Chapter 10

SUDAN

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Sudan is a country of fragile ecosystems, frequent droughts, and, as a result, pressing challenges to address the national priorities of food security, water supply, and public health. An examination of Sudan's ecological zones indicates that the majority of its land is quite vulnerable to changes in temperature and precipitation. More than half the country can be classified as desert or semidesert, with another quarter arid savanna. The country's inherent vulnerability is evident in the fact that food security in Sudan is mainly determined by rainfall, particularly in rural areas, where 70 percent of the population lives (Republic of the Sudan, MEPD 2003).

Sudan lies in the tropical zone, between latitudes 3° and 22°N and longitudes 22° and 38°E. Mean annual temperatures vary between 26° and 32°C across the country. Rainfall, which supports the overwhelming majority of the country's agricultural activity, is erratic and varies significantly from the northern to the southern regions of the country. Overall, the country's land and water resources can be classified into four major ecological regions:

1. Arid and semiarid ecosystems, which occur in the northern and central parts of the country and represent over 50 percent of total area with about 125 million hectares. Summer temperatures can often exceed 43°C, and sandstorms blow across the Sahara from April to September, with rainfall averaging about 200 millimeters per year and rarely exceeding 700 millimeters per year.

2. Savanna ecosystems (clay), which are typified by low rainfall and the prevalence of clay soils and represent about 5 percent of total area, with about 12 million hectares.

3. Savanna ecosystems (sand), which are typified by low rainfall and the prevalence of sandy soils. They represent about 3 percent of the country's total area, with about 8 million hectares.

This chapter was written prior to the independence of South Sudan, and it covers both the north and the south.

4. Southern flood-prone ecosystems, which are located below latitude 10°N and represent about 3 percent of the total area, with about 8.5 million hectares. Their climatic conditions are more equatorial, with an average annual temperature of about 29°C and average annual rainfall greater than 1,000 millimeters per year.

Traditional subsistence agriculture dominates the Sudanese economy, with over 70 percent of the population dependent for their livelihoods on crop production, livestock husbandry, or both. The agricultural sector is dominated by small-scale farmers—who typically live in conditions of persistent poverty and are reliant on rainfed and traditional agricultural practices. This combination renders them highly vulnerable to climate variability, as evidenced by the widespread suffering in rural areas during past droughts. Indeed, chronic drought is one of the most important climate risks facing Sudan. Recurring series of dry years have become a normal occurrence in the Sudan–Sahel region. Drought is threatening the existing cultivation of about 12 million hectares of rainfed mechanized farming and 6.6 million hectares of traditional rainfed cropland (Balgis-Osman et al. 2005). Pastoral and nomadic groups in the semiarid areas of Sudan are also affected. Poverty is deeply entrenched in rural areas, where more than 20 million people live on less than $1 a day. Sudan's diverse agroecological zones and abundant surface water offer the potential to produce a range of crops as well as livestock. Yet production consistently remains quite low, due in large part to an agricultural system that is not well adapted to rainfall variability and prolonged drought events.

Sudan also faces numerous other development challenges. For example, land degradation and desertification brought on by human land-use pressures and recurrent drought affect large areas and threaten already vulnerable arable zones. Depletion of forests—primarily for household fuel consumption—threatens biological diversity and human communities and reduces the other valuable products and services that forests provide.

The process involved in developing Sudan's National Adaptation Programme of Action (NAPA) examined each of these ecosystems as distinct zones, each meriting its own locally driven assessment of priority interventions to address looming climate risks. In arid and semiarid zones, frequent droughts exacerbate declining soil fertility, low agricultural productivity, and persistent food insecurity. Frequent droughts also afflict savanna areas, where they compound the problems of overgrazing, soil erosion, and outbreaks of public health epidemics such as malaria. In southern areas, chronic flooding and frequent malaria outbreaks impose great strains on communities and infrastructure, newly emerging from decades of civil strife.

A trend of decreasing annual rainfall is contributing to drought conditions in many parts of Sudan. Moreover, the coefficient of variability of rainfall shows an overall increasing trend, suggesting greater rainfall unreliability. The variability in rainfall is most serious in the arid northern parts of the country, where the average variability now exceeds 100 percent (Zaki-Eldeen 2009). The situation is less serious in the central parts of the country, where average rainfall variability ranges from 20 to 60 percent, and in the south, where it varies between 15 and 20 percent. At the national level, however, there is a trend toward greater rainfall variability, increasing at a rate of about 0.2 percent per year (FAO 2011). These rainfall patterns are associated with serious drought episodes throughout the country—even in the south. The hardest-hit areas are in the western and northern regions, in the semiarid portions of the Nile basin. A succession of dry years from 1978 to 1987 resulted in severe social and economic impacts, including many human and livestock fatalities; nearly 3 million people living along the Nile and in urban areas had to be resettled. Problems will increase if these trends continue without efforts to adapt.

Sudan has been actively seeking to mainstream adaptation to climate change in its development process by including climate and vulnerability in the sectoral and development policies that complement the climate change and environmental policies embodied in the 10-year Comprehensive National Strategy (1992–2002) and the 25-year Comprehensive National Strategy Outlines. Many ongoing national policy processes have aims parallel to climate change adaptation, such as the poverty reduction strategy (2004–2008), the malaria roll-back program, and water harvesting.

In an attempt to address climate change and related issues, Sudan has already completed several activities. It ratified the United Nations Framework Convention on Climate Change (UNFCCC) in 2003 and submitted its initial national communication the same year. The Higher Council for Environment and Natural Resources (HCENR), the government's national focal point for the UNFCCC, plays an advisory policymaking role with regard to climate-related initiatives. The HCENR is also the national executing agency for Sudan's NAPA, completed in 2007, which focuses on major climate impacts and vulnerabilities in five regions representing the different ecological settings across the country.

This chapter is meant to further the understanding of policymakers concerning the potential impact of climate change on agriculture in Sudan, along with various adaptation options. The chapter begins with a review of some national statistics that will help characterize the capacity of the population to adapt to climate change. We also look at Sudan's land base and current agricultural situation. After this we show the results of crop models that incorporate climate projections from recent global models. Finally, we incorporate those results into a global model for food and agricultural supply and demand that takes into account demographic and economic projections for Sudan.

Review of the Current Situation and Trends

Economic and Demographic Indicators

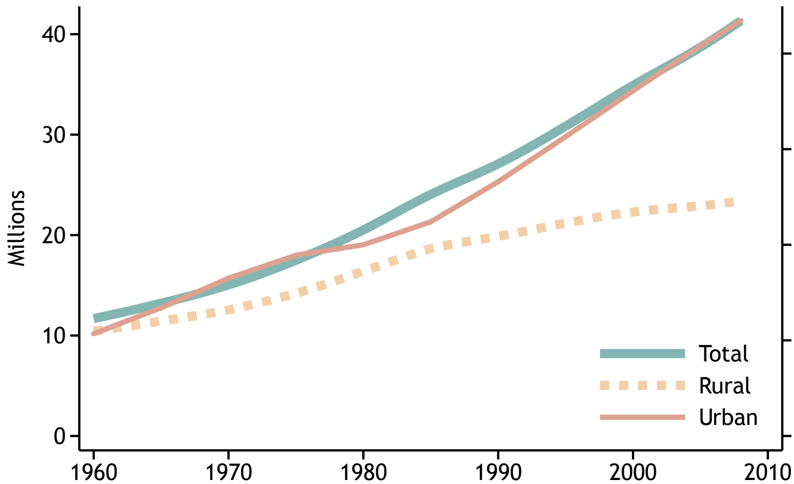
Population

Figure 10.1 shows the total and rural population of Sudan (left axis) as well as the share of the population that is urban (right axis). Figure 10.2 shows the geographic distribution of the population within Sudan. Both are estimates based on census data and other sources. Table 10.1 provides additional information concerning rates of population growth.

As Figure 10.1 shows, the population of Sudan was estimated at just over 41 million in 2008. Assessments of annual population growth rates vary from around 2.1 to 2.6 percent, placing Sudan's rate of population growth among the highest in the world (Republic of the Sudan, MEPD 2007). Its overall population density is about 10 people per square kilometer, but the density on arable land is considerably higher, at 63 people per square kilometer—and higher still on cultivated land, with about 370 people per square kilometer. Much of the population is clustered in central Sudan and along the Nile River (Republic of Sudan, MEPD 2007). Though annual rates of growth are projected to fall by 2050, the population is still projected to double over that period. Meanwhile, the proportion of urban residents is projected to increase from around 40.0 percent in 2005 to 60.7 percent by 2030, suggesting that almost all (94 percent) of the country's population growth will be accounted for by urban areas during this period. Historically, the population of Sudan has been highly mobile. On average, 40 percent of the population is believed to be on the move every year, especially in the semiarid regions of western Sudan. There are different systems of migration, but currently rural-to-urban is the most common pattern.

