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Climate Change and Agriculture in the Sudan

Impact pathways beyond changes in mean rainfall and temperature

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ABSTRACT

Several environmental changes have occurred in the Sudan in the past; several are ongoing; and others are projected to happen in the future. The Sudan has witnessed increases in temperature, floods, rainfall variability, and concurrent droughts. In a country where agriculture, which is mainly rainfed, is a major contributor to gross domestic product, foreign exchange earnings, and livelihoods, these changes are especially important, requiring measurement and analysis of their impact. This study not only analyzes the economy-wide impacts of climate change, but also consults national policy plans, strategies, and environmental assessments to identify interventions which may mitigate the effects.

We feed climate forcing, water demand, and macro-socioeconomic trends into a modelling suite that includes models for global hydrology, river basin management, water stress, and crop growth, all connected to the International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT). The outcomes of this part of the modeling suite are annual crop yields and global food prices under various climate change scenarios until 2050. The effects of such changes on production, consumption, macroeconomic indicators, and income distribution are assessed using a single country dynamic Computable General Equilibrium (CGE) model for the Sudan. Additionally, we introduce yield variability into the CGE model based on stochastic projections of crop yields until 2050.

The results of the model simulations reveal that, while the projected mean climate changes bring some good news for the Sudan, extreme negative variability costs the Sudan cumulatively between 2018 and 2050 US$ 109.5 billion in total absorption and US$ 105.5 billion in GDP relative to a historical mean climate scenario without climate change.

Keywords: global climate change, local yield changes, the Sudan, climate variability, interventions

1. INTRODUCTION

After the secession of the Republic of South Sudan in 2011, the area of the Sudan was reduced to 1.8 million km^2, which still makes it a vast country with considerable diversity of ecology, topography, and people. Mean annual temperatures vary between 26°C and 32°C 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 annually, (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 the United Nations (UN) (2017), the population of the Sudan will double by 2050 from the current population of about 40.5 million inhabitants. The economy is projected to resume steady growth of an average of 3.6 percent annually over the next five years and a growth rate of 3.5 percent in 2022 (IMF 2016). The secession of South Sudan reduced the growth of the country's GDP from 2.5 percent in 2010 to -1.2 percent in 2011 and -3.0 percent in 2012 (IMF 2016). It has also forced some structural changes on the economy, including an increase in the agricultural share in GDP from 28.9 percent in 2011 to 30.4 percent in 2012 and a decline in the share of industry from 26.5 percent in 2011 to 24.5 percent in 2012. Agriculture remained an important contributor to GDP, given declining oil production. The agriculture sector contributed 30.1 percent to GDP in 2016 with an annual growth rate of 5.5 percent from 2015 (CBoS 2017).

The demand for food in the Sudan is projected to grow due to a growing population and growing incomes. Staple food demand, consisting of cereals and roots, is 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 to 3.4 million tonnes (OECD-FAO 2017). From 2017 to 2030, demand for these three products is projected to increase by 35, 56, and 157 percent, respectively. Moreover, demand for fats and meat products will increase by 100 percent and 22 percent, respectively, between 2017 and 2030. 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 percent, respectively. Although remaining gaps could be filled with imports, this would add to challenges at the national level for the government budget and trade deficits, as well as the international challenge of making adequate supplies of food available to a growing population worldwide.

Households in the Sudan are predominantly rural dwellers, accounting for 73 percent of the population (MHRDL 2013). Among rural households, 58 percent live below the poverty line compared to 27 percent of urban households. Rural households mainly rely on agriculture as their main livelihood – 65.4 percent of the rural population work in agriculture compared to only 8.9 percent in urban areas.

Besides population and income growth that together trigger an increasing demand for food, water, and energy, the Sudan is subject to several environmental changes (FAO 2017; FAO 2016; USAID 2016; FAO 2015; Sayed and Abdala 2013; Taha et al. 2013). The country is reliant on agriculture with the sector accounting for one third of GDP and one-half of foreign exchange earnings and providing livelihoods to more than half of the Sudanese people (CBoS 2016). As 93 percent of annually cultivated land in the country is rainfed, such environmental changes are especially important, affecting the entire economy and the livelihoods of all directly or indirectly.

The objectives of this study are to estimate the effects of changes in the global and local climate on the Sudanese economy and people and propose policy interventions to mitigate their negative 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 insights that any environmental, economic, or policy intervention in one of these three components will affect the others (Nielson et al. 2015). This study is the first that applies such a comprehensive approach to address the issue of climate change in the Sudan. It includes models for global hydrology, river basin management, water stress, and a crop growth model connected to the International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) with end-point impacts on the Sudanese economy as a whole examined through the use a Computable General Equilibrium (CGE) model of the economy of the Sudan. The CGE model simulates effects at the macro-level and for different economic sectors using detailed representations of the agriculture, industry and service sectors, examines changes in income and expenditures of different household groups, and models returns to and employment of different factors of production.

The findings of this study are expected to be useful to stakeholders in the Sudan, especially policy makers, to better enable them to anticipate the economic impacts of climate change in a detailed way and to assess the suitability of options for interventions. While aiming to contribute to scientific knowledge and filling a research gap in a country where such studies are lacking, the study also presents various national strategies and action plans to mitigate the impacts of climate change.

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 and the published research with the aim of extracting actionable policy interventions that can facilitate adaptation to global and local climate change. Section 3 describes the biophysical, stochastic and economic models used in the analysis. Here we also provide a detailed description of the climate projections and our suggested policy interventions. In Section 4, we present and discuss the results obtained from the modeling suite and, finally, Section 5 provides conclusions and policy implications.

2. AGRICULTURE AND CLIMATE CHANGE IN NATIONAL POLICIES AND ACTION PLANS IN THE SUDAN

Main characteristics of Sudanese agriculture

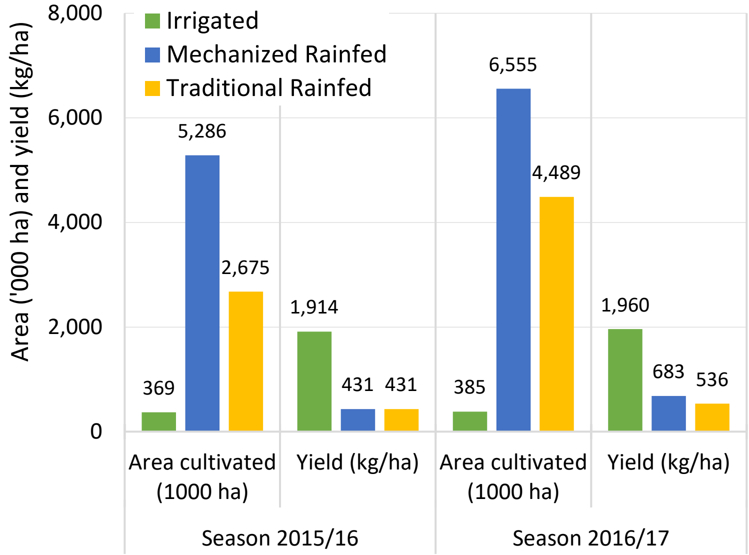
Agriculture in the Sudan is practiced under two major farming systems, rainfed, both mechanized and traditional, which occupies more than 90 percent of the cultivated land, and irrigated, which makes up the remainder. Additionally, the sector is divided into three major subsectors, cropping, livestock, and forestry/fisheries, contributing 39, 60, and 1 percent, respectively, to agricultural GDP in 2015/16 (CBoS 2016). This highlights the importance of livestock, which has become even more important in contributing to foreign exchange earnings, especially with the shrinking contribution of oil exports.

Agriculture provides a livelihood to 65 percent of the population, especially in rural areas and for poorer households. With respect to household income, 61 percent of households in the poorest income quintile rely on agriculture as their main livelihood compared to only 20 percent of households in the wealthiest quintile (World Bank 2015; CBS 2009). Thus, the agricultural sector is central to any poverty reduction policies and programs. Moreover, agriculture is the main employer in the country. It employed 47 percent of the labor force in 2011, including 41 percent of male and 63 percent of female workers. These shares are even more prominent in rural areas. Agriculture provides 65 percent of total rural employment – 59 percent of male and 82 percent of female workers (MHRDL 2013).

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

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 2015). This can be observed in the main crops, namely sorghum, cotton, groundnut, sesame, millet, and wheat. Other agricultural subsectors, such as sugar cane, gum Arabic, livestock (particularly live sheep and camels), and hides and skins are closer to their potential. Sorghum production during the last decade (only the last two seasons are shown in Figure 2.1) in the major farming systems of the country shows low productivity in the rainfed sectors, which represents more than 95 percent of the total sorghum-cultivated land compared to the irrigated sector. Productivity in the rainfed sectors is less than one-third of that of the irrigated sector (Figure 2.1).

Figure 2.1: Sorghum, area cultivated and yield in seasons 2015/16 and 2016/17 in the Sudan, by production method



Data source: MAF (2017).

In addition, harvested area and yields of crops fluctuate due to dependence on unpredictable rains, recurrent occurrences of droughts, pest infestation, and low application of fertilizer and other inputs (World Bank 2015).

Millet, which is a main staple food in Western Sudan and produced in the traditional rainfed sector of Darfur and Kordufan, is low yielding with an average productivity of less than 240 kg/hectare per year. The low productivity is mainly due to low input use usually, no purchased inputs, such as fertilizers, are used on millet. Besides, the amount and stability of rainfall affects and eventually determines production. Sorghum, sesame, millet, and pasture species are primarily grown in the traditional rainfed sector that is generally characterized by low crop productivity, associated with low usage rates of inorganic fertilizers and improved seed.

