THE ECONOMIC AND FOOD SECURITY IMPLICATIONS OF CLIMATE CHANGE IN MALI

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Abstract. The study focuses on economic and food security implications of projected climate change on Malian agriculture sector. Climate change projections made by two global circulation models are considered. The analysis focuses on the effects on crops, forages, and livestock and the resultant effects on sectoral economics and risk of hunger in Mali. Results show that under climate change, crop yield changes are in the range of minus 17% to plus 6% at national level. Simultaneously, forage yields fall by 5 to 36% and livestock animal weights are reduced by 14 to 16%. The resultant economic losses range between 70 to $142 million, with producers gaining, but consumers losing. The percentage of population found to be at risk of hunger rises from a current estimate of 34% to an after climate change level of 64% to 72%. A number of policy and land management strategies can be employed to mitigate the effects of climate change. In particular, we investigate the development of heat resistant cultivars, the adoption of existing improved cultivars, migration of cropping pattern, and expansion of cropland finding that they effectively reduce climate change impacts lowering the risk of hunger to as low as 28%.

1. Introduction

Greenhouse gas induced climatic change may worsen climatic conditions in many developing countries. Rosenzweig and Iglesias (1994) argue that low latitude regions, where most of the developing world is located, may be hard hit by climatic change. According to the Intergovernmental Panel on Climate Change (2001), there are few, if any, detailed climate change impact assessments focused on developing countries. The intent of this study is to partially fill that gap carrying out a comprehensive biophysical and economics based climate change impact assessment for the agricultural sector of Mali, particularly, highlighting the food security implications.

While the study focuses on the economic and food security implications of climate change, additional factors that may impact future food security conditions in Mali are also considered. Vitale (2001), Coulibaly (1995) and Olsson (1991)

Climatic Change (2005) 68: 355–378

argue that the pressure to grow more food has resulted in degradation of Mali's natural resource base. Slow technological adoption and a high population growth lead to increased land use intensity with cultivation moving into more and more marginal lands coupled with shortened fallow periods (Kuyvenhoven et al., 1998; Benjaminsen, 2001).

Added to these challenges is risk. Farming in Mali faces high climatic risk that influences farmers' decision making with regards to production of various crops (Kruseman et al., 2001). Thus, we will consider climate change impact in conjunction with resource degradation, expansion of cropland, adoption of existing improved cultivars, and climatic risk.

2. Previous Studies

A number of studies focusing on the agricultural impact of climate change, such as Adams et al. (1998), Mendelsohn et al. (1994); Rosenzweig and Hillel (1998) and U.S. Global Research Program (2001), have concluded that climate change was not likely to cause a serious threat to U.S. and global food security. Yet, they warned that marked regional differences might exist. Adams et al. (1999) and Lewandrowski and Schimmelpfennig (1999) review the evidence indicating that U.S. agriculture on a continental scale stands resilient to climate change with higher yields for some crops in (cold) northern regions, and lower yields in (warm) southern regions. Reilly et al. (2002, 2003) provided a recent U.S. level assessment and found that with an increase in atmospheric temperature and CO_2 concentration, yields for crops in many regions increased substantially. The exception was the low latitude warm regions, the South and Southeast U.S., where yields decreased.

In a developing country setting, Downing (1992) studied the implications of climate change for the water balance in Zimbabwe and found that, over the entire surface of the country, water evaporation increased by 15% under a 1 °C increase in temperature, while with a 2 °C temperature increase, the country's core agricultural zone would be reduced by 67% due to high evaporation rates. Yates and Strzepek (1998) examined economic and agronomic responses of the Egyptian agriculture. They found minor gains in economic welfare for Egypt, owing mainly to improved irrigation management of Aswan dam. The dam's storage capacity improved due to alterations in the projected pattern of wet and dry months. Using time series data on rainfall, production, and other weather and agronomic data for Niger, Mohamed et al. (2002a, b) argue that by 2025 climate change might lower millet yields by 13%, groundnuts by 11to 25%, and cowpeas by 30%. Using crop simulation models and climate change scenarios generated from Global Circulation Models, Chipanshi et al. simulated climate change impact on the productivity of maize and sorghum crops in Botswana. They concluded that yields might decrease by 10 to 36% in case of maize and 10 to 31% for sorghum. In their global study, Rosenzweig and Hillel (1998) concluded that climate change might not peril world food supplies;

yet, they identified tropical and temperate regions, such as Sub Saharan Africa, to be vulnerable to climate change.