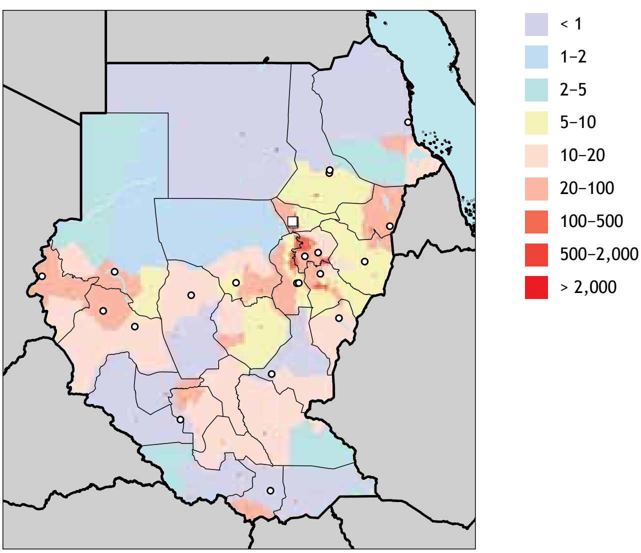
Climate variability, directly and indirectly, is a key driver of displacement and forced migration. There are an estimated 6 million internally displaced

FIGURE 10.1 Population trends in Sudan: Total population, rural population, and percent urban, 1960–2008



Source: *World Development Indicators* (World Bank 2009).

FIGURE 10.2 Population distribution in Sudan, 2000 (persons per square kilometer)



Source: CIESIN et al. (2004).

TABLE 10.1 Population growth rates in Sudan, 1960–2008 (percent)

Decade	Total growth rate	Rural growth rate	Urban growth rate
1960–1969	2.5	1.8	6.9
1970–1979	3.1	2.6	5.1
1980–1989	2.8	2.0	5.6
1990–1999	2.6	1.2	5.7
2000–2008	2.1	0.6	4.4

Source: Authors' calculations based on *World Development Indicators* (World Bank 2009).

persons in Sudan; they are displaced largely by drought, desertification, and famine in the north and by conflict, famine, and flood-induced epidemics in the south. The hardest-hit areas over the past three decades have been the western and northern regions in the semiarid portions of the Nile basin. A succession of dry years from 1978 to 1987, for example, resulted in the resettlement of almost 3 million people along the Nile Valley and urban peripheries, particularly Khartoum. Climate change is believed to be among the key factors contributing to the Darfur conflict (UNEP 2007).

Another factor is economic: uneven patterns of growth have resulted in great disparities between urban and rural areas and between regions. This has contributed to growing inequalities and an increasing urban informal sector, accounting for more than 60 percent of gross domestic product (GDP) (UNDP 2008).

Vulnerability to Climate Change

Table 10.2 provides some data on indicators of the population's vulnerability and resiliency to economic shocks: levels of education, literacy, and malnutrition and concentration of labor in poorer or less dynamic sectors.

The country is characterized by a moderately educated population, as is evidenced by the 61 percent literacy rate shown in Table 10.2. The level of primary school enrollment is relatively high due to the country's policy of free education for all children 6–13 years of age. The low level of secondary school education is due to the fact that males are required to enroll in military service before completing school (Library of Congress Federal Research Division 2004). Regional disparities exist, with most schools located in the prosperous north and urban centers, leaving the south and rural areas lagging behind in learning. Furthermore, girls' education levels fall behind those of boys. For example, at the primary school level there are 80 girls for every

TABLE 10.2 Education and labor statistics for Sudan, 2000s

Indicator	Year	Percent
Primary school enrollment: Percent gross (three-year average)	2007 2009[a]	66.4 71.0
Secondary school enrollment: Percent gross (three-year average)	2007	33.4
Adult literacy rate	2000	60.9
Percent with vulnerable employment (in agriculture on own farm or as a day laborer)	2009[b]	20.0
Under-five malnutrition (weight for age)	2000	38.4

Source: *World Development Indicators* (World Bank 2009).
[a]See also Republic of Sudan, Ministry of Welfare and Social Security, NPC/GS (2010).
[b]See also Republic of Sudan, CBS (2010).

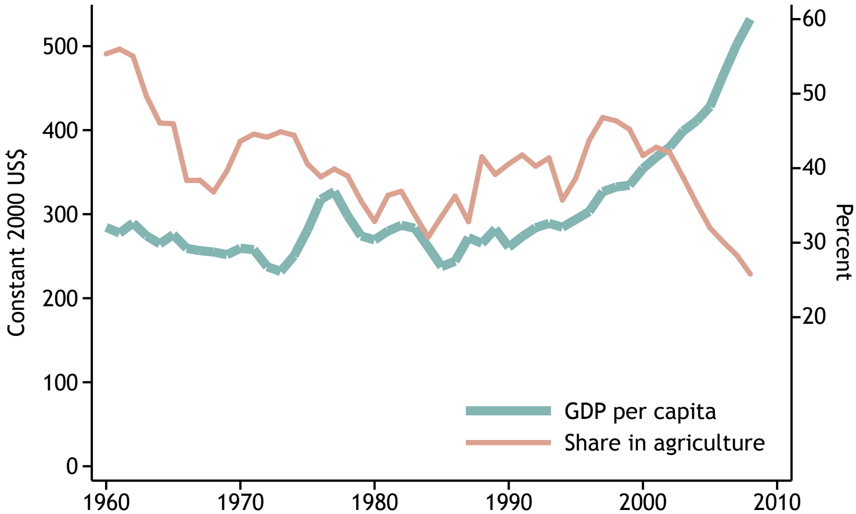
100 boys. Enrollment rates for girls are worse among those internally displaced by conflict and nomads. In spite of these challenges, the country has recorded improvements in the sector. The gross enrollment rate in basic education increased in northern Sudan from 65 percent in 2004 to 71 percent in 2009. The literacy rate for people between 15 and 24 years of age increased from 27.0 percent in 1990 to 69.0 percent in 2009 and to 72.5 percent in 2010 (UNDP 2011). The current education levels form a foundation for climate change advocacy through learning and will prove critical to the effectiveness of various mitigation strategies.

The level of child malnutrition in Sudan remains very serious. The recent UN Millennium Development Goals progress report for Sudan (UNDP 2011) assesses the nutrition situation in the country as characterized by high levels of underweight, chronic malnutrition, and acute malnutrition. Nationally, 31 percent of children under the age of five are moderately or severely underweight (UNDP 2011). An equal proportion (32.5 percent) suffers from moderate or severe chronic malnutrition. The proportions vary significantly between states. This points to the extreme low levels of caloric availability, which are not surprising given that the country has just recently emerged from civil wars that are associated with reduced agricultural productivity and incomes. The implication is that the population will have a low rate of productivity and be highly vulnerable to extreme events of climate change, which affects agricultural productivity and reduces food reserves.

Income

Over the decade 1999–2008, Sudan's economy witnessed its longest and strongest growth episode, driven by the discovery of oil in 1999 (Figure 10.3).

FIGURE 10.3 Per capita GDP in Sudan (constant 2000 US$) and share of GDP from agriculture (percent), 1960–2008



Source: *World Development Indicators* (World Bank 2009).
Note: GDP = gross domestic product; US$ = US dollars.

The size of its economy, measured by gross national product, has grown fivefold—from $10 billion in 1999 to $53 billion in 2008. Per capita income, a rough measure of the living standard of average citizens, increased from $348 to $532 over the same period. In contrast, before oil was discovered, per capita income hardly changed over four decades, remaining within the $200–$300 range.

However, growth has not been sufficiently broad based, and there are significant disparities between urban and rural areas as well as between regions. This contributes to growing inequalities and an increasing urban informal sector, currently accounting for more than 60 percent of GDP. This state of affairs has been encouraging a rural–urban migration that might weaken agricultural productivity and deepen poverty in both urban and rural areas. The agricultural sector has performed poorly in the past decade. Although it remains an important sector, its share of GDP in the economy has declined, the rate of growth of rural incomes has decreased, and the level of poverty in rural areas remains high. The average annual growth rate of the agricultural sector between 2000 and 2008 was 3.6 percent, substantially lower than the 10.8 percent during the previous decade (FAO 2011).

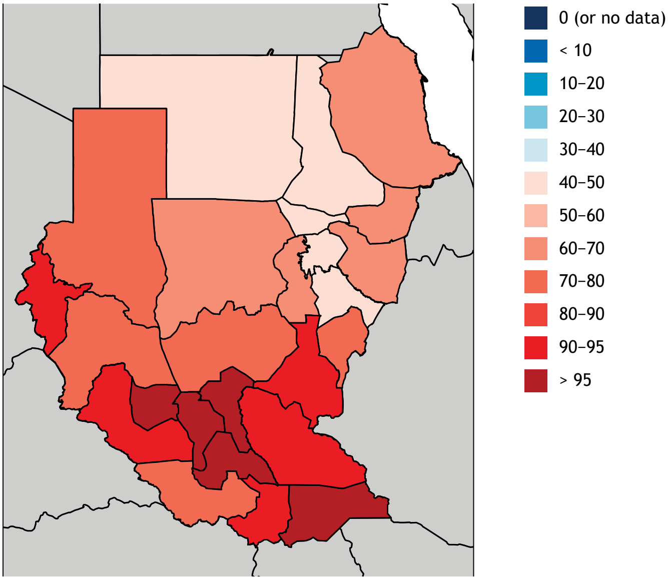
Poverty

A country's vulnerability and resiliency to economic shocks can be assessed from the status of its progress toward the United Nations Millennium Development Goals (MDGs). Sudan has made progress toward achieving the MDGs in the areas of education, infant and child mortality, and access to water and sanitation (UNDP 2011). However, poverty remains widespread throughout the country. In southern Sudan, approximately half of the population (50.6 percent) is below the official poverty line. The poverty headcount ratio in rural areas (55.4 percent) is more than double the ratio in urban areas (24.4 percent). Poverty rates vary significantly between states: three out of four people are poor in Northern Bahr el Ghazal state (75.6 percent), but only one in four people in Upper Nile state is poor (25.7 percent). In the northern states, the level of food deprivation varies significantly, with 44 percent in the Red Sea region and 15 percent in the Gezira and River Nile region. At the household level, the rate of food deprivation is higher in female-headed households (37 percent) than in male-headed households (31 percent), reflecting that males have more access to education and income. The rate of food deprivation also differs according to household size, ranging from 5 percent in households of one or two members to 49 percent in households with more than nine members (Faki et al. 2009; IFAD 2011).