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 average fertilizer application of 7.3 kg/ha compared to 17 kg/ha in Ethiopia (ranked 115th) (World Bank 2015). This, however, is different than it was in the Sudan in the mid-1970s when 80 kg/ha were used and during the 1980s when 70 kg/ha were applied on average. While this partially explains the declining trends in the production of different crops in the Sudan, it also shows the need for stimulating fertilizer usage, as well as ensuring that agricultural policies conducive to increased input use in agriculture 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, government encourages domestic production despite no comparative advantage for its production in the Sudan. The average wheat yield in the Sudan is half that of Chad, one quarter that of Ethiopia, and only 7 percent that of Egypt (World Bank 2015). Wheat yields in the Sudan are among the lowest in the world. Similar developments and characteristics are observed in groundnut and sesame production in the Sudan.

Next to rainfall variability and the low usage of inputs, 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 may pave the way for further policy reforms, including for other crops.

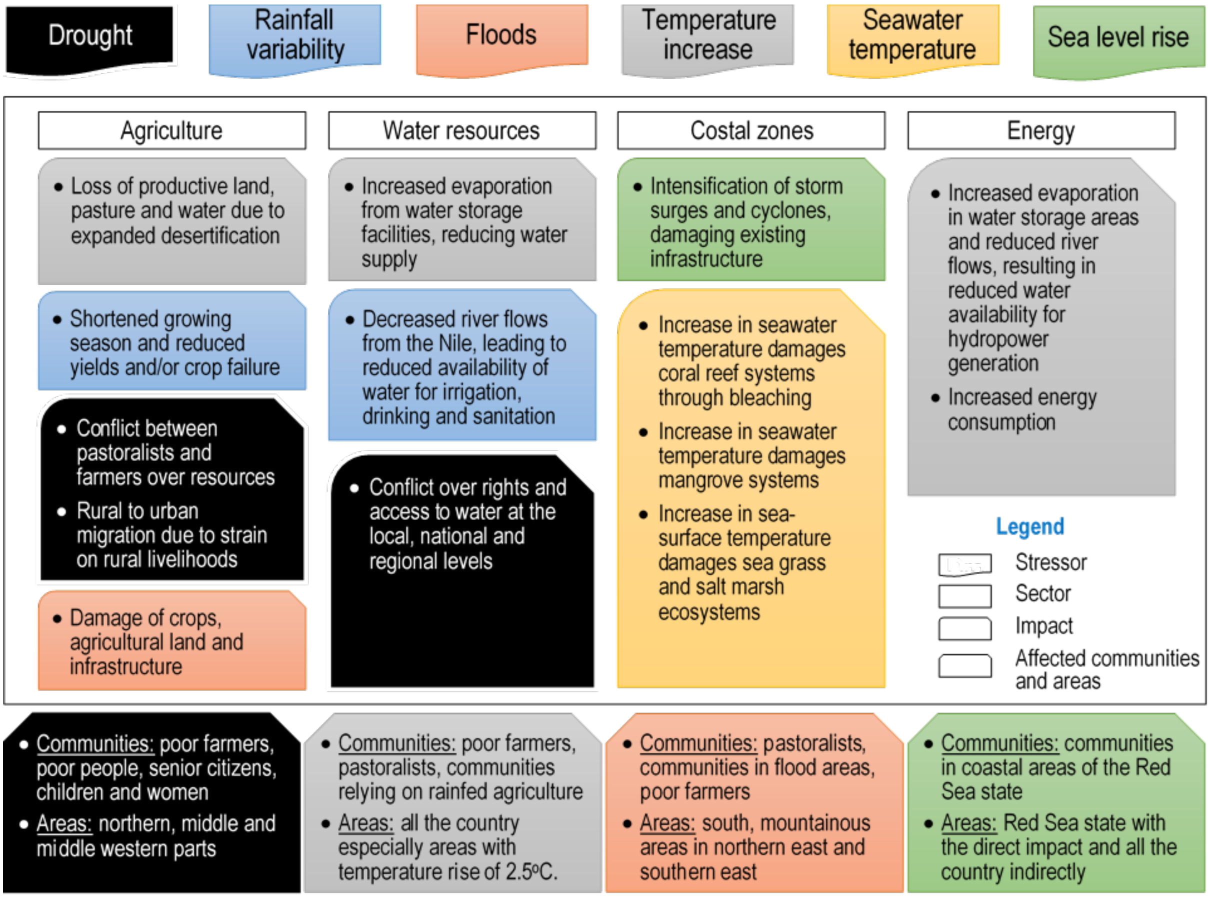
Environmental challenges to Sudanese agriculture

The increase in global temperature will affect all the Sudan. Vulnerable sectors to rises in temperature are particularly rainfed agriculture, aquaculture, natural ecology systems and biodiversity, water resources, and energy (production and consumption). This ultimately increases the vulnerability of certain communities, such as poor farmers, pastoralists and generally communities that rely on rainfed agriculture (Figure 2.2).

But the Sudan will not only experience changes in mean temperature, which are projected to increase by up to 3°C by 2050, and precipitation, which is projected to increase by 4 percent per decade, but also increasing rainfall variability with increased frequency of both droughts and floods (USAID 2016). Floods, flashfloods, and possibly landslides affect the southern and southeastern parts of the country as well as the mountainous areas in the northeast, while droughts affect more the northern parts and areas in the middle and middle west of the country. Communities that are most vulnerable to droughts and floods are pastoralists, poor farmers, and generally poor families with senior members, children, and women (Sayed and Abdala 2013). Figure 2.2 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.

It is important to note that climate impacts summarized in Figure 2.2 point to the connection between climate change in the Sudan and agricultural productivity. It shows that four climate stressors – temperature increase, rainfall variability, droughts, and floods – affect the agricultural sector and ultimately reduce its productivity. This predominantly affects poor farmers, poor people, senior citizens, children, and women particularly in the northern, middle, and middle-western parts of the country.

Figure 2.2: Climate stressors and their potential impact on sectors, areas, and communities in the Sudan



Source: Authors' elaboration.
Note: Colors are used to associate climate stressors to impacts and affected communities

Recommended interventions

After the mainstreaming of environmental and natural resource management issues in national development plans, many climate-related recommendations featured in these plans. Additionally, these plans and several studies conducted by non-governmental organizations and academics, identified environmental stressors, sectors, and affected population groups and areas in the Sudan (FAO 2017; USAID 2016; FAO 2015; Sayed and Abdala 2013; Taha et al. 2013).[1] The plans and studies generally focused on responses to climate risk and climate change threats on the agricultural and rural development sectors. This is not only because agriculture is an important sector for the livelihood of most of the Sudanese population and the Sudanese economy, but also because it is the sector in the economy which is most affected by changes in climate.

The suggested interventions include: (1) investing in infrastructure to protect against flooding; (2) developing programs and projects for mitigation of and adaptation to the effects of climate change 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 and the full utilization of

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

rainfall and seasonal streams outside the Nile Basin, using groundwater, and developing drought resistant crop varieties; and (5) treating water as a scarce resource and enhancing its efficient use, especially in irrigated agriculture, to best utilize Sudan's share of Nile water.

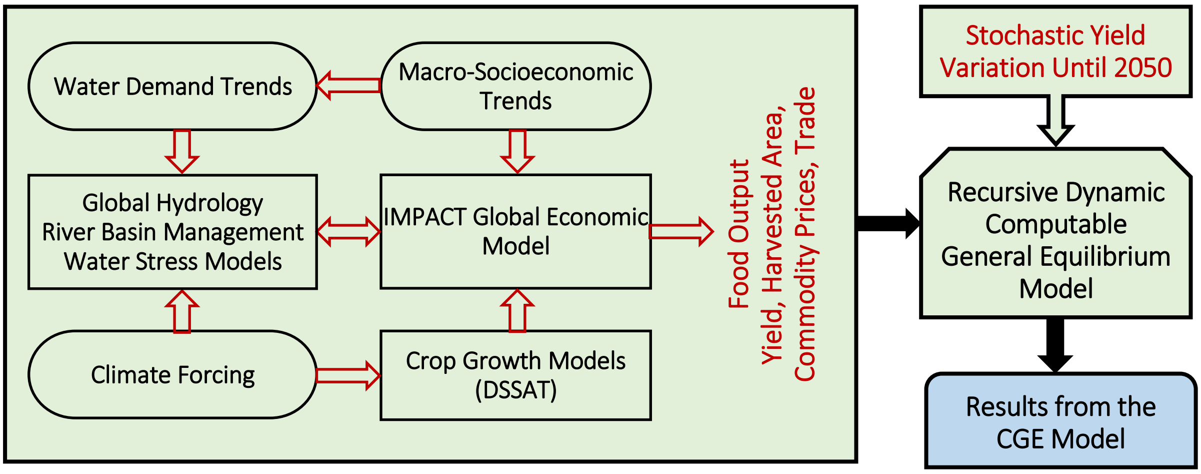
In a recent assessment of climate change adaptation options for the Sudan, it is stressed that adaptation measures should "focus on reducing sensitivity, improving resilience to variability and extremes, and improving heat tolerance and water efficiency in agricultural production" (WFP 2017: pp 37).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

3. ANALYTICAL METHODS

Due to the integrated nature of food, water, and energy systems and the limited availability of natural resources, policy makers need to consider the synergies and tradeoffs between the interlinked components of socio-ecological systems. It is almost impossible to address one dimension, e.g. food security, without affecting progress towards desired outcomes in other areas, such as water security, energy and water use, or environmental sustainability. This makes it necessary to incorporate key interlinkages between the food, water, and energy sectors in policy design as well as in any supporting analyses.