Studies have also shown that while climate change may adversely affect agriculture in some regions, human adaptations, such as changing planting and harvesting dates or shifting cropping patterns, may help mitigate the negative effects, as reviewed or studied in Adams et al. (1998, 1999), Rosenzweig and Hillel (1998), Schimmelpfennig et al. (1996), and Kaiser et al. (1993). Adaptation may also occur through changes in market and trade conditions (Adams et al., 1998; Reilly et al., 2002; Rosenzweig and Hillel, 1998; Yates and Strzepek, 1998).

3. Mali: Background and Climate Change Projections

Mali is located just south of the Sahara desert with its northern region, Tombouctou, being part of the desert. Mali is broadly categorized into three climatic zones: the Saharo-Sahalian, the Sahelo-Sudanian, and Sudano-Guinean zones (Wang 'ati). The Saharo-Sahelian zone is extremely dry with an annual rainfall of 100–200 mm. with 50–100% inter-annual variability. The Sahelo-Sudanian zone and Sudano-Guinean zones have annual rainfall of 200–400 mm and 400–800 mm, respectively, with 25–50% inter-annual rainfall variability.

Climate change projections made by two of the Global Circulation Models (GCMs), Hadley Center Coupled Model (HADCM-University of E. Anglia, U.K) and Canadian Global Coupled Model (CGCM - University of Victoria, Canada), are used in this study. Figure 1 presents the projected changes in temperature

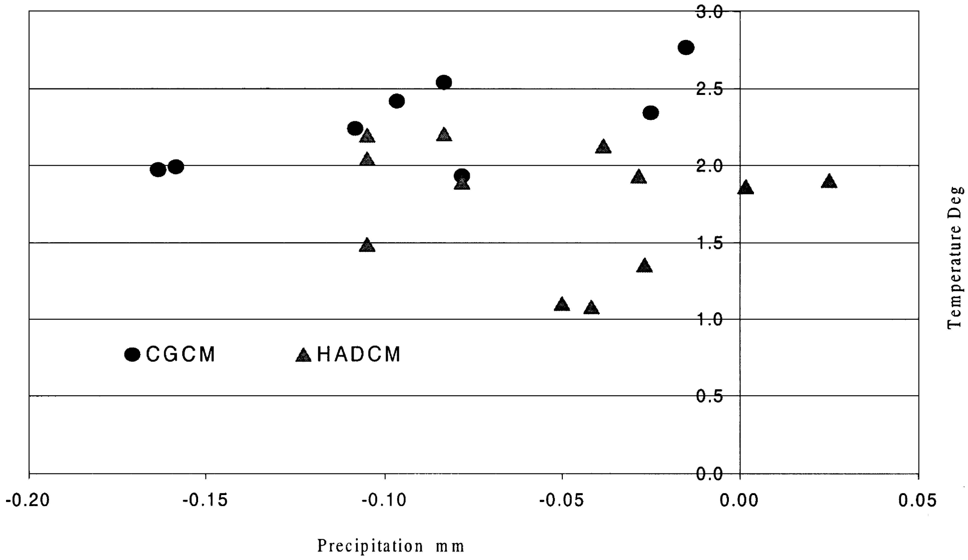

Figure 1. The projected changes in precipitation and temperature for Mali.

and precipitation for year 2030* as differenced from the base temperature and precipitation of 1960–91 period. Climate change projections made by HADCM and CGCM were obtained from the Data.

Distribution Center of the IPCC.[1] In Figure 1, triangles correspond to twelve HADCM grids and circles correspond to eight CGCM grids covering 72 weather stations located in various geographical areas in Mali. The projections indicate that Mali may face a hotter, drier future. The CGCM projections for temperature are generally higher than those by HADCM. Temperature is predicted to increase in every grid cell. Five of the eight CGCM grids showing increases in temperature of more than two degrees centigrade, while eight of the twelve HADCM grids show increases of less than two degrees centigrade. On the precipitation side, ten of the twelve HADCM grids show a decrease, while all of the eight CGCM grids show a decrease.

The GCM based projections for climate change in Mali portend an extension, or perhaps continuation, of recent observed changes in the climate of West Africa. Namely, Gommes and Petrassi (1994) and Jenkins et al. (2002) argue that since the early sixties, regional rainfall patterns in West Africa have shifted mainly in favor of lower annual average rainfall. All and all, the climate prognosis for Mali, as suggested by the recent climatic changes and projected by HADCM and CGCM, is 'hotter and dryer.'