Figure 10.4 shows the human poverty map of Sudan using the human poverty index (HPI) as a measure of poverty in different states. The HPI, as a composite measure of human development, combines three observable and measurable dimensions of human well-being or deprivation: the ability to live long (longevity), the ability to acquire knowledge (knowledge ability), and the ability to live comfortably (decent standard of living). See http://hdr.undp.org/en/statistics/indices/hpi/.

The nutrition situation in Sudan is poor, characterized by high levels of underweight, chronic malnutrition, and acute malnutrition. Nationally, one-third (31 percent) of children under the age of five are moderately or severely underweight, and a similar number (32.5 percent) suffer from moderate or severe chronic malnutrition (Republic of Sudan, Ministry of Welfare and Social Security, NPC/GS 2010). In fact, the national level of acute malnutrition is just below the internationally recognized standard indicating a nutrition emergency. These figures, too, vary significantly between states. Figure 10.5 nevertheless shows a gradual improvement in two noneconomic correlates of poverty—life expectancy and under-five mortality.

FIGURE 10.4 Poverty in Sudan, circa 2005 (percentage of population below US$2 per day)



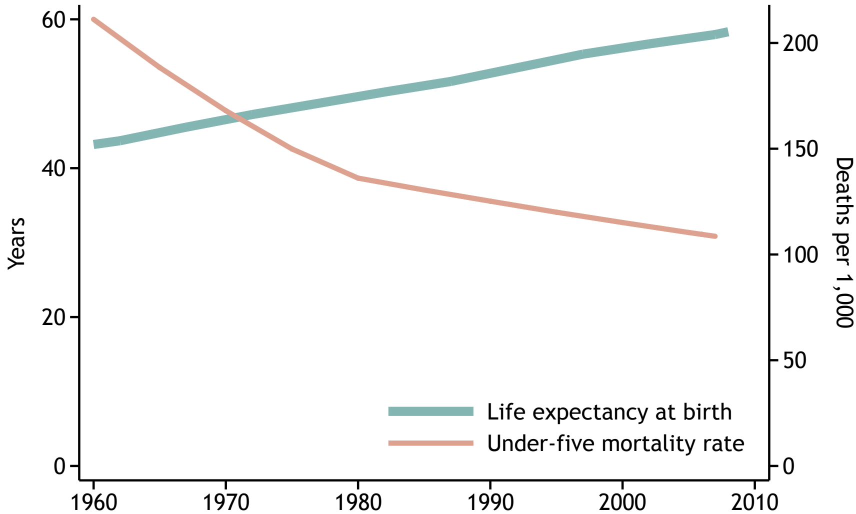
Source: Wood et al. (2010).
Note: Based on 2005 US$ (US dollars) and on purchasing power parity value.

Review of Land Use, Potential, and Limitations

Arable land (around 84 million hectares) constitutes about one-third of the total land area of Sudan, but only 21 percent of its arable land is cultivated (Metz 1991; FAO 2010). More than 40 percent of the total area of Sudan consists of pasture and forests (FAO 2010). Nearly all livestock are grazed on natural pasture. The annual production of animal feed is estimated at 78 million tons; production fluctuates from year to year, affected by varying rainfall and fire hazards. Forests and woodlands are used to meet the population's demand for wood products and are exposed to pressure from both agricultural expansion and demand for firewood.

Agriculture is the backbone of Sudan's economy. It is characterized by three major production systems: irrigated, rainfed semimechanized, and rainfed traditional agriculture. These farming systems are used for both crop and livestock production. Forestry is also an important subsector. Traditional

FIGURE 10.5 Well-being indicators in Sudan, 1960–2008



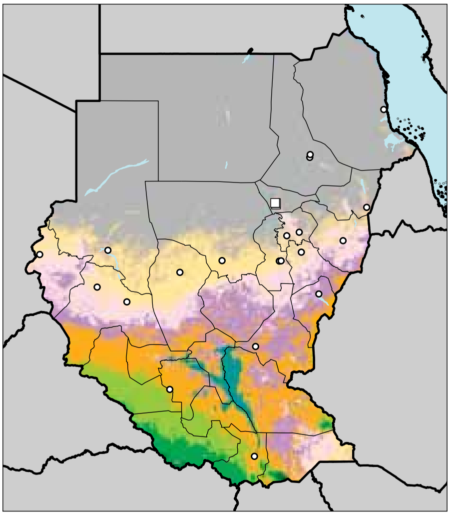
Source: *World Development Indicators* (World Bank 2009).

subsistence agriculture is a common practice of more than 70 percent of the population who depend on it for their livelihoods. Small-scale farmers dominate the sector and typically live in persistent poverty, which renders them vulnerable to climate variability, as evidenced by the widespread suffering in rural areas during past droughts.

Figure 10.7 shows the locations of protected areas, including parks and reserves. These locations provide important protection for fragile environmental areas, which may also be important for tourism. Sudan has about 27 protected areas, amounting to more than 7 percent of the country's total area. There are 3,246 reserved forests (not reflected in the current map), with a total area of 12.3 million hectares.

Figure 10.8 shows travel times to urban areas. There has been a notable improvement in the road network, which was expanded from 3,358 kilometers in 2000 to 6,211 kilometers in 2008. Most of this expansion is in irrigated areas of the central and northern parts of the country, connecting big cities to rural areas, without extending to the vast rainfed production areas. The rural feeder roads are very poor, resulting in high transport costs, a small share of

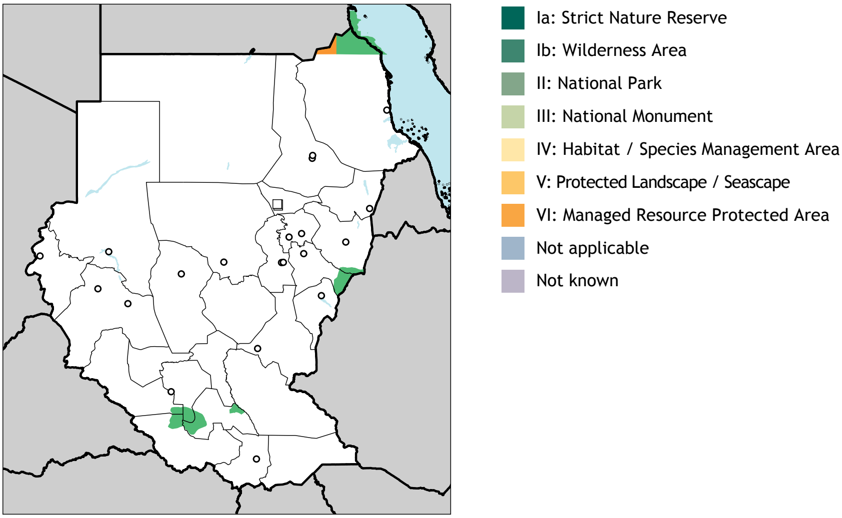
FIGURE 10.6 Land cover and land use in Sudan, 2000



- Tree cover, broadleaved, evergreen
- Tree cover, broadleaved, deciduous, closed
- Tree cover, broadleaved, open
- Tree cover, broadleaved, needle-leaved, evergreen
- Tree cover, broadleaved, needle-leaved, deciduous
- Tree cover, broadleaved, mixed leaf type
- Tree cover, broadleaved, regularly flooded, fresh water
- Tree cover, broadleaved, regularly flooded, saline water
- Mosaic of tree cover/other natural vegetation
- Tree cover, burnt
- Shrub cover, closed-open, evergreen
- Shrub cover, closed-open, deciduous
- Herbaceous cover, closed-open
- Sparse herbaceous or sparse shrub cover
- Regularly flooded shrub or herbaceous cover
- Cultivated and managed areas
- Mosaic of cropland/tree cover/other natural vegetation
- Mosaic of cropland/shrub/grass cover
- Bare areas
- Water bodies
- Snow and ice
- Artificial surfaces and associated areas
- No data

Source: GLC2000 (Bartholome and Belward 2005).

FIGURE 10.7 Protected areas in Sudan, 2009



Sources: Protected areas are from the World Database on Protected Areas (UNEP and IUCN 2009). Water bodies are from the World Wildlife Fund's Global Lakes and Wetlands Database (Lehner and Döll 2004).

product sales revenues for farmers, high input prices, and ultimately low incentives to producers.

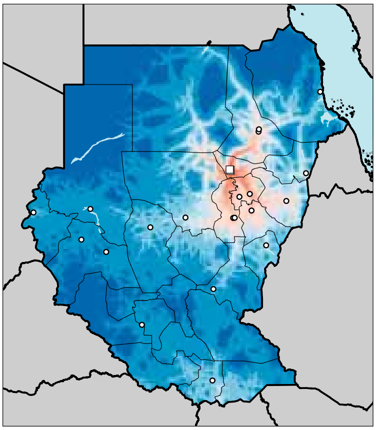
Figures 10.9–10.11 show the estimated yield and growing areas for key cereal crops—sorghum, millet, and wheat. Sorghum is the main staple foodgrain in Sudan; it is produced under all production systems and occupies the largest cultivated area, at around 50 percent of field crop area (Table 10.3).