This study addresses the policy questions of what are the socioeconomic impacts of climate change on the Sudan both in general and, more specifically, in the agricultural sector, and what are the adaptation options the country might exercise. To address these research questions, we implement an integrated modeling suite to evaluate the impact of climate scenarios on economic growth, food security. and welfare, and the policy interventions that aim to mitigate the negative consequences of these climate-related challenges.

Figure 3.1: Model interaction within the modeling suite



Source: Authors' compilation and Robinson et al. (2015).

The modeling suite consists of three major components (Figure 3.1). The first simulates the impact of local and global climate changes on agriculture through the International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) modeling system and is presented in the left panel of Figure 3.1. The second component is a stochastic analysis that produces probability distributions of crop yields in the Sudan reflecting climate variability. This component is presented in the top-right corner of Figure 3.1. The third component is a dynamic Computable General Equilibrium (CGE) model of the Sudan economy which integrates results from the other components and simulates effects on the Sudanese economy. The modeling components are described in the following subsections.

The biophysical analysis component

Climate projections from four global climate models are used in this study to analyze the likely effects on the national economy of climate change for the Sudan, i.e., climate forcing. We use four climate models from the Coupled Model Intercomparison Project (CMIP5) archive (https://cmip.llnl.gov/cmip5/), including HadGEM2-ES, NorESM1-M, GFDL-ESM2M, and MIROC-ESM-CHEM. These projections were downscaled to a 0.5°×0.5° global grid through the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP – https://www.isimip.org/). The HadGEM2-ES projection is driven by the Representative Concentration Pathway (RCP) 8.5, NorESM1-M by RCP 4.5 and RCP 8.5, GFDL-ESM2M by RCP 4.5, while MIROC-ESM-CHEM is driven by RCP 4.5 and RCP 8.5. This makes for a total of six climate scenarios, in addition to a no climate change scenario, which together provide a reasonably broad range of plausible changes in precipitation and temperature in the Sudan around 2050.[2]

The IMPACT modelling system is at the center of this biophysical component (Figure 3.1). IMPACT is a system of linked models around a core multi-market economic model of global production, trade, demand, and prices for agricultural commodities (Robinson et al. 2015). The core model is linked to biophysical modules, including hydrology, river basin management, crop water stress, and crop growth 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 operate 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 multi-market 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 used in the IMPACT model 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 intervals 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 growth 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.

[2] See Appendix Table 1 for more details on precipitation and temperature changes, climate moisture index values, and ranking of climate scenarios.

The stochastic component

Because climate change may result in extreme weather shocks which may heavily affect food prices, this study aims to capture the impact of weather variability by conducting an uncertainty analysis. In recent years, many large-scale economic simulation models that are used to study agricultural markets, e.g., ESIM, GTAP, FAPRI, and Aglink-Cosimo, have incorporated stochastic features in order to address market uncertainty and to engage in systematic sensitivity analysis.

A significant component of the uncertainty around production and prices of crops based on historical data can be explained by yield variations, which, in turn, are mainly caused by weather fluctuations (Burrell & Nii-naate 2013). Therefore, we use yield data for six major crops[3] 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 applied by Artavia et al. (2015), who calculate them as deviates from 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 $z_{i,j} = y_{i,j} / \hat{y}_{i,j} - 1$. If the historical time series are stationary, the expected values of the stochastic variables (yield deviates) are zero. We found standard deviations of the yield deviates being in the range of 0.1 to 0.3. According to the Dickey-Fuller test for stationarity, all the deviates are stationary at 5 percent significance level and the normality test[4] shows that all variables, except irrigated groundnut yields, are normally distributed at the 5 percent significance 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 cumulative distribution function 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 percent level.

After obtaining the simulated random variables, we selected the 5 percent quantile values of the cumulative distribution function, which we consider the worst-case scenario of climate variability. The selected crop yield shocks are implemented in the model as changes to total factor productivity. In this context, the scenario should be interpreted as a limit below which the yields may decrease only in five percent of cases. In all the other 95 percent of cases, the results will fall above this threshold.

The Computable General Equilibrium model component

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

[3] 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).

[4] 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.

Sudan, which distinguishes several agricultural and agro-processing sectors as well as industrial and services sectors. The model is based on a post-separation Social Accounting Matrix for the Sudan for the year 2012 (Siddig et al. 2016). A detailed description of the model structure and equations can be found in Diao and Thurlow (2012). In addition, Wiebelt et al. (2013; 2015) and Breisinger et al. (2013) provide additional insights on the core parameters of the model. Al-Riffai et al. (2017) implemented a similar approach to that used here to assess synergies and trade-offs amongst water, energy, and food policies in Egypt.

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 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 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 constant elasticity of substitution 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, most working-age people engage in activities that contribute to 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, capital 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 (SAM) built by Siddig et al. (2016). Given the importance of agriculture for income generation and the satisfaction of consumption needs, the SAM captures the sectors of crop production and their linkages to other sectors such as food processing, other manufacturing, and services. The SAM 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, rubber, and 13 crop production activities, most of them differentiated by irrigated and mechanized and traditional rainfed production modes for a total of 26 crop activities. 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 world (foreign savings) are collected in a savings pool from which investment is financed.

The model includes three macroeconomic accounts: a 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 to absorption 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.[5]

Simulation scenarios and major findings

We simulate one baseline scenario with no climate change as a reference (NoCC), six climate change scenarios (CC1 to CC6) for which we consider the local impact pathway via yield changes in the Sudan (LocCC1 to LocCC6), and the global impact pathway via world market price changes (GlobCC1 to GlobCC6) as well as the combined effect via local and global impact pathways (we only refer to the combined effect for CC1). Moreover, we simulate the effect of climate variability on top of CC1 (VarCC1) and an intervention scenario with measures to increase crop productivity in the Sudan on top of VarCC1 (CropProd).

The baseline scenario: no climate change

In order to use the model to estimate costs imposed on the Sudan by climate change, we start by specifying a hypothetical dynamic baseline path to 2050 that reflects development trends, policies, and priorities in the absence of climate change (NoCC). This baseline is not a forecast, but instead provides a counterfactual – a reasonable trajectory for growth and structural change of the Sudanese economy in the absence of climate change that is used as a basis for comparison with climate change scenarios.

In the baseline, underlying rates of labor force growth and arable land growth, sectoral productivity growth, world prices, remittances, foreign aid, and foreign and capital inflows are

[5] Driven by the limited access to foreign exchange and the resultant foreign 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 percent in May 2012, which forced a 66 percent 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 intervenes if the exchange rate exceeds a band of + or -3 percent around the closing rate of the previous day (Jenkins et al. 2013). Accordingly, a flexible exchange rate regime is applied in the model.

imposed exogenously. Annual GDP growth rates until 2022 are taken from the IMF's World Economic Outlook (2016). From 2022 onward to 2050, we preserved the final year's growth rate, which is projected to be stable. The labor force growth is based on UN population growth projections (UN 2017), while total factor productivity (TFP) trends for individual sectors in agriculture, industry and services are set in conformity with GDP projections for aggregated agriculture, industry and services sectors (World Bank 2017). World market price changes for agricultural commodities are taken from IMPACT simulations. These simulations neglect climate change but take into account world market price changes that result from population growth and changing consumption preferences. Moreover, we assume a balanced closure for investment and savings for our very long-run simulations with real investment fixed to its initial absolute share of absorption, while private savings rates adjust in order to generate the necessary savings. The resulting average annual baseline growth rate of GDP over the period 2012 to 2050 is 3.7 percent, while per capita income grows at an average annual rate of 2 percent, which entails roughly a doubling in baseline per capita income over this period.

Climate change scenarios

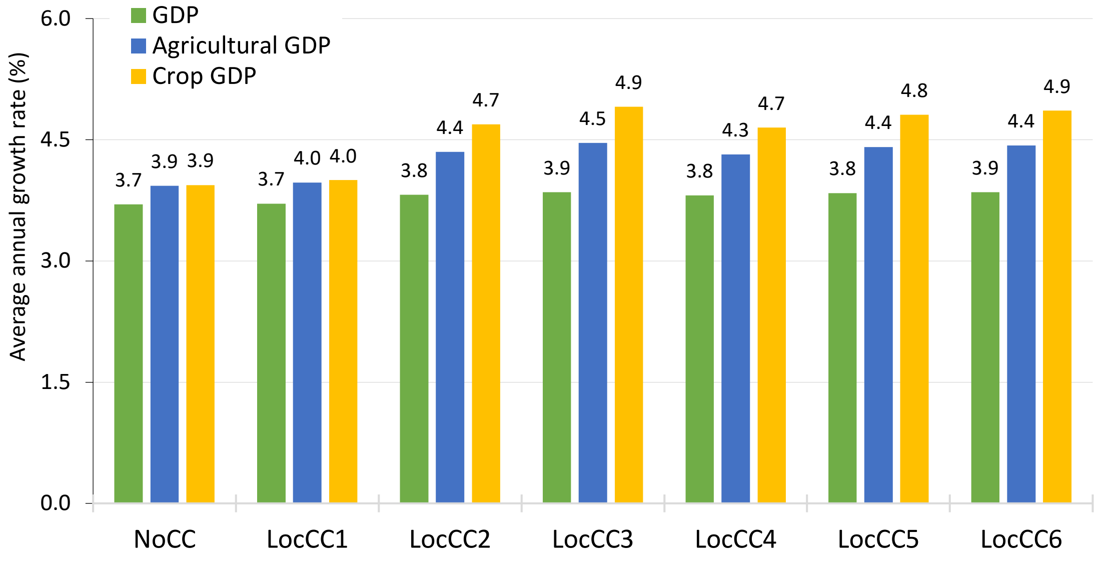
For this study, six scenarios are used to simulate the potential effects of local and global climate change over the period 2012 to 2050 (CC1 to CC6). For each climate change scenario, a distinction is made between two impact pathways: 1) local climate change effects (LocCC1 to LocCC6) are climate change induced yield changes derived from the DSSAT models and enter the production functions at the level of total factor productivity in the CGE model and 2) global climate change effects (GlobCC1 to GlobCC6) enter the CGE model as changes in world market prices. The local and global impacts of climate scenarios are thus based on outputs of the biophysical modeling components. Namely, local yield changes as TFP shifters for the local climate change impacts and global yield changes together with other global supply and demand drivers mediated through the IMPACT model resulting in world price changes entering the CGE model as global climate change impact.