4. Analytical Framework

To study the economic and food security implications of climate change for Mali, we felt the need to look at effects on crops, forages, and livestock and how these effects translate into overall food production and market environment. To do this, a collection of biophysical and economic models is used, along with a procedure to compute risk of hunger. The biophysical models used are: Erosion Productivity Impact Calculator (EPIC—Williams et al., 1989), Phytomas Plant Growth Model (PHYGROW—Rowan, 1995), and Nutrition Balance Analyzer Model (NUTBAL—Stuth et al., 1999). The economic model used is Mali Agriculture Sector Model (MASM—Chen et al., 1999; Butt 2002). The procedure for computing risk of hunger is an adaptation of a FAO (1996) methodology. Each of these items is reviewed below.

4.1. BIOPHYSICAL MODELS

As stated above EPIC, PHYGROW and NUTBAL were employed to project the biophysical effects of climate change on crops, forages, and livestock.

*GCMs projections are given for three time slices of 2010–2040, 2040–2070 and 2070–2100. In this study, we will focus on the 2010–2040 time.

4.1.1. *EPIC Based Crop Simulations*

EPIC (Williams et al., 1989) was used to simulate crop growth under alternative weather conditions and crop management practices. EPIC uses daily weather information data as well as information on farm management practices, such as planting date, tillage, fertilization, manure management, and crop rotation. EPIC has been widely used in the previous climate change studies including Adams et al. (1998), Adams et al. (1999) and Reilly et al. (2002).

In this study, EPIC was used to simulate sorghum, millet, cotton, cowpeas, groundnuts, and maize yields in 85 Malian agro-ecological zones characterized by differences in soil types and climate. Simulations were run for a 40 yr period. EPIC simulations were performed under both base, before climate change and alternative, after climate change conditions with the alterations in climate being those predicted by HADCM and CGCM.

4.1.2. *PHYGROW Based Grass/Forage Simulations*

PHYGROW is used herein to simulate rangeland and pasture land forage yields. The model utilizes data on plant species, weather, grazing utilization, physical and hydrologic characteristics of soils, physical responses and competitive potential of multiple plant species, preferences and dry matter intake of multiple grazers, and the associated stocking density rules (Rowan, 1995). In turn, the model predicts quantity and relative quality of available forage, and daily water balance-run-off, drainage, transpiration, soil evaporation, canopy/litter interception, and soil moisture.

PHYGROW simulations were performed only for the Sikasso region of Mali. This region was selected due both to its importance as a production region and also the unavailability of data on plant communities elsewhere in Mali. Twelve agro-ecological zones were studied, which covered about 72% of the land area in Sikasso. Forage yield sensitivity to climate change in Northern Sikasso, a relatively dry area, was assumed to be representative of other regions in Mali and thus was applied to all regions outside Sikasso.

4.1.3. *NUTBAL Based Livestock Simulations*

NUTBAL (Stuth et al., 1999) was used to project the rate of gain of cattle, sheep, and goats as well as their dietary requirements. The model input includes: (i) breed attributes of the cattle, sheep and goat herds as well as their typical physiological profiles through a production cycle, (ii) feed and forage nutritional quality attributes, (iii) metabolic modifiers, (iv) environmental conditions including maximum/ minimum temperature, humidity, and wind speed, (v) grazing pressure (kg. forage/ head), and (vi) the kind and amount of supplemental feeds available. The model produces results on animal feed/forage requirements, weight gain/loss, manure output, and milk production. The dominant breed was selected for simulation with West African Zebu for cattle, West African Djallonke for sheep, and Djallonke for goats. These animals/breeds were simulated for the Sahara, Sahel, Soudan, and Preguinean agro-ecological zones.

4.2. MALI AGRICULTURE SECTOR MODEL

Mali Agriculture Sector Model (MASM), developed by Chen et al. (1999) and adapted for use in this study by Butt (2002), was used to examine the consequences of climate change and ongoing land degradation in Mali. The model simulates economic conditions in the agriculture sector of Mali that include prices, production, and trade of various crop and livestock commodities. Methodologically, the model is based on mathematical programming following concepts developed by Samuelson (1952); and Takayama and Judge (1971) as reviewed by McCarl and Spreen (1980), and Norton and Schiefer (1980).

In terms of geo-graphic scale, MASM is a national level model that incorporates agrological diversity in the agriculture sector across nine geographical production regions, as shown in Figure 2.[2] The model simulations provide results on production, consumption, trade, and prices of crop and livestock commodities at regional and national levels.[3] It also provides the impact of changes in the economic and biophysical environment of agriculture sector on producers' and consumers' benefits for engaging in production and consumption as estimated by producer and consumer surplus measures; more on this is explained later. The model also incorporates

Figure 2. Geographic view of different producing regions in Mali.

climate variability following Lambert et al. (1996) using a whitened historical yield distribution to model climatic variability.[4]