Sesame seeds and groundnuts are the main oil crops in terms of area and value of production as well as export earnings (Tables 10.3–10.5). In cultivated areas, the two oilseed crops are among the top five crops, at 12 percent and 6 percent for sesame and groundnuts, respectively.

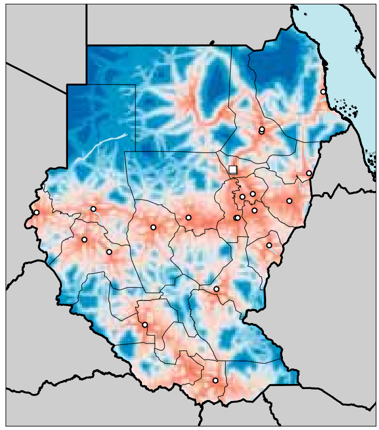
Wheat is one of the main foodgrains; demand is increasing in urban areas due to changes in consumption patterns (see Table 10.5). Consumption has increased from less than 500,000 tons in the 1970s to around 2 million tons in 2009.

Millet is also an important foodcrop, particularly in western Sudan. It is second to sorghum in cultivated area, occupying more than 18 percent of the total area of field crops (see Table 10.3). It is produced under both traditional and mechanized rainfed systems, predominantly on small farms.

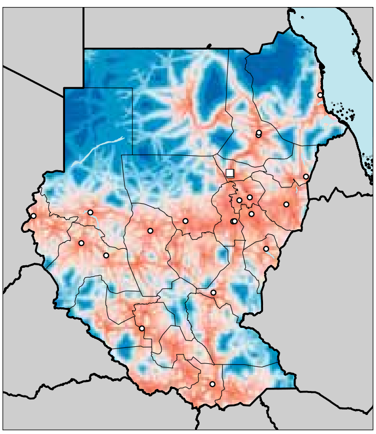
FIGURE 10.8 Travel time to urban areas of various sizes in Sudan, circa 2000



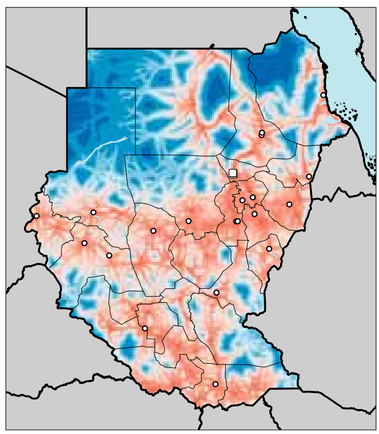
To cities of 500,000 or more people



To cities of 100,000 or more people



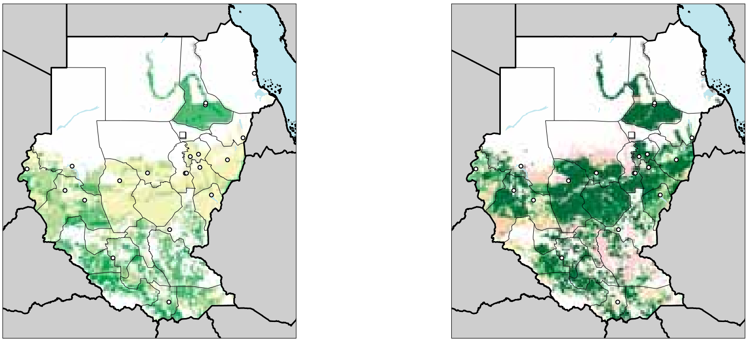
To towns and cities of 25,000 or more people



To towns and cities of 10,000 or more people

Source: Authors' calculations.

FIGURE 10.9 Yield (metric tons per hectare) and harvest area density (hectares) for rainfed sorghum in Sudan, 2000

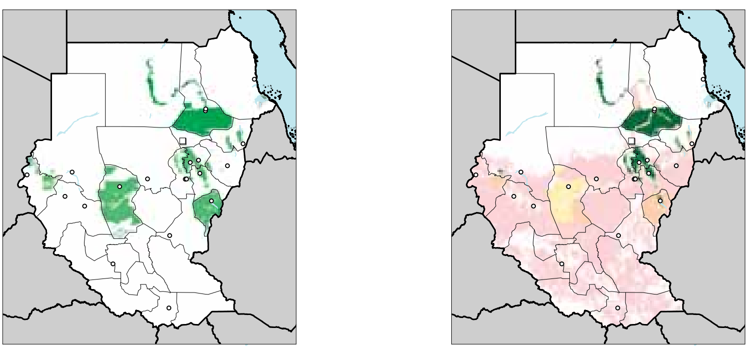


< 0.5 MT/ha
0.5–1 MT/ha
1–2 MT/ha
2–4 MT/ha
> 4 MT/ha

< 1 ha
1–10 ha
10–30 ha
30–100 ha
> 100 ha

Source: SPAM (Spatial Production Allocation Model) (You and Wood 2006; You, Wood, and Wood-Sichra 2006, 2009).
Note: ha = hectare; MT/ha = metric tons per hectare.

FIGURE 10.10 Yield (metric tons per hectare) and harvest area density (hectares) for irrigated wheat in Sudan, 2000

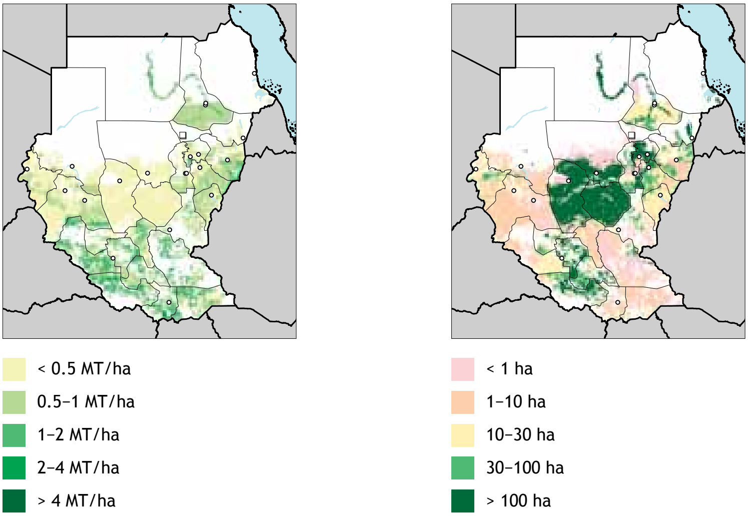


< 0.5 MT/ha
0.5–1 MT/ha
1–2 MT/ha
2–4 MT/ha
> 4 MT/ha

< 1 ha
1–10 ha
10–30 ha
30–100 ha
> 100 ha

Source: SPAM (Spatial Production Allocation Model) (You and Wood 2006; You, Wood, and Wood-Sichra 2006, 2009).
Note: ha = hectare; MT/ha = metric tons per hectare.

FIGURE 10.11 Yield (metric tons per hectare) and harvest area density (hectares) for rainfed millet in Sudan, 2000



Source: SPAM (Spatial Production Allocation Model) (You and Wood 2006; You, Wood, and Wood-Sichra 2006, 2009).
Note: ha = hectare; MT/ha = metric tons per hectare.

TABLE 10.3 Harvest area of leading agricultural commodities in Sudan, 2006–2008 (thousands of hectares)

Rank	Crop	Percent of total	Harvest area
	Total	100.0	12,561
1	Sorghum	52.1	6,543
2	Millet	18.3	2,296
3	Sesame seeds	11.7	1,470
4	Groundnuts	5.7	715
5	Wheat	2.0	253
6	Other fresh vegetables	1.9	240
7	Seed cotton	1.2	151
8	Cowpeas	0.9	110
9	Other pulses	0.7	90
10	Melon seeds	0.6	81

Source: FAOSTAT (FAO 2010).
Note: All values are based on the three-year average for 2006–2008.

TABLE 10.4 Value of production for leading agricultural commodities in Sudan, 2005–2007 (millions of constant 2000 US$)

Rank	Crop	Percent of total	Value of production
	Total	100.0	4,539.0
1	Sorghum	15.0	682.6
2	Other fresh fruit	8.8	399.8
3	Potatoes	7.0	318.5
4	Tomatoes	6.7	302.3
5	Groundnuts	5.9	269.4
6	Dates	5.9	267.7
7	Other fresh vegetables	5.8	262.0
8	Mangoes, mangosteens, and guavas	5.4	246.5
9	Sesame seeds	5.2	235.7
10	Okra	4.4	200.1

Source: FAOSTAT (FAO 2010).
Notes: All values are based on the three-year average for 2005–2007. US$ = US dollars.

TABLE 10.5 Consumption of leading food commodities in Sudan, 2003–2005 (thousands of metric tons)

Rank	Crop	Percent of total	Food consumption
	Total	100.0	10,940
1	Sorghum	23.3	2,553
2	Wheat	13.5	1,474
3	Other vegetables	8.8	959
4	Sugar	7.3	799
5	Fermented beverages	6.2	678
6	Other fruits	4.7	514
7	Tomatoes	4.4	483
8	Millet	4.3	467
9	Sugarcane	3.1	344
10	Beef	3.1	343

Source: FAOSTAT (FAO 2010).
Note: All values are based on the three-year average for 2003–2005.