Accumulated yield changes for the Sudan in the baseline (NoCC) as well as six climate change scenarios for the period 2013-2050 together with the difference from the baseline are presented in Appendix Table 2. Under NoCC, accumulated yield changes in the Sudan are all positive and vary between 15 and 138 percent. Under the driest scenario CC1, some of the accumulated yield changes are negative and most yield changes are lower than under NoCC, but some are also substantially higher. Under the wettest scenario CC6, all yield changes except for irrigated maize are higher than under NoCC.

Positive changes in local yield are expected to have direct positive effects on agriculture, which benefit from higher yields per hectare and thus higher production values. The increased profitability will also draw additional production factors into agriculture. In addition, the changes in productivity affect prices in complex ways throughout the economy. The effects of the changes in local yield are reflected in the aggregated results from the CGE shown in Figure 3.2. The resulting average annual growth in GDP at factor cost as well as agricultural and crop GDP at factor cost under the local impact pathways of the six climate scenarios are higher than those of the NoCC scenario. CC1 can be described as the driest scenario in the Sudan, while scenario CC6 is the wettest scenario and this is reflected by the substantially higher average annual GDP growth (national, agriculture, and crops) under CC6. This finding of positive yield effects of climate change in the Sudan is in line with recent WFP (2017) projections in which the average change in rainfall across three different climate models under three different climate change scenarios is increasing.

As a next step, the global impact pathway of the climate scenarios on the Sudanese economy via world prices is documented in Appendix Table 3, which shows accumulated world market price changes in the baseline as well as in six climate change scenarios. With few exceptions, world market prices are higher under the climate change scenarios than in the baseline. World market prices are particularly high under CC1, where they vary between 4 and 64 percent above the baseline.

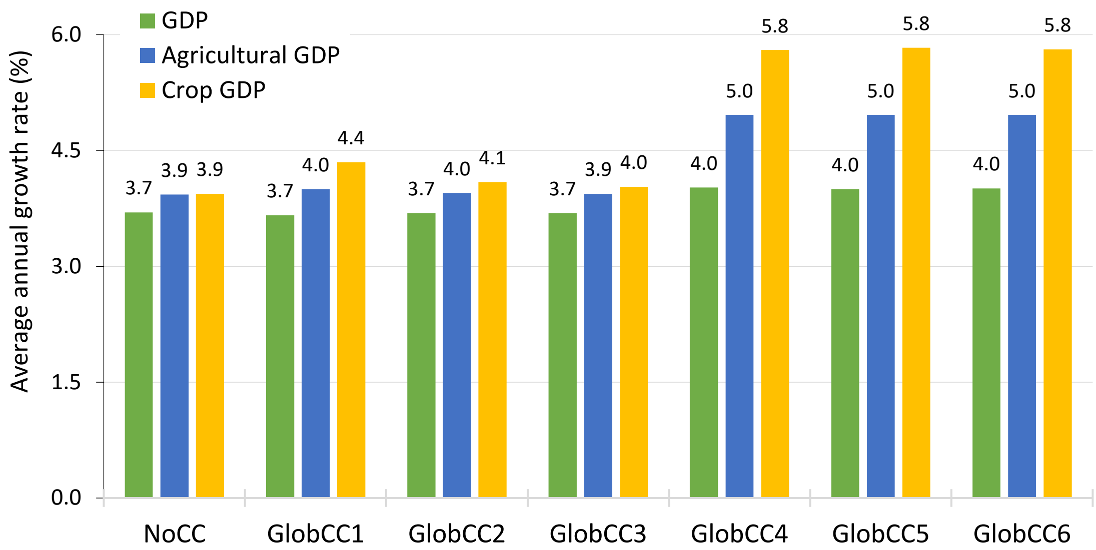
Figure 3.2: Impacts of local climate change through local yield impact pathways on growth of GDP, agricultural GDP, and crop GDP, average annual growth, 2013 to 2050



Source: Results from Sudan CGE model.

The severity of the impact of these world market price changes on any country depends on the degree of trade openness of the country, the degree of trade integration, and the composition of traded commodities and their significance in the economy. In the Sudan, these world market price changes result in producer price changes for agricultural commodities (Appendix Table 5). Domestic prices decline more strongly under the global impact pathway of CC1 (GlobCC1) than under the baseline. Generally, changes in the size and the sign of output prices are mixed due to different supply, demand, and trade structure for each commodity. Accordingly, it is not straight forward to specify how global climate change will impact domestic output prices.

Figure 3.3: Impacts of global climate change on growth of GDP, agricultural GDP, and crop GDP at factor cost, average annual growth rates, 2013 to 2050



Source: Results from Sudan CGE model.

Average annual changes in GDP – national, agriculture and crops – of the Sudanese economy caused by the global impact pathway of climate change are depicted in Figure 3.3. World market prices of agricultural commodities are higher under the dryer scenario (CC1) than under the wetter scenario (CC6). 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. This is explained by globally higher temperatures and lower precipitation resulting in lower yields world-wide and, therefore, lower output and supply. As a result, the stronger the change in climate globally, the larger are increases in world prices.[6]

The impact on the domestic economy therefore, depends on the trade orientation of affected markets. Generally, impacts are negative if the Sudan is a net importer and positive if the Sudan is a net exporter of the particular good under consideration.

Of course, annual GDP growth rates are very aggregate and hide a lot of underlying detail. Therefore, we will present some of the detailed results later in the results section.

Stochastic yield variation scenario

Given the negative weather events in the region recently, especially the sequence of droughts, 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, needs to be considered in the analysis of climate change. Though limited, findings from studies investigating future climates of the Sudan stress that it is not the mean changes in temperature and precipitation that will negatively affect Sudanese agriculture and livelihoods. Rather, it is rainfall variability (WFP 2017; USAID 2016; Rhodes 2012). This is considered in the stochastic yield variation scenario. Yield changes by crop under the climate variability scenario are presented in Appendix Table 4 and are compared to yields under the baseline scenario.[7] Appendix Table 4 shows yield under climate variability to be much lower than under the baseline for all crops.

By way of summary, average annual changes in GDP, agricultural GDP, and crop GDP caused by four selected simulations plus the NoCC scenario are presented in Figure 3.4. The four simulations for which results are presented are all based on the driest climate scenario (CC1) – the isolated local impact pathway (LocCC1), the isolated global impact pathway (GlobCC1), the combination of the global and local impact pathways (CC1), and the stochastic yield variation scenario (VarCC1).[8]

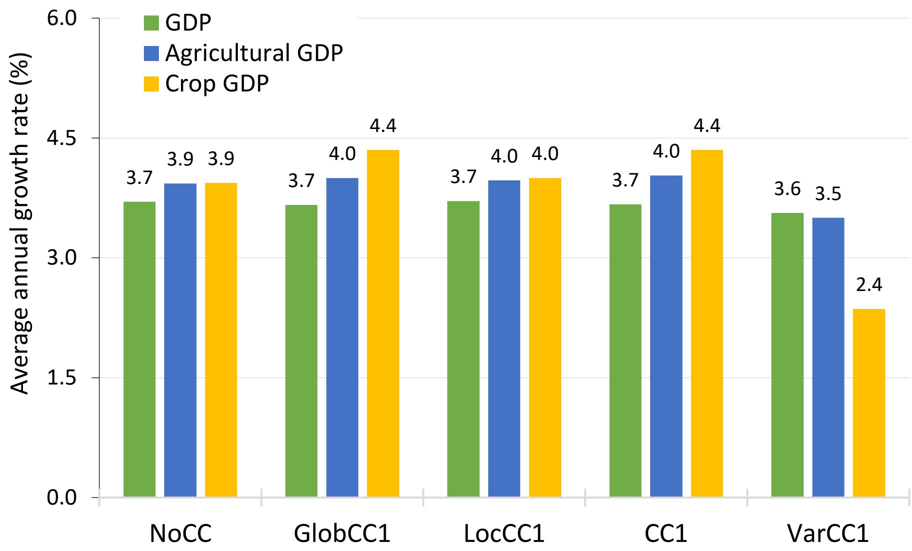
The results in Figure 3.4 indicate that average annual GDP growth rates will be lower under variable climate projections, especially the crops component of agriculture, which grows on average by only 2.4 percent compared to 4.4 percent under no variability and 3.9 percent under no climate change. This confirms the conclusions of previous research (WFP 2017; Siam and Eltahir 2017; Rhodes 2012) that climate variability generates a more negative impact in the Sudan relative to mean changes in precipitation. A detailed analysis of the costs of the projected climate variability in the Sudan is presented in the following section.

