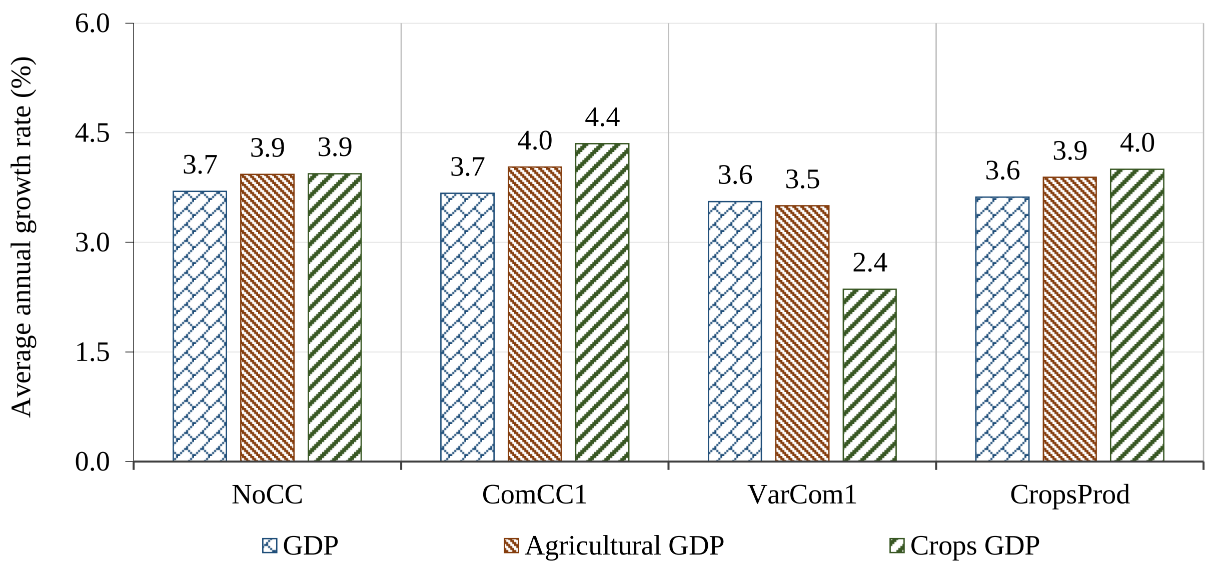

Figure 8: Average annual growth rate in GDP at factor cost (2013-2050) including intervention scenario

Source: Study's CGE model.

Further detail on the impact of the different simulation scenarios on other variables in the economy are presented in the following results 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) for the Sudan. In addition, we focus our presentation of results on the four 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 **Error! Reference source not found.**. 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$ 137.3 billion as compared to no climate change accumulatively for the period between 2018 and 2050 (Table 1). These findings partially agree with those of WFP (2017), which project average rainfall across three different climate models under three different climate change scenarios until 2100 to increase.

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 (2.6% less than the NoCC as shown in the fourth and fifth columns of Table 1).

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

Simulations	Accumulated values (2018-50)		Deviation from NoCC	
	SDG billions	US$ billions	US$ billions	%
No climate change	18,962.0	4,309.6	0.0	0.0
Global climate change	19,349.4	4,397.6	88.0	2.0
Local yield changes	19,165.4	4,355.8	46.2	1.1
Combined climate changes	19,566.3	4,446.9	137.3	3.2
Climate variability	18,480.2	4,200.0	-109.5	-2.5
Productivity intervention	19,237.3	4,372.1	62.6	1.5

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 changes in world prices of food especially in the last ten years between 2040 and 2050. This leads the combined climate impact to be a loss of US$ 27.9 billion throughout the same period despite an accumulated benefit of US$ 40.1 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	16,849.5	3,829.4	0.0	0.0
Global climate change	16,532.8	3,757.4	-72.0	-1.9
Local yield changes	17,026.2	3,869.6	40.1	1.0
Combined climate changes	16,726.8	3,801.5	-27.9	-0.7
Climate variability	16,385.4	3,724.0	-105.5	-2.8
Productivity intervention	16,506.4	3,751.5	-78.0	-2.0

Source: Model results and authors calculations.