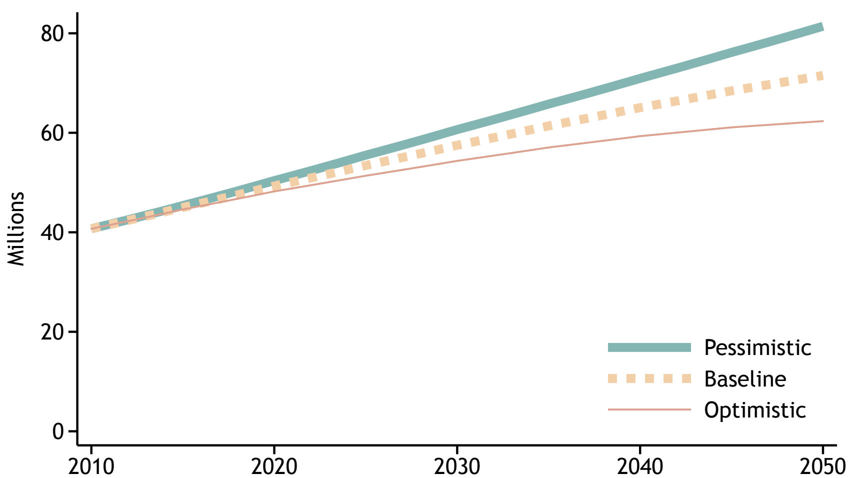
Sudan is also endowed with a wealth of livestock resources, estimated at more than 140 million cattle, sheep, goats, and camels. Various livestock production systems are used in almost all agroecological zones, predominantly rainfed. Milk and meat are the leading agricultural commodities in terms of value of production. For the period 2006–2008, cow's milk and beef accounted for 26 percent and 13 percent, respectively, of the total value of the top 20 agricultural commodities.

Scenarios for the Future

Economic and Demographic Indicators

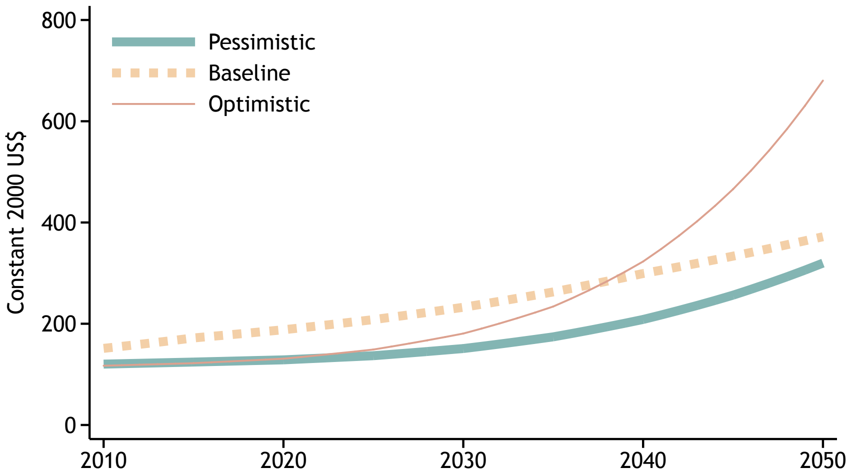
Population projections by the UN Population Division through 2050 show annual population growth rates falling below current rates but population continuing to increase (Figure 10.12). Challenges associated with such population growth include increased demand for food, intensive pressure on land and other natural resources, and a probable increase of rural–urban migration, with implications for urban water, health, and education services. In the low-variant scenario, the population increases by only 50 percent between 2010 and 2050, but in the high-variant scenario the population doubles in that time period.

FIGURE 10.12 Population projections for Sudan, 2010–2050



Source: UNPOP (2009).

FIGURE 10.13 Gross domestic product (GDP) per capita in Sudan, future scenarios, 2010–2050



Sources: Computed from GDP data from the World Bank Economic Adaptation to Climate Change project (World Bank 2010), from the Millennium Ecosystem Assessment (2005) reports, and from population data from the United Nations (UNPOP 2009).
Note: US$ = US dollars.

Projections of future per capita GDP also show an increasing trend (Figure 10.13). However, unless there is improvement in the performance of agriculture to enhance its contribution to the national GDP, the disparities between urban and rural areas and between regions will continue.

Biophysical Analysis

Climate Models

In Figure 10.14 we see the changes in annual precipitation projected by the four general circulation models (GCMs) used in our analysis with the A1B scenario.[1] Two of the models, ECHAM 5 and MIROC 3.2, generally show most of the southern part of Sudan getting wetter, a very favorable outcome, particularly for the semiarid regions. The CNRM-CM3 model shows the

1 CNRM-CM3 is National Meteorological Research Center–Climate Model 3. MIROC 3.2 is the Model for Interdisciplinary Research on Climate, developed at the University of Tokyo Center for Climate System Research. CSIRO Mark 3 is a climate model developed at the Australia Commonwealth Scientific and Industrial Research Organisation. ECHAM 5 is a fifth-generation climate model developed at the Max Planck Institute for Meteorology in Hamburg. The A1B scenario is a greenhouse gas emissions scenario that assumes fast economic growth, a population that peaks midcentury, and the development of new and efficient technologies, along with a balanced use of energy sources.

western part of Sudan getting wetter. There are a few patches of lower annual precipitation in these maps, but they are small.

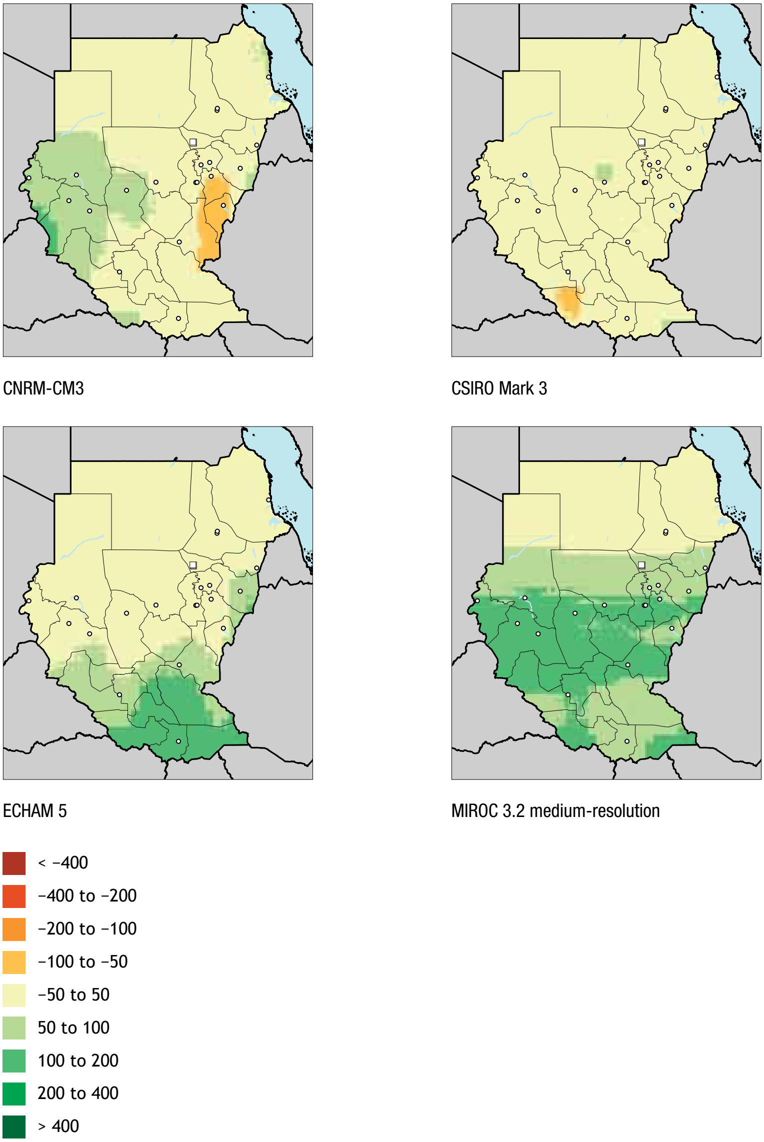
Although changes in annual precipitation are predicted to be mostly nonexistent or positive, the story for temperature change is different. All four GCMs show Sudan getting warmer, by 0.5°C to as much as 3°C for two of the models in the northern reach of the country (Figure 10.15). The ECHAM 5 model does not show increases of 3°C, but it does project increases of 2°–2.5°C in the northern three-quarters of the country. Higher temperatures would increase evaporation and reduce soil moisture, increasing plants' water requirements—an unfavorable trend, particularly if associated with a lower level of precipitation and insufficient irrigation water. The CSIRO Mark 3 model shows only moderate increases in temperature, with all but very small patches in the range of 1°–1.5°C. The MIROC 3.2 model shows only modest temperature increases in the south, unlike in the north.

Crop Models

The Decision Support Software for Agrotechnology Transfer crop simulation software was used to compute yields under the current climate and compare those to computations based on the future climate. All four models show a yield loss of 5–25 percent of baseline (2000 climate) over most of the country's sorghum harvest area (Figure 10.16). In the marginal cultivated areas of the semidry zone, three of the four models show some loss of the baseline area. These results would have serious implications for Sudan's food security, because sorghum is the main staple cereal grain supporting the rural population. Those same three models show some limited gain in baseline area that could potentially offset part of the loss in yield in most of the rest of the cropped land. The CNRM-CM3 GCM is different from the other three in that it predicts an increase in cultivable area and large yield declines (greater than 25 percent) in much of the eastern portion of the country.