[6] The global scenarios include only world market price changes, but no local yield changes.

[7] The way the shocks are implemented via total factor productivity affects both producer and consumer prices with the effect being directly on producer prices. Consumer price is then the outcome of changes in the producer price as well as the domestic price of imports, including taxes and subsidies, if any.

[8] The stochastic yield projections are implemented on top of CC1, which combines both the local and the global impact pathways.

Figure 3.4: Impacts of climate change and climate variability on growth of GDP, agricultural GDP, and crop GDP at factor cost, average annual growth rate, 2013 to 2050



Source: Results from Sudan CGE model.

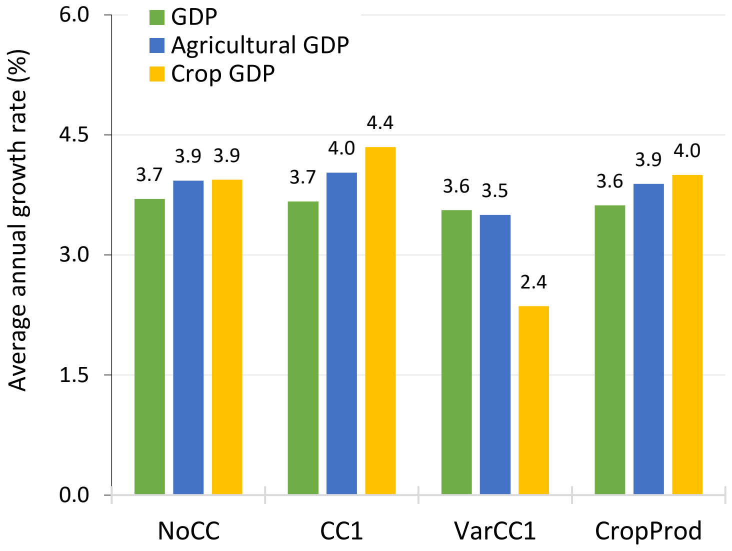
An intervention scenario

Besides the scenarios that reflect climate change, this study proposes interventions that are meant to support the Sudanese economy to adapt to 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 agriculture, and investing in extension services with the objectives of reducing and encountering the negative consequences of climate variability. The advantage of the method used here compared to previous assessments (FAO 2017; USAID 2016; FAO 2015; Sayed and Abdala 2013; Taha et al. 2013) is that it can simulate the effects of such interventions in monetary terms at both the sectoral and the national levels.

For countering the reduction in annual growth rates due to climate variability, we used the modeling suite to determine what level of productivity enhancement is required to produce a level of growth in crop GDP similar to that of no climate change, but under climate variability circumstances. This was found to be accomplished by improving the productivity of rainfed crops by 4 percent annually in the first three years (2018 to 2020) of the analytical period and 2.5 percent annually afterwards until 2050. For irrigated crops, the simulated increase in productivity is 2 percent annually in the first three years and 1 percent annually afterwards until 2050. These productivity shifters are applied on top of VarCC1, and the scenario is named “CropProd”. 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 in the Sudan to be among the lowest in the world (World Bank 2015).

Figure 3.5 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 national GDP, agricultural GDP, and crop GDP to close to their NoCC baseline levels.

Figure 3.5: Impacts of climate change, climate variability, and policy interventions on growth of GDP, agricultural GDP, and crop GDP at factor cost, average annual growth rate in the Sudan, 2013 to 2050



Source: Results from Sudan CGE model.

4. RESULTS AND DISCUSSION

To present meaningful long-term (2013 to 2050) results in a country like the Sudan, where the macroeconomic environment is relatively unstable with considerable exchange rate variations and growing inflation, and in order to make comparable revenue and expenditure streams over time, we apply the following measures to the real macroeconomic indicators. First, we calculate the future present-values of the indicators by applying a 5 percent annual discount rate from 2013 to 2050 to the local currency (Sudanese pound - 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.

Results are presented in this section for the following scenarios: 1) the baseline (NoCC), 2) the driest climate change scenario with combined local and global impact pathway (CC1), 3) climate variability (VarCC1), and 4) productivity enhancement as a policy intervention to encounter climate variability (CropProd).

Table 4.1: Accumulated discounted total absorption between 2018 and 2050 in Sudanese pounds, US (2012) dollars, and percentage

	Accumulated values (2018 to 2050)		Deviation from NoCC	
Simulations	**SDG billions**	**US$ billions**	**US$ billions**	**%**
Baseline (NoCC)	18,962.0	4,309.6	0.0	0.0
Climate change (CC1)	19,566.3	4,446.9	137.3	3.2
Climate variability (VarCC1)	18,480.2	4,200.0	-109.5	-2.5
Intervention (CropProd)	19,237.3	4,372.1	62.6	1.5

Source: Results from Sudan CGE model and authors' calculations. Note: SDG = Sudanese pound

Results obtained for discounted total absorption converted into US$ are presented in Table 4.1. 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$ 137.3 billion as compared to no climate change cumulatively for the period between 2018 and 2050. These findings are in line with those of WFP (2017), which project average rainfall until 2100 to increase in the Sudan across three different climate models under three different climate change scenarios.

However, considering variability in climate variables and, in particular, recurrent droughts, the accumulated loss in absorption relative to no climate change (i.e. without climate variability), will be US$ 109.5 billion, a 2.5 percent reduction compared to NoCC (as shown in the fourth and fifth columns of Table 4.1).

Discounted values for total GDP under the different simulation scenarios are presented in Table 4.2. Results for GDP indicate that climate change will result in an accumulated loss of US$ 27.9 billion in the period 2018-2050. This is the combined effect of improved domestic yields (Figure 3.2) and higher world market prices for agricultural products (Figure 3.3).

Table 4.2: Accumulated discounted GDP between 2018 and 2050 in Sudanese pounds, US (2012) dollars, and percentage

	Accumulated values (2018 to 2050)		Deviation from NoCC	
Simulations	**SDG billions**	**US$ billions**	**US$ billions**	**%**
Baseline (NoCC)	16,849.5	3,829.4	0.0	0.0
Climate change (CC1)	16,726.8	3,801.5	-27.9	-0.7
Climate variability (VarCC1)	16,385.4	3,724.0	-105.5	-2.8
Intervention (CropProd)	16,506.4	3,751.5	-78.0	-2.0

Source: Results from Sudan CGE model and authors' calculations. Note: SDG = Sudanese pound.

This implies that there will be no need to adapt to climate change, as climate change has a positive impact on absorption, i.e., consumption and investment. But climate variability leads to dramatic losses of absorption and requires adaptation measures, which if implemented, i.e., the policy intervention scenario of the study, improve total absorption in the country.

The climate variability scenario reduces the cumulative 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 a genuine justification for investing in drought-tolerant crop varieties and agricultural extension programs oriented towards increasing farmers' resilience to climate variability and coping mechanisms. Results of the productivity scenario (CropProd) support the benefits that can accrue from such interventions, leading to an accumulated benefit of US$ 62.6 billion in absorption relative to the no climate change baseline.

In short, both climate change and climate variability lead to losses of US$ 27.9 billion and US$ 105.5 billion, respectively in GDP. These potential losses require that adaptation measures be put in place. The adaptation measures, if implemented in the way described in this study, cannot fully compensate for all of the GDP losses caused by climate change and climate variability, but will reduce them by US$ 28 billion over the period from 2018 to 2050.

Table 4.3 presents aggregate results focusing on the agricultural sector. They include the accumulated (2018 to 2050) present-values of agricultural GDP in US$ as well as present-values of deviations from the no climate change scenario for ten-year intervals. Results indicate that agricultural GDP is about US$ 86 billion higher under climate change (CC1) compared to the no climate change baseline (NoCC), which is the combined effects of higher yields in the Sudan as well as higher crop prices for agricultural products. Under the climate variability scenario, however, agricultural GDP declines by US$ 92.7 billion.

Considering the time dimension, the results in the four right columns of Table 4.3 show that most of the losses under the climate variability scenario occurs in the second half of the period, 2030-40 and 2040-50. This is explained by the cumulative impact of year-to-year yield variability expressed by our stochastic components of the modeling suite.

Table 4.3: Accumulated present-values of agricultural GDP and changes between 2018 and 2050 in billions of US$ (2012 prices)

Simulations	Value (US$ billions) 2018 to 2050	Deviation from NoCC (US$ billions) 2018 to 2050	2018 to 2020	2020 to 2030	2030 to 2040	2040 to 2050
Baseline (NoCC)	1,141.9	0.0	0.0	0.0	0.0	0.0
Climate change (CC1)	1,228.1	86.2	1.3	18.9	38.9	27.7
Climate variability (VarCC1)	1,049.1	-92.7	-1.3	-6.3	-26.5	-59.0
Intervention (CropProd)	1,172.9	31.0	-0.5	7.5	16.3	7.8

Source: Results from Sudan CGE model and authors' calculations.

The impact of the four scenarios on individual household groups is depicted by the difference in the average annual real household consumption expressed in absolute changes in billions of SDG and in percentage change from the baseline (NoCC), shown in Table 4.4. It shows the results of the four scenarios for the ten household groups included in this study classified by location (rural and urban) and income quintiles. Under CC1, both rural and urban households will be better off compared to NoCC with the former gaining more than the latter due to their reliance on agriculture that benefits from wetter climate thereby generating more income. Under the climate variability scenario, welfare losses are stronger for rural households, especially for poor rural households.