The climate variability scenario reduces the accumulated GDP by US$ 105.5 billion throughout the period, while reducing total absorption by US$ 109.5 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$ 62.6 billion in absorption 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 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 relative to 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 second half of the period (2030-40 and 2040-50). This is explained by that the increasing variability that is estimated by our stochastic components of the modeling suite.

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

Simulations	Value (US$ billion)	Deviation from NoCC (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	1228.1	86.2	1.3	18.9	38.9	27.7
Variability	1049.1	-92.7	-1.3	-6.3	-26.5	-59.0
Productivity	1172.9	31.0	-0.5	7.5	16.3	7.8

Source: Model results and authors calculations.

The impact of the four scenarios on the individual household group is depicted 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.

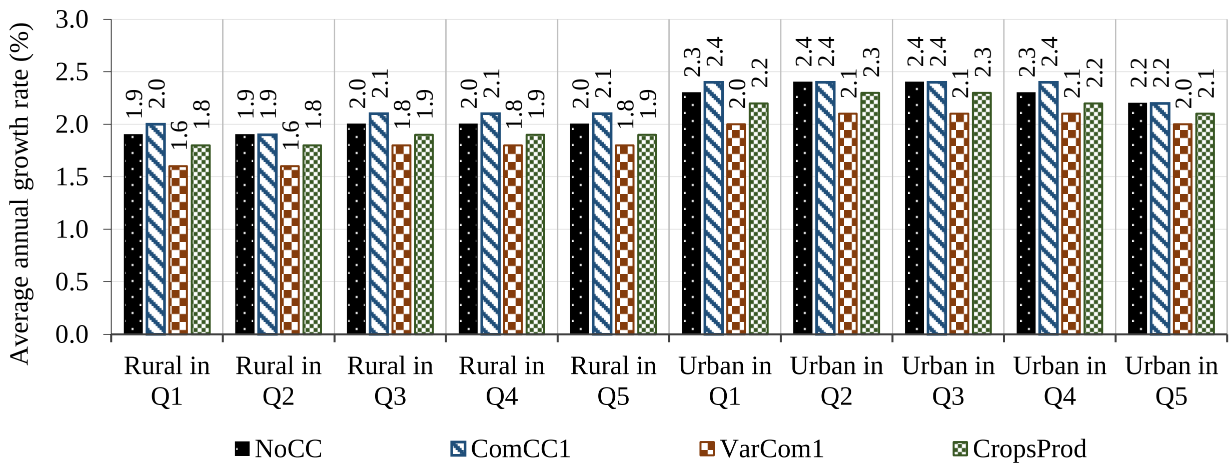

Figure 9: Average annual change in equivalent variation (percentage 2013-2050)

Source: Model results and authors calculations.

These results are not only conceivable, but they are also very important because they relate to the fact that the majority of the poor in the Sudan are rural dwellers and they are reliant on agriculture as major source of income and livelihood. This implies that such households will be most sensitive to climate variability and measures need to be put in place in order for their vulnerability to be reduced. To put that into prospect, total household losses under the climate variability scenario as measured by the indirect compensations is US$ 9.7 billion throughout the period (2018-50), which makes them 0.3% worse off than them under the no climate change scenario.

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, intensity and stability. In this study, we combine various models to assess the impact of changes and variability of climate variables 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 into 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 outcome of simulating projected mean yield changes (a measure of local climate) after discounting it annually by 5% and converting it to US$ will accumulatively (2018-2050) make the country's GDP better off by US$ 40.1 billion compared to no climate change scenario. At the same time, global price changes create an adverse effect on the GDP causing a loss of US$ 72.0 billion compared to no climate change scenario. These two effects combined create a loss of US$ 27.9 billion compared to the no climate change scenario.

Accounting for extreme climate variability as obtained from our stochastic estimation of historical yield changes, which we 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$ 109.5 billion in total absorption and US$ 105.5 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 and 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 enhancements for crops in the rainfed sector are 4% annually in the first three years (2018-2020) and 2.5% annually afterwards until 2050, while for crops in the irrigated agriculture they are 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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