For wheat (Figure 10.17), all four models show negative impacts, ranging from a complete loss of the baseline area to a yield loss of between 5 percent and more than 25 percent of baseline. The areas most affected will be central Sudan (in the area of the Gezira Scheme irrigation project and along the White and Blue Niles) and part of the River Nile state. Although these areas, particularly central Sudan, produce 75 percent of the country's wheat, they are considered marginal areas for wheat production, with the current temperatures relatively warm for wheat growing. The research challenge will be to develop appropriate wheat production technologies that will mitigate the effects of climate change.

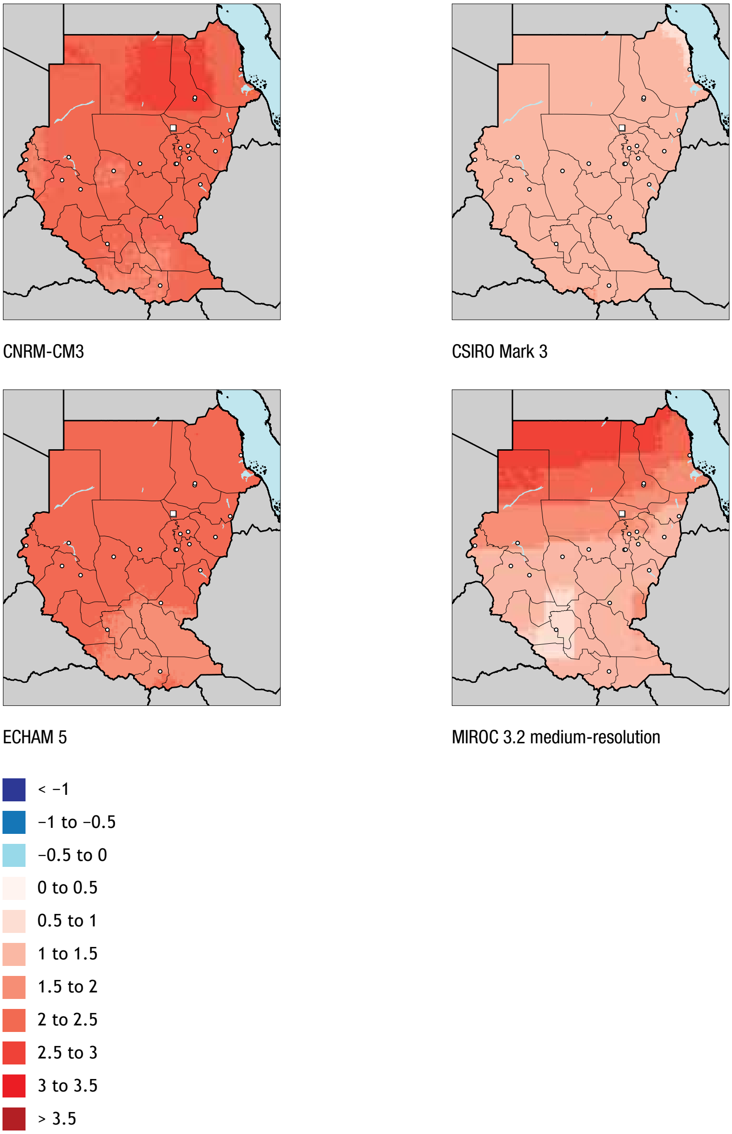
FIGURE 10.14 Changes in mean annual precipitation in Sudan, 2000–2050, A1B scenario (millimeters)



Source: Authors' calculations based on Jones, Thornton, and Heinke (2009).

Notes: A1B = greenhouse gas emissions scenario that assumes fast economic growth, a population that peaks midcentury, and the development of new and efficient technologies, along with a balanced use of energy sources; CNRM-CM3 = National Meteorological Research Center–Climate Model 3; CSIRO = climate model developed at the Australia Commonwealth Scientific and Industrial Research Organisation; ECHAM 5 = fifth-generation climate model developed at the Max Planck Institute for Meteorology (Hamburg); GCM = general circulation model; MIROC = Model for Interdisciplinary Research on Climate, developed by the University of Tokyo Center for Climate System Research.

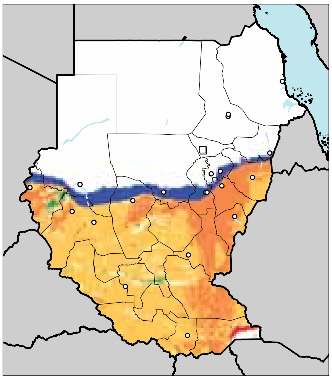
FIGURE 10.15 Changes in monthly mean maximum daily temperature in Sudan for the warmest month, 2000–2050, A1B scenario (°C)



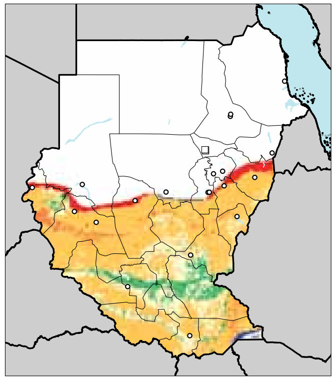
Source: Authors' calculations based on Jones, Thornton, and Heinke (2009).

Notes: A1B = greenhouse gas emissions scenario that assumes fast economic growth, a population that peaks midcentury, and the development of new and efficient technologies, along with a balanced use of energy sources; CNRM-CM3 = National Meteorological Research Center–Climate Model 3; CSIRO = climate model developed at the Australia Commonwealth Scientific and Industrial Research Organisation; ECHAM 5 = fifth-generation climate model developed at the Max Planck Institute for Meteorology (Hamburg); GCM = general circulation model; MIROC = Model for Interdisciplinary Research on Climate, developed by the University of Tokyo Center for Climate System Research.

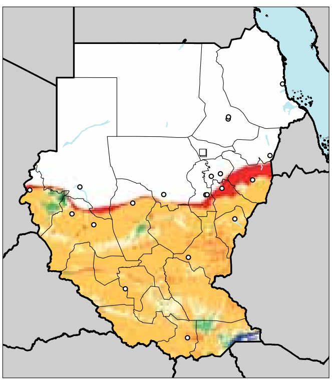
FIGURE 10.16 Yield change under climate change: Rainfed sorghum in Sudan, 2000–2050, A1B scenario



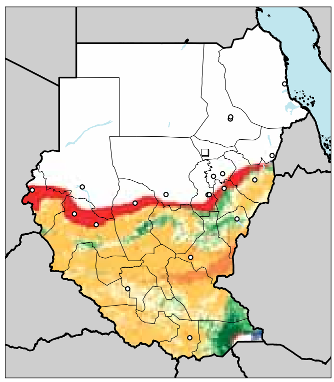
CNRM-CM3



CSIRO Mark 3



ECHAM 5



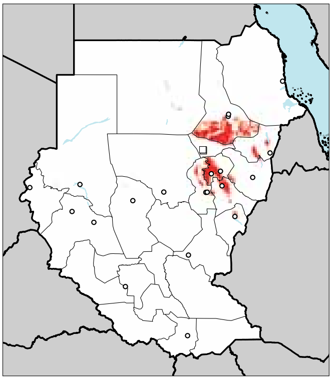
MIROC 3.2 medium-resolution

- Baseline area lost
- Yield loss >25% of baseline
- Yield loss 5–25% of baseline
- Yield change within 5% of baseline
- Yield gain 5–25% of baseline
- Yield gain > 25% of baseline
- New area gained

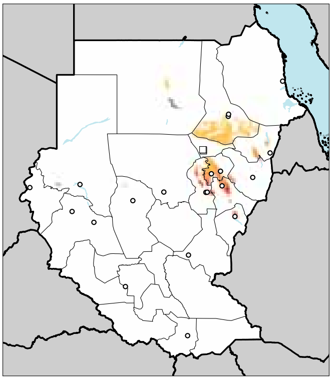
Source: Authors' calculations.

Notes: A1B = greenhouse gas emissions scenario that assumes fast economic growth, a population that peaks midcentury, and the development of new and efficient technologies, along with a balanced use of energy sources; CNRM-CM3 = National Meteorological Research Center–Climate Model 3; CSIRO = climate model developed at the Australia Commonwealth Scientific and Industrial Research Organisation; ECHAM 5 = fifth-generation climate model developed at the Max Planck Institute for Meteorology (Hamburg); GCM = general circulation model; MIROC = Model for Interdisciplinary Research on Climate, developed by the University of Tokyo Center for Climate System Research.

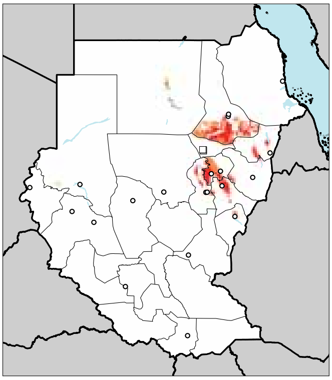
FIGURE 10.17 Yield change under climate change: Irrigated wheat in Sudan, 2000–2050, A1B scenario



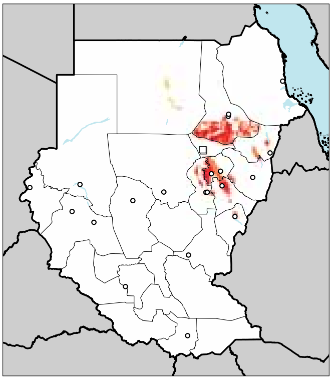
CNRM-CM3



CSIRO Mark 3



ECHAM 5



MIROC 3.2 medium-resolution

- Baseline area lost
- Yield loss >25% of baseline
- Yield loss 5–25% of baseline
- Yield change within 5% of baseline
- Yield gain 5–25% of baseline
- Yield gain > 25% of baseline
- New area gained

Source: Authors' calculations.