Table 4.4: Impact of climate change, climate variability, and policy interventions on real household consumption, change in SDG (billions) and percentage

	Initial value in NoCC (SDG billion)	Initial shares in NoCC (%)	Average annual change (SDG billion) NoCC	CC1	VarCC1	Crop-Prod	Average annual change (% from NoCC) CC1	VarCC1	Crop-Prod
All households	196.5	100.0	4.2	4.4	3.9	4.1	4.1	-7.6	-2.0
Quintile 1	18.3	9.3	0.4	0.4	0.3	0.4	6.5	-9.8	-4.0
Quintile 2	29.5	15.0	0.6	0.6	0.6	0.6	5.2	-8.3	-2.6
Quintile 3	36.0	18.3	0.8	0.8	0.7	0.8	5.0	-8.2	-2.3
Quintile 4	49.0	24.9	1.1	1.1	1.0	1.1	4.0	-7.1	-1.6
Quintile 5	63.6	32.4	1.4	1.4	1.3	1.4	2.8	-6.9	-1.2
Rural households	117.5	59.8	2.4	2.5	2.2	2.3	5.3	-8.2	-2.6
Rural in Q1	15.6	7.9	0.3	0.3	0.3	0.3	7.1	-9.8	-4.5
Rural in Q2	22.5	11.5	0.4	0.5	0.4	0.4	5.7	-8.3	-3.1
Rural in Q3	24.3	12.4	0.5	0.5	0.5	0.5	5.7	-8.4	-2.9
Rural in Q4	26.8	13.6	0.6	0.6	0.5	0.5	4.7	-7.2	-1.9
Rural in Q5	28.3	14.4	0.6	0.6	0.5	0.6	4.4	-7.8	-1.9
Urban households	78.9	40.2	1.8	1.9	1.7	1.8	2.8	-7.1	-1.1
Urban in Q1	2.7	1.4	0.1	0.1	0.1	0.1	3.9	-9.7	-2.3
Urban in Q2	7.0	3.6	0.2	0.2	0.2	0.2	4.2	-8.2	-1.6
Urban in Q3	11.7	6.0	0.3	0.3	0.3	0.3	3.9	-7.8	-1.3
Urban in Q4	22.2	11.3	0.5	0.5	0.5	0.5	3.3	-7.1	-1.4
Urban in Q5	35.3	18.0	0.8	0.8	0.7	0.8	1.7	-6.3	-0.7

Source: Results from Sudan CGE model and authors' calculations. Note: SDG = Sudanese pound.

These results are not only conceivable, but they are also very important because they relate to the fact that most of the poor in the Sudan are rural dwellers and reliant on agriculture as their major source of income and livelihoods. This implies that such households will be most sensitive to climate variability, Measures need to be put in place for their vulnerability to be reduced. To put that into prospect, total household losses under the climate variability scenario as measured by real household consumption is US$ 111.4 billion over the period 2018 to 2050. Of these, US$ 64.3 billion are the losses of rural households, which makes them 3.3 percent worse off than under the no climate change scenario.

These losses are reversed under the policy intervention scenario (CropProd) into gains of US$ 64.1 billion for all households, of which US$ 40.8 billion accrue to rural households, while US$ 23.2 billion are the gains of urban households, all compared to the NoCC scenario. Nonetheless, households would still be worse off not only under the climate variability scenario, but also under the policy intervention scenario if the results are to be compared to the climate change scenario (CC1).

5. CONCLUSIONS AND POLICY IMPLICATIONS

In the Sudan, the agriculture sector accounts for more than a third of GDP. It is also an important contributor to foreign exchange earnings and to people's livelihoods. Being mainly rainfed, agriculture in the Sudan is vulnerable to variations in rainfall amounts and timing. In this study, we combine various biophysical and economic models to assess the impacts of climate change and variability on the Sudanese economy out to 2050.

We use the IMPACT model system, which includes global hydrology, river basin management, water stress, and the DSSAT crop simulation models linking to a core multi-market model. The model system is driven by climate forcing data, projected water demand, and macro-socioeconomic trends. The results of these modeling components, which include annual crop yields and international market prices under various climate change scenarios until 2050, are combined with stochastic projections of yield variation. These results are then fed into a single country recursive dynamic CGE model for the Sudan to assess the economy-wide impacts of climate change under various scenarios.

Based on our analysis, we draw several conclusions regarding both the method we applied and the effects of climate change in the Sudan.

With respect to methods, complex socio-ecological systems need complex models for analysis. The impact pathways of climate change are complex, with many indirect, price-mediated effects. Therefore, the complexity of the modeling suite used is helpful for analyzing the impacts of climate change. However, while a lot of attention goes to climate change and adaptation strategies, what we have already today is heightened climate variability, which has negative consequences in some years that go beyond the average temperature and precipitation effects of climate change in the Sudan. A stochastic model component introducing yield volatility based on historical data is able to demonstrate this. Because climate change projections often involve the expectation that climate becomes more variable, stochastic model components may be essential to comprehensively depict the effects of climate change.

Regarding climate change in the Sudan, the simulation results reveal that the outcome of projected local yield changes will lead to a cumulative (2018 to 2050) increase in the country's GDP by US$ 40 billion or 1 percent compared to no climate change. At the same time, global price changes create an adverse effect on GDP causing a loss of US$ 72 billion or 1.9 percent compared to no climate change. These two effects combined create a loss of US$ 28 billion compared to the no climate change scenario.

Accounting for climate variability through our stochastic estimation of historical yield changes, which we added on top of the combined climate change scenario, worsens the situation further for the Sudan. For the period from 2018 to 2050, they cumulatively cause a loss of US$ 109.5 billion in total absorption and US$ 105.5 billion in GDP relative to no climate change. Similar effects are observed at the household level with the climate variability scenario hitting poor rural households more than urban and rich households.

The effect of climate change on the agricultural sector is quite positive due to higher world market prices for agricultural products and higher yields in the Sudan. As a result, the cumulative (2018 to 2050) increase in agricultural GDP compared to no climate change is simulated to be US$ 86 billion. The effect of climate variability however, is a loss of US$ 93 billion.

Climate change effects in the Sudan are likely to affect different farmers to different extents. This is because of regional and farm level differences in the composition of production and the different yield effects for different crops under climate change. In addition, the product-specific global climate effects on the Sudanese economy in general and the agricultural sector in particular depend on the general tradability of the respective commodities and on the extent to which they are actually traded. Finally, the product specific net trade situation determines whether a given global price change constitutes a positive or a negative effect on the terms of trade of the Sudan. With higher prices of agricultural commodities until 2050 in the case of climate change, the positive welfare effects on the Sudan will be more positive the higher net exports are.

Finally, we derive policy implications based on the recommendations of reviewed studies as well as our simulation results. First, the negative effects of climate change and increased variability on Sudanese agriculture could be mitigated 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 the potential effect of such measures and found that the negative consequences of climate variability can be compensated at the macroeconomic level by productivity improvements. The suggested productivity enhancements for crops in the rainfed sector are 4 percent annually in the first three years of the period analyzed (2018 to 2020) and 2.5 percent annually afterwards until 2050. For crops in irrigated agriculture, the required productivity enhancements are 2 percent annually in the first three years and 1 percent annually afterwards until 2050. At the household level, the negative consequences of extreme climate variability will be considerably reduced by the introduction of drought-tolerant varieties that improve crop productivity.

Second, given the complex impact pathways of climate change on agriculture in the Sudan, it would be helpful for strategy and policy development in the agricultural sector if the analytical capacity to analyze these impacts would be strengthened. This may partially happen within academia or other research institutions in the Sudan, but also through the development of networks with international researchers and international organizations. It seems realistic that national simulation model components are best handled by Sudanese experts in order to explore local climate change impact pathways, such as through local yields. Global impact pathways which indirectly affect Sudanese agriculture via world market price mediated effects of climate induced effects elsewhere, however, require global biophysical as well as economic simulation modeling frameworks which are typically handled by large scale international teams of researchers.

REFERENCES

Al-Riffai, P., C. Breisinger, A. Mondal, C. Ringler, M. Wiebelt, and T. Zhu. 2017. *Linking the Economics of Water, Energy, and Food: A Nexus Modeling Approach*. Egypt Strategy Support Program Working Paper 04, Cairo: International Food Policy Research Institute.

Artavia, M., Grethe, H., and G. Zimmermann 2015. "Stochastic market modeling with Gaussian Quadratures: Do rotations of Stroud's octahedron matter?" *Economic Modelling*, 45, 155–168.

Breisinger, C., T. Zhu, P. Al-Riffai, G. Nelson, R. Robertson, J. Funes, and D. Verner. 2013. "Economic impacts of climate change in Syria." *Climate Change Economics*, 4 (1): 1-30.

Burrell, and A.Z. Nii-Naate. 2013. *Partial stochastic analysis with the European Commission's version of the AGLINK-COSIMO model*. JRC Reference Report EUR 25898 EN. Seville, Spain: Joint Research Centre of the European Commission. http://ftp.jrc.es/EURdoc/JRC76019.pdf.

CBoS (Central Bank of the Sudan). 2016. *The 56th Annual Report of the Central Bank of the Sudan*. Khartoum: CBoS. http://www.cbos.gov.sd/sites/default/files/annual2016.pdf.

CBoS (Central Bank of the Sudan). 2017. *The 57th Annual Report of the Central Bank of the Sudan*. Khartoum: CBoS. https://cbos.gov.sd/sites/default/files/annual_17.pdf.

CBS (Central Bureau of Statistics). 2009. *National Benchmark Household Survey*. Khartoum: CBS.

Diao, X. and J. Thurlow. 2012. "A Recursive Dynamic Computable General Equilibrium Model." In *Strategies and Priorities for African Agriculture: Economywide Perspectives from Country Studies*, edited by X. Diao, J. Thurlow, S. Benin, and S. Fan. pp. 17-50. Washington D.C.: International Food Policy Research Institute.

Ebaidalla, M. E. 2017. *Parallel Market for Foreign Exchange in Sudan: Determinants and Impact on Macroeconomic Performance*. An ERF Annual Conference paper, Amman, Jordan, March 2017. http://erf.org.eg/wp-content/uploads/2017/03/Macr_ERF23AC_EbaidallaMahjoub.pdf.

FAO (Food and Agriculture Organization of the United Nations). 2017. *Study on small-scale family farming in the Near East and North Africa region. Focus country: Sudan*. Rome: FAO. http://www.fao.org/3/a-i5985e.pdf. Accessed on September 11, 2017.

FAO (Food and Agriculture Organization of the United Nations). 2016. AQUASTAT website. Rome: FAO. http://www.fao.org/nr/water/aquastat/countries_regions/SDN/. Accessed on September 4, 2017.

FAO (Food and Agriculture Organization of the United Nations). 2015. *Country Programming Framework for Sudan Plan of Action (2015-2019): Resilient Livelihoods for Sustainable Agriculture, Food Security and Nutrition*. Rome: FAO.

FAO (Food and Agriculture Organization of the United Nations). 2012. *The Land Cover Atlas of Sudan*. Rome: FAO http://www.fao.org/3/a-be896e.pdf.

IMF (International Monetary Fund). 2016. World Economic Outlook Database. Washington, DC: IMF. http://www.imf.org/external/pubs/ft/weo/2016/01/weodata/index.aspx.

Jenkins, P., Y. Kim, H. Shi, and K. Gerling. 2013. *Sudan: Selected Issues*. Country Report No. 13/320. Washington, DC: International Monetary Fund. https://www.imf.org/external/pubs/ft/scr/2013/cr13320.pdf.

Jones, J.W., G. Hoogenboom, C.H. Porter, K.J. Boote, W.D. Batchelor, L. Hunt, P.W. Wilkens, U. Singh, J. Gijsman, and J.T. Ritchie. 2003. "The DSSAT cropping system model." *European Journal of Agronomy*, 18: 235-265.

MAF (Ministry of Agriculture and Forestry). 2017. *Unpublished data on crop production, area and yields*. Khartoum: General Administration of Planning and Agricultural Economics, MAF.

MEPD (Ministry of Environment, Natural Resources and Physical Development). 2015. *National Biodiversity Strategy and Action Plan 2015 - 2020*. Khartoum: Higher Council for Environment and Natural Resources, MEPD, Republic of Sudan.

MHRDL (Ministry of Human Resources Development and Labor). 2013. *Sudan Labor Force Survey 2011* (SLFS 2011). Khartoum: MHRDL.

Rhodes, R. 2012. *Changes in long-term variability of the rains of Sudan*. MSc thesis, Department of Meteorology, University of Reading, Reading, UK. Accessed online on April 3, 2018 at: http://www.met.reading.ac.uk/~jb013101/files/publications/dissertation_rhodes2012_sudan.pdf.

Robertson, R., G. Nelson, T. Thomas, and M. Rosegrant. 2012. "Incorporating Process-Based Crop Simulation Models into Global Economic Analyses." *American Journal of Agricultural Economics*, 95: 228-235.

Robinson, S., D. Mason, S. Islam, T.B. Sulser, R.D. Robertson, T. Zhu, A. Gueneau, G. Pitois, and M.W. Rosegrant. 2015. *The International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT): Model description for version 3*. IFPRI Discussion Paper 1483. Washington, DC: International Food Policy Research Institute. http://ebrary.ifpri.org/cdm/ref/collection/p15738coll2/id/129825.

Sayed, M.A. and B. Abdala. 2013. *Sudan Environmental and Climate Change Assessment*. ECCA No. 3226-SD Rome: International Fund for Agricultural Development (IFAD).

Siam, M. and E. Eltahir. 2017. "Climate change enhances interannual variability of the Nile river flow." *Nature Climate Change* 7, 350-354.

Siddig, K., S. Elagra, H. Grethe, and A. Mubarak. 2016. *A Post-Separation Social Accounting Matrix for the Sudan*. Working Paper 92. Department of Agricultural Economics, Faculty of Life Sciences. Berlin: Humboldt-Universität zu Berlin.

Taha, A., T. Thomas, and M. Waithaka. 2013. "Sudan." In *East African agriculture and climate change: A comprehensive analysis*. Edited by M. Waithaka, G.C. Nelson, T.S. Thomas, and M. Kyotalimye. Chapter 10, pp. 279-311. Washington, D.C.: International Food Policy Research Institute (IFPRI) http://ebrary.ifpri.org/cdm/ref/collection/p15738coll2/id/127933.

UN (United Nations). 2017. *World Population Prospects: The 2017 Revision*. Custom data acquired via website. New York: Department of Economic and Social Affairs, Population Division. Accessed on June 30, 2018. https://esa.un.org/unpd/wpp/DataQuery/.

USAID (United States Agency for International Development). 2016. *Climate Change Risk in Sudan: Country Fact Sheet*. Washington, DC: USAID.

WFP (World Food Program). 2017. *Food security and climate change assessment: Sudan*. Rome: WFP. Accessed on April 2, 2018. https://www.weadapt.org/placemarks/maps/view/34636.

Wiebelt, M., C. Breisinger, O. Ecker, P. Al-Riffai, R. Robertson, and R. Thiele. 2013. "Compounding food and income insecurity in Yemen: Challenges from climate change." *Food Policy*, 43: 77-89.

Wiebelt, M., P. Al-Riffai, C. Breisinger, and R. Robertson. 2015. "Who bears the costs of climate change? Evidence from Tunisia." *Journal of Developing Areas*, 49 (2): 1-21.

World Bank. 2015. Su*dan Country Economic Memorandum: Realizing the Potential for Diversified Development*. Washington, DC: World Bank.

World Bank. 2017. *World Development Indicators*. Database. Washington, DC: World Bank. http://data.worldbank.org/products/wdi.

Zhu, T. and C. Ringler. 2012. "Climate Change Impacts on Water Availability and Use in the Limpopo River Basin." *Water* 4: 63–84.

APPENDICES

Appendix Table 1: Climate change scenarios and associated General Circulation Models and RCPs

Scenario name	Global Circulation Model (GCM)	Representative Concentration Pathways (RCP)	Temperature (°C) and precipitation (%) changes	Climate moisture index	Ranking from driest (1) to wettest (6)
LocCC1/GlobCC1/CC1	HadGEM2	RCP8p5	+3.64/-6.1	0.1312	1
LocCC2/GlobCC2/CC2	NorESM1	RCP8p5	+2.16/22.1	0.1724	5
LocCC3/GlobCC3/CC3	NorESM1	RCP4p5	+1.51/20.8	0.1714	3
LocCC4/GlobCC4/CC4	GFDL	RCP4p5	+1.43/2.5	0.1453	2
LocCC5/GlobCC5/CC5	MIROC	RCP8p5	+2.72/41.1	0.1986	6
LocCC6/GlobCC6/CC6	MIROC	RCP4p5	+2.04/21.4	0.1716	4
CC1	HadGEM2	RCP8p5	+3.64/-6.1	0.1312	1
VarCC1	HadGEM2	RCP8p5	+3.64/-6.1	0.1312	1
CropProd	HadGEM2	RCP8p5	+3.64/-6.1	0.1312	1

Source: Authors' compilation.

Notes: Climate moisture index is defined as the ratio of annual precipitation to annual potential evapotranspiration.