Notes: A1B = greenhouse gas emissions scenario that assumes fast economic growth, a population that peaks midcentury, and the development of new and efficient technologies, along with a balanced use of energy sources; CNRM-CM3 = National Meteorological Research Center–Climate Model 3; CSIRO = climate model developed at the Australia Commonwealth Scientific and Industrial Research Organisation; ECHAM 5 = fifth-generation climate model developed at the Max Planck Institute for Meteorology (Hamburg); GCM = general circulation model; MIROC = Model for Interdisciplinary Research on Climate, developed by the University of Tokyo Center for Climate System Research.

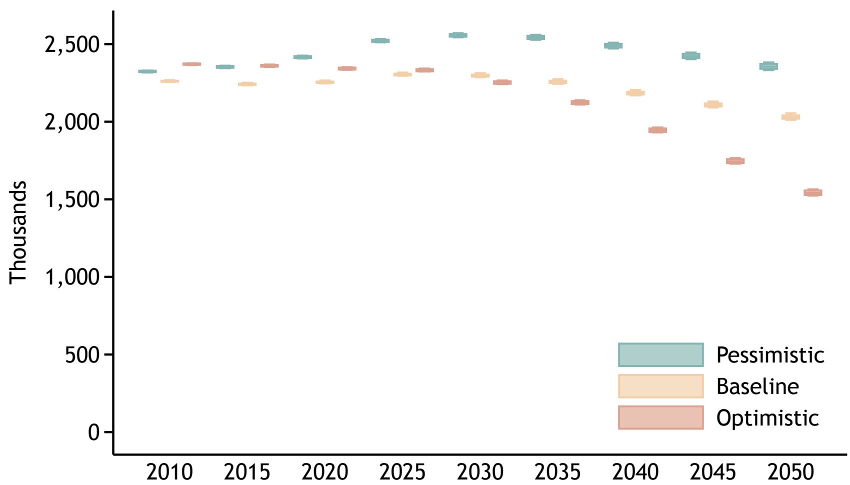
Vulnerability

Figure 10.18 shows the impact of future GDP and population scenarios on the number of malnourished children under age five in Sudan. Figure 10.19 shows the share of children who are malnourished. Figure 10.20 shows the average daily kilocalorie availability. In the optimistic scenario, lower demand for food and higher per capita GDP are favorable to consumers, and the optimistic trend accordingly shows increasing kilocalorie availability per capita and fewer malnourished children. Even the pessimistic scenario shows reasonably favorable outcomes: by 2050, there will be fewer malnourished children and greater kilocalorie consumption than in 2010. Although the number of malnourished children will rise slightly through 2030, the malnutrition rate will fall due to an increase in total population that will include an increase in the number of children under the age of five.

Agricultural Outcomes

The yield and area of sorghum will both increase, implying that total production must increase. The world price of sorghum will also rise (Figure 10.21). However, the demand for sorghum is likely to be driven mainly by population growth and

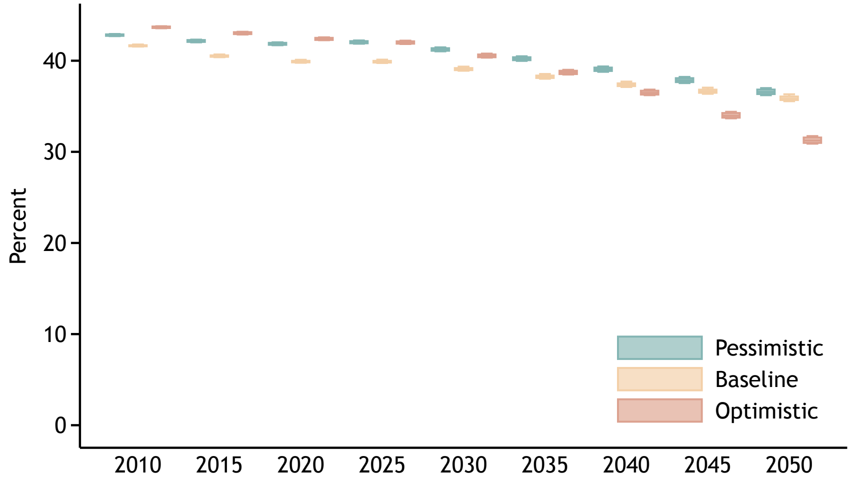
FIGURE 10.18 Number of malnourished children under five years of age in Sudan in multiple income and climate scenarios, 2010–2050



Source: Based on analysis conducted for Nelson et al. (2010).

Note: The box and whiskers plot for each socioeconomic scenario shows the range of effects from the four future climate scenarios.

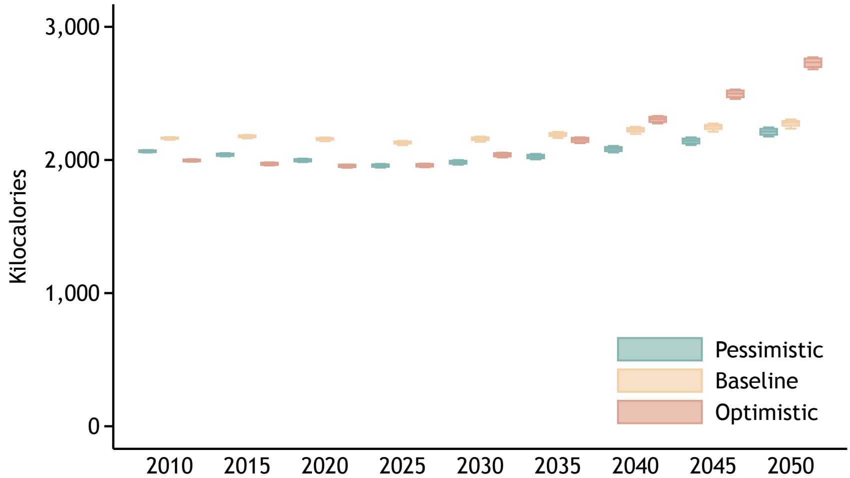
FIGURE 10.19 Share of malnourished children under five years of age in Sudan in multiple income and climate scenarios, 2010–2050



Source: Based on analysis conducted for Nelson et al. (2010).

Note: The box and whiskers plot for each socioeconomic scenario shows the range of effects from the four future climate scenarios.

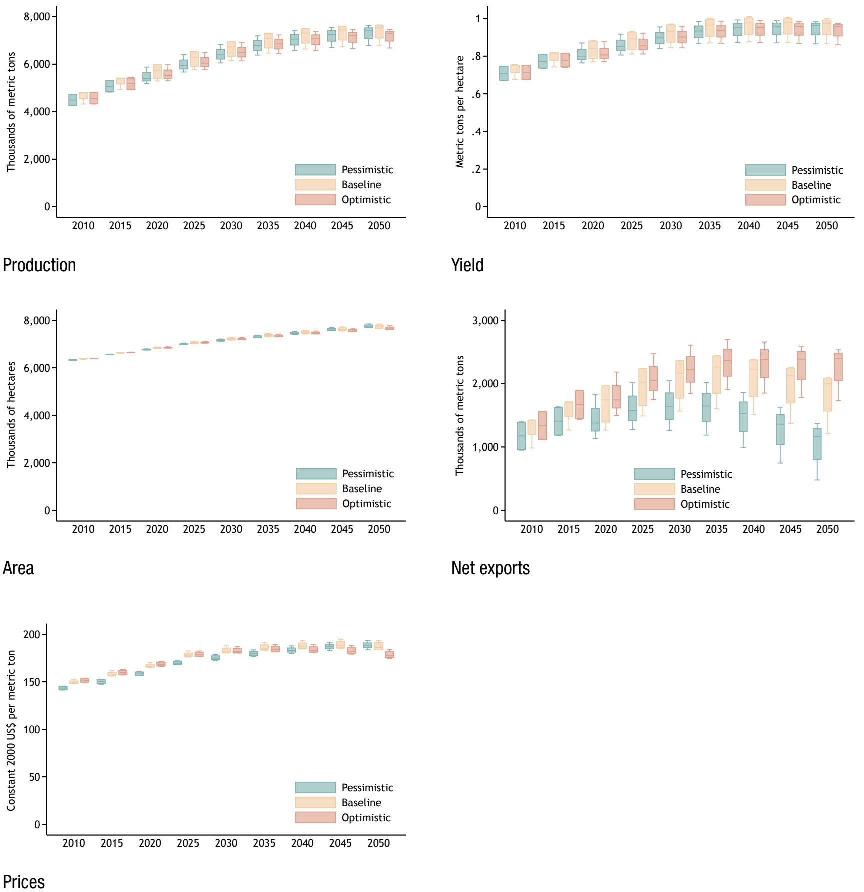
FIGURE 10.20 Kilocalories per capita in Sudan in multiple income and climate scenarios, 2010–2050



Source: Based on analysis conducted for Nelson et al. (2010).

Note: The box and whiskers plot for each socioeconomic scenario shows the range of effects from the four future climate scenarios.