Global Circulation Model acronyms:

- HadGEM2-A: Hadley Global Environment Model 2 – Atmosphere
- NorESM: Norwegian Climate Center's Earth System Model
- GFDL: Geophysical Fluid Dynamics Laboratory's model
- MIROC: Model for Interdisciplinary Research on Climate

Appendix Table 2: Accumulated yield changes in the Sudan between 2013 and 2050, absolute change and deviation from no climate change scenario (NoCC), percent

	NoCC	CC1	ΔCC1	CC2	ΔCC2	CC3	ΔCC3	CC4	ΔCC4	CC5	ΔCC5	CC6	ΔCC6
Cotton – irrigated	48.8	50.3	1.5	73.2	24.5	80.8	32.1	78.2	29.4	70.4	21.6	76.6	27.8
Cotton – mechanized rainfed	33.8	23.2	-10.5	61.6	27.9	64.9	31.2	48.6	14.9	64.1	30.4	65.0	31.2
Sorghum – irrigated	87.7	144.0	56.4	151.7	64.0	163.5	75.9	155.5	67.8	156.0	68.3	160.3	72.6
Sorghum – mechanized rainfed	18.8	4.5	-14.3	19.2	0.3	25.4	6.6	16.3	-2.5	20.5	1.7	23.6	4.8
Sorghum – traditional rainfed	18.8	4.5	-14.3	19.2	0.3	25.4	6.6	16.3	-2.5	20.5	1.7	23.6	4.8
Wheat – irrigated	46.4	36.0	-10.4	60.4	14.1	76.6	30.3	75.6	29.3	61.6	15.2	70.7	24.3
Wheat – traditional rainfed	46.4	36.0	-10.4	60.4	14.1	76.6	30.3	75.6	29.3	61.6	15.2	70.7	24.3
Maize – irrigated	32.3	-29.5	-61.8	20.7	-11.7	32.2	-0.2	1.3	-31.1	11.2	-21.2	25.4	-7.0
Maize – traditional rainfed	32.5	-27.0	-59.5	31.4	-1.1	51.4	18.9	22.8	-9.7	48.7	16.2	48.2	15.7
Groundnut – irrigated	40.6	39.8	-0.8	56.4	15.8	65.3	24.7	61.5	21.0	57.7	17.2	61.9	21.3
Groundnut – traditional rainfed	14.3	-10.2	-24.5	25.4	11.1	26.1	11.8	10.3	-4.1	24.7	10.4	26.2	11.9
Millet – irrigated	42.1	55.0	12.9	68.1	26.0	77.7	35.6	64.5	22.4	83.0	40.9	74.4	32.3
Millet – mechanized rainfed	44.2	58.1	13.9	88.7	44.5	94.5	50.4	75.0	30.8	110.1	65.9	96.9	52.7
Millet – traditional rainfed	44.2	58.1	13.9	88.7	44.5	94.5	50.4	75.0	30.8	110.1	65.9	96.9	52.7
Sesame – irrigated	40.6	39.8	-0.8	56.4	15.8	65.3	24.7	61.5	21.0	57.7	17.2	61.9	21.3
Sesame – mechanized rainfed	14.3	-10.2	-24.5	25.4	11.1	26.1	11.8	10.3	-4.1	24.7	10.4	26.2	11.9
Sesame – traditional rainfed	14.3	-10.2	-24.5	25.4	11.1	26.1	11.8	10.3	-4.1	24.7	10.4	26.2	11.9
Sugar – irrigated	31.4	14.4	-17.0	36.6	5.2	44.3	12.9	30.7	-0.8	34.5	3.1	40.8	9.4
Fruit – irrigated	39.3	33.6	-5.7	57.6	18.2	62.3	23.0	60.5	21.1	52.6	13.3	58.5	19.2
Fruit – traditional rainfed	39.3	33.6	-5.7	57.6	18.2	62.3	23.0	60.5	21.1	52.6	13.3	58.5	19.2
Vegetables – irrigated	58.7	73.7	15.0	119.4	60.7	119.5	60.7	98.9	40.2	131.4	72.7	124.8	66.0
Vegetables – traditional rainfed	58.7	73.7	15.0	119.4	60.7	119.5	60.7	98.9	40.2	131.4	72.7	124.8	66.0
Egyptian bean – irrigated	45.4	68.5	23.1	78.5	33.1	80.0	34.6	78.3	32.9	76.9	31.5	78.2	32.8
Sunflower – irrigated	18.8	-5.2	-24.1	37.2	18.4	37.7	18.9	19.6	0.8	47.0	28.1	41.9	23.1
Sunflower – mechanized rainfed	18.8	-5.2	-24.1	37.2	18.4	37.7	18.9	19.6	0.8	47.0	28.1	41.9	23.1
Other crops	21.8	13.1	-8.7	48.1	26.2	56.2	34.4	31.0	9.2	73.2	51.4	61.6	39.8

Source: IMPACT results.

Appendix Table 3: Accumulated world market price changes between 2013 and 2050, absolute change and deviation from no climate change scenario (NoCC), percent

	NoCC	CC1	ΔCC1	CC2	ΔCC2	CC3	ΔCC3	CC4	ΔCC4	CC5	ΔCC5	CC6	ΔCC6
Cotton	22.3	51.4	29.1	30.2	7.9	26.5	4.2	28.7	6.4	45.5	23.2	33.7	11.4
Sorghum	6.0	29.0	23.0	14.1	8.1	10.4	4.4	14.4	8.4	20.3	14.3	13.8	7.8
Wheat	19.3	43.3	24.0	21.0	1.7	18.4	-0.9	16.8	-2.5	32.7	13.4	24.2	4.9
Maize	33.3	97.5	64.2	64.9	31.6	55.9	22.5	44.1	10.8	91.1	57.7	70.1	36.8
Groundnut	7.7	58.2	50.5	29.0	21.3	18.5	10.8	20.8	13.1	40.4	32.7	25.9	18.2
Millet	13.1	40.1	27.0	21.8	8.7	8.2	-4.9	17.6	4.5	5.5	-7.6	5.7	-7.4
Sesame	7.7	58.2	50.5	29.0	21.3	18.5	10.8	20.8	13.1	40.4	32.7	25.9	18.2
Sugar	28.5	39.1	10.6	31.4	2.8	31.0	2.4	33.1	4.5	38.3	9.7	32.8	4.3
Fruit	19.7	47.4	27.8	30.9	11.3	25.8	6.1	28.6	9.0	43.2	23.6	32.1	12.4
Vegetables	38.2	56.7	18.5	43.0	4.8	39.1	1.0	41.2	3.1	56.0	17.8	45.7	7.6
Egyptian bean	11.3	29.6	18.3	18.2	7.0	15.8	4.6	15.1	3.8	25.9	14.6	17.5	6.3
Sunflower	3.3	14.5	11.2	0.7	-2.6	-3.3	-6.6	-6.3	-9.6	9.6	6.3	2.7	-0.6
Other crops	5.0	8.7	3.7	-1.2	-6.2	-2.5	-7.5	4.4	-0.6	5.4	0.4	1.4	-3.6

Source: Results from IMPACT.

Appendix Table 4: Accumulated and average annual change in yields between 2013 and 2050 under the baseline, variability, and policy intervention scenarios, percent

	NoCC	VarCC1	ΔVarCC1	CropProd	ΔCropProd
Cotton – irrigated	48.8	-35.3	-84.1	0.7	-48.1
Cotton – mechanized rainfed	33.8	-62.4	-96.1	24.6	-9.1
Sorghum – irrigated	87.7	5.2	-82.5	41.2	-46.5
Sorghum – mechanized rainfed	18.8	-151.1	-169.9	-64.1	-82.9
Sorghum – traditional rainfed	18.8	-151.1	-169.9	-64.1	-82.9
Wheat – irrigated	46.4	-101.5	-147.9	-65.5	-111.9
Wheat – traditional rainfed	46.4	-101.5	-147.9	-14.5	-60.9
Maize – irrigated	32.3	-177.9	-210.2	-141.9	-174.2
Maize – traditional rainfed	32.5	-182.6	-215.1	-95.6	-128.1
Groundnut – irrigated	40.6	-57.0	-97.6	-21.0	-61.6
Groundnut – traditional rainfed	14.3	-184.8	-199.1	-97.8	-112.1
Millet – irrigated	42.1	-93.4	-135.5	-57.4	-99.5
Millet – mechanized rainfed	44.2	-90.4	-134.5	-3.4	-47.5
Millet – traditional rainfed	44.2	-90.4	-134.5	-3.4	-47.5
Sesame – irrigated	40.6	-69.0	-109.6	-33.0	-73.6
Sesame – mechanized rainfed	14.3	-119.0	-133.3	-32.0	-46.3
Sesame – traditional rainfed	14.3	-119.0	-133.3	-32.0	-46.3
Sugar – irrigated	31.4	-71.1	-102.6	-35.1	-66.6
Fruit – irrigated	39.3	33.6	-5.7	33.6	-5.7
Fruit – traditional rainfed	39.3	33.6	-5.7	33.6	-5.7
Vegetables – irrigated	58.7	73.7	15.0	73.7	15.0
Vegetables – traditional rainfed	58.7	73.7	15.0	73.7	15.0
Egyptian bean – irrigated	45.4	68.5	23.1	104.5	59.1
Sunflower – irrigated	18.8	-5.2	-24.1	30.8	11.9
Sunflower – mechanized rainfed	18.8	-5.2	-24.1	81.8	62.9
Other crops	21.8	13.1	-8.7	100.1	78.3

Source: Results from IMPACT and Authors' compilation.

Appendix Table 5: Average annual change between 2013 and 2050 of producer prices under selected climate change scenarios, percent

	No CC	GlobCC1	LocCC1	CC1	VarCC1	CropProd
Cotton	-0.263	-0.501	-0.215	-0.371	0.019	-0.513
Sorghum	-0.455	-0.676	-0.959	-1.236	0.823	0.273
Wheat	-0.167	-0.235	0.003	-0.044	2.770	2.184
Maize	-0.373	-0.365	0.946	0.999	1.539	1.913
Groundnut	0.030	0.053	0.056	0.079	1.200	1.314
Millet	-0.304	-0.841	-0.301	-0.794	0.309	-0.570
Sesame	0.041	-0.015	0.055	0.007	1.383	1.635
Sugar	0.178	0.215	0.553	0.605	2.514	1.845
Fruit	-0.345	-0.757	-0.225	-0.629	-0.508	-0.785
Vegetables	-0.551	-0.680	-0.742	-0.885	-1.066	-1.054
Egyptian bean	-0.316	-0.895	-0.280	-0.797	-0.633	-0.949
Sunflower	0.026	-0.283	0.303	0.080	-0.029	-0.967
Other crops	-0.344	-0.285	-0.137	-0.074	-0.497	-2.280

Source: Results of Sudan CGE model.

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