FIGURE 10.21 Impact of changes in GDP and population on sorghum in Sudan, 2010–2050



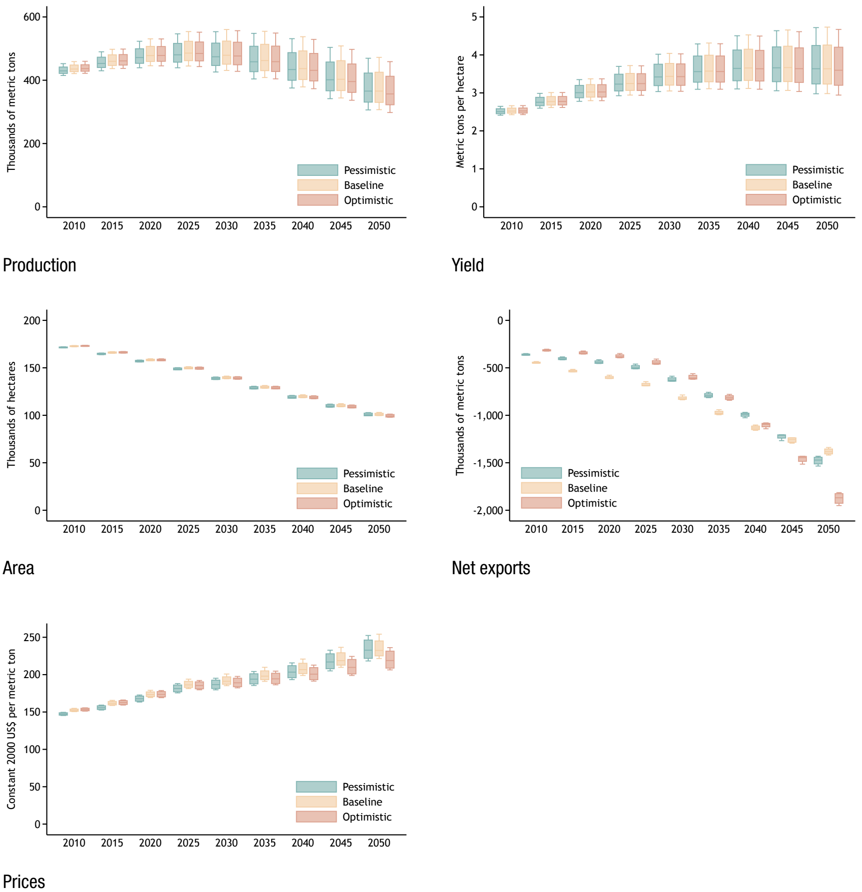
Source: Based on analysis conducted for Nelson et al. (2010).

Notes: The box and whiskers plot for each socioeconomic scenario shows the range of effects from the four future climate scenarios. GDP = gross domestic product; US$ = US dollars.

internal market forces. The model shows more uncertainty about net exports of sorghum, as indicated by the lengthening of the whisker plots. This is because of variance in both production and consumption demand, which will lead to a higher variance in the difference between the two, which is net exports.

For wheat (Figure 10.22), the model has two distinct features: first, the modeled changes in production and yield show more uncertainty, and second, both the area harvested and production are shown decreasing, with area decreasing the more rapidly of the two, even though the world market price

FIGURE 10.22 Impact of changes in GDP and population on wheat in Sudan, 2010–2050

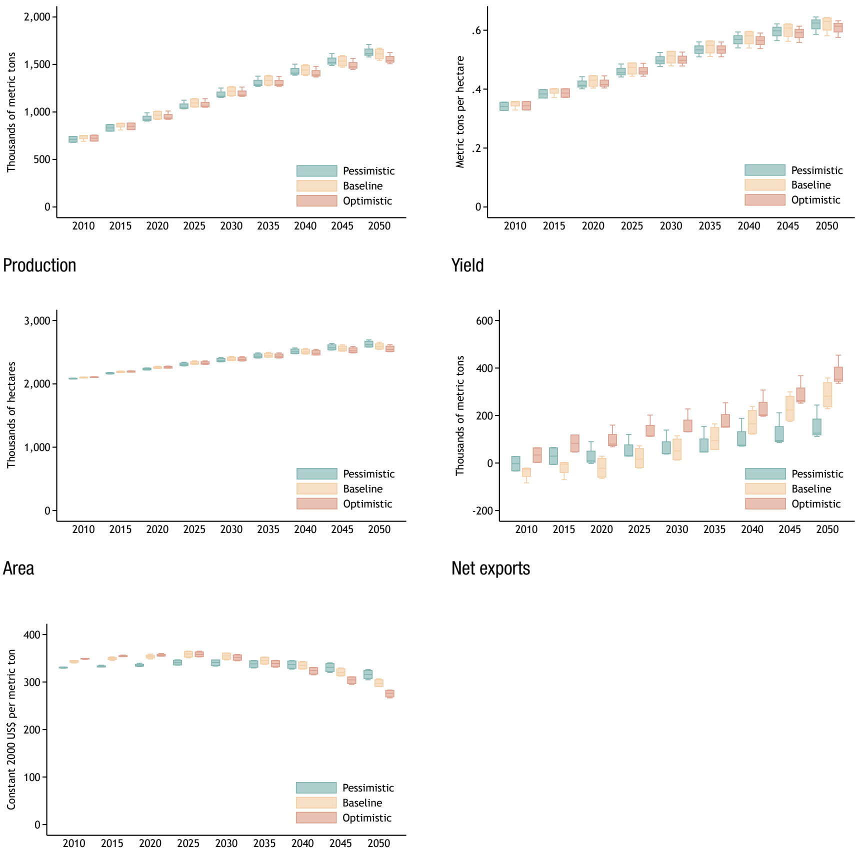


Source: Based on analysis conducted for Nelson et al. (2010).

Notes: The box and whiskers plot for each socioeconomic scenario shows the range of effects from the four future climate scenarios. GDP = gross domestic product; US$ = US dollars.

will be increasing. This is a reflection of the climate model showing higher temperatures that will result in area and yield losses (as computed by the crop model) in the main wheat-producing areas of central Sudan. Sudan is likely to become more dependent on imports to meet its demand for wheat as a result of climate change over time.

FIGURE 10.23 Impact of changes in GDP and population on millet in Sudan, 2010–2050



Production

Yield

Area

Net exports

Prices

Source: Based on analysis conducted for Nelson et al. (2010).

Notes: The box and whiskers plot for each socioeconomic scenario shows the range of effects from the four future climate scenarios. GDP = gross domestic product; US$ = US dollars.

In the model results for millet (Figure 10.23), yield increases by almost 70 percent, and with area increasing by more than 20 percent, production necessarily more than doubles. The production boost outpaces any increase in consumer demand, resulting in an increase in exports. The world millet price holds mostly constant through 2030, then falls off gradually.

Conclusions and Policy Recommendations

The majority of Sudan is prone to risk of climate change and indeed may already be seeing its effects through decreased and erratic rainfall patterns, extended droughts, and desertification. These events, coupled with such actions of farmers as nutrient mining of the soils and poor erosion defenses in a bid to meet their basic needs, have led to land degradation and natural destruction. Given that the country is heavily reliant on climate-dependent agriculture, appropriate coping strategies are vital, especially for the vulnerable groups who depend on agriculture for their livelihood. Suitable strategies come from understanding the form in which and the extent to which the country is exposed to climate risks. This chapter has analyzed the vulnerability of Sudan to climate change based on various economic, demographic, agricultural, and land use indicators. Several GCMs were used to assess the country's susceptibility under different scenarios.

The crop models generally indicated negative outcomes, at least for rainfed sorghum and irrigated wheat. Although the yield losses and area losses projected for sorghum are significant, the losses for wheat appear devastating. The crop models do not allow for technological change, but the global International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) does. With technological change, the situation for sorghum does not appear nearly as bad as it does in the crop model, and the production of sorghum appears likely to keep pace with domestic demand. This is not the case for wheat. Unless a major scientific breakthrough for wheat is forthcoming, Sudan will end up importing most of its wheat, because the temperatures from climate change are likely to become too high for successful wheat cultivation. IMPACT suggests that millet would be a very successful crop in Sudan and that exports of millet would likely rise.

Our analysis has also revealed an unclear pattern of rainfall but warmer conditions throughout the country, which could be detrimental to soil moisture and crop production. Our findings also predict future loss of yields for both irrigated wheat and sorghum from previously cultivated land. But in the case of sorghum, some of the losses may be offset by gains in yield stemming from both formerly and newly cultivated lands. Although increased production is predicted for all key crops with the exception of wheat, such gains will not be accompanied by exports to the world market, suggesting that the internal demand for food will be more than what can be supplied by the domestic markets.

Policies that promote the development and testing of new agricultural technologies (such as high-yielding varieties and hybrids that are resistant to drought and heat stress) and improved water harvesting and management techniques should be developed to enable the enhanced productivity that matches the food needs of a rising population. But development and testing of technologies is only part of the solution: an active agricultural extension service, integrated with the agricultural research institutions, will be important for communicating these developments to farmers. Establishing early warning systems responsible for the collection, sharing, and distribution of weather data in a timely manner will also moderate the impacts of climate change.

Institutional partnerships, coordination, and collaboration are required to integrate and coordinate approaches to ensure the effective long-term adaptation of strategies. It is important that programs work with vulnerable communities at the local level, applying a bottom-up approach to project planning. Such an approach can generate valuable lessons for adaptation success and also for sharing with vulnerable communities outside Sudan.

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