Climatic variability for seven crops is included in the form of 12 yrs of detrended yield history in each of the producing regions (Butt, 2002). The supporting data was obtained from Institut d'Economie Rurale (IER), Ministère du Développement Rural, Government of Mali under collaboration with the Sustainable Agriculture and Natural Resource Management (SANREM) project. In regards to climatic variability, MASM uses the framework of stochastic programming with recourse (Dantzig, 1955; Lambert et al., 1996), where model simulation is conducted in two stages. In the first stage, the model allocates land to crops in a producing region considering regional yield distributions. In the second stage, the model computes production, prices, and trade (import/export) of seven crops given a yield outcome. Two important elements in the second stage are subsistence crop production behavior by farmers and the trade. The subsistence crop production behavior is modeled traditionally, as reviewed in Calkins (1981), where farmers' decision to sell crops in the market takes place after satisfying their home consumption needs for food. Consumption and trade are conditional on prices (under a yield outcome) as determined in the domestic regional markets under fixed trade prices. See Butt (2002) for modeling details. The base model is calibrated against economic conditions of the Malian agriculture sector in 1996 for seven crop and three livestock products.

4.3. RISK OF HUNGER

Climate change may influence food security as found by Rosenzweig et al. (1995); and Rosenzweig and Hillel (1998). Winters et al. (1998) argue that Africa, due to its low import capacity, may face substantial drop in consumption of food due to climate change impact on the productivity of agriculture sector. Kassim (1998) also pointed out to the possibility of climate change leading to increased reliance of Sub Saharan African countries on foreign sources of food including trade and food aid. Hence, the impact of climate change on food security in Mali needs a detailed consideration. For this purpose, we adapt the FAO (1996) methodology for calculating 'Risk of Hunger' (ROH), which shows the percentage of population that is malnourished in a country or a region. The computation of ROH requires estimates of availability of food, population, nutritional requirements, and a measure of inequality in access to food. Information on population, nutritional requirements, and estimates of inequality in access to food are drawn from FAO (1996), while food supplies are computed from MASM results on production and trade of crop and livestock products that account for about 80% of calorie consumption in Mali.

The main advantage of using the ROH measure as an indicator of food security is its policy relevance. As the measure depends on food production and its trade, the impact of various agents of change in the agriculture sector, e.g. climate change, policy interventions, etc., can be assessed on food security through their impact on food availability. The major limitation of the measure is its heavy reliance on food availability as a measure of food security. Smith (1999) argue that while improving food availability is important, access to food is the ultimate key to food security, which is inadequately captured by the ROH methodology. Smith and Haddad (2001), however, find statistical evidence, using panel data from 63 developing countries, of strong impact of increased availability of food on reduction of malnutrition; the impact being strong for countries with low food availability, such as those in Sub-Saharan Africa, lending credibility to using the measure in our assessment of climate change impact on food security. Butt and McCarl (2003) discuss this further.

5. The Assessment Methodology

The analysis employed four principal steps. First, climate change projections from HADCM and CGCM were obtained from the Data Distribution Center of IPCC (Figure 1). The respective climate change projections were imposed on the data from 72 weather stations across the whole country. Second, the biophysical models were run to obtain the impact on crop, forage, and livestock. Third, an array of potential adaptations was considered. Fourth, biophysical impacts were incorporated into the economic model to assess the overall economic and food security implications of climate change and adaptive strategies.

5.1. BIOPHYSICAL ASSESSMENTS

The biophysical models, EPIC and PHYGROW, were run under the existing and projected climate change. The climate change runs were made with CO_2 level set at 1.5 times the current level of 330 ppmv (Adams et al., 1999; Reilly et al., 2002). Each simulation was run for a period of 40 yrs and results across 85 various agro-ecological zones in Mali were obtained and appropriately weighted to the nine MASM production zones basis.[5]

5.1.1. *The Impact on Crop Yields*

Results from EPIC simulations of climate change, as projected by HADCM and CGCM, show that cotton and millet were relatively resilient crops. Cotton yields increased in most cases, while millet showed different responses depending on the simulation zone. The elevated CO_2 level benefited cotton due to the biological characteristics of the crop.[6]

Sorghum was the most susceptible crop to the projected climate change, as its yields decreased significantly. Results showed that relatively humid areas of Mali would be more resilient to climate change compared with drier areas. Table I shows nationally averaged changes in mean and variation of crop yields under the projected climate change.

Under the HADCM scenario, collectively 33 of the 48 crop-region cases simulated showed yield losses. In the drier and lower productivity regions of Mali,

TABLE I
Nationally area weighted changes in mean and variation in crop yields under the projected climate (percentage changes from base climate)

	Mean		Coefficient of variation	
	HADCM	CGCM	HADCM	CGCM
Maize	−11.2	−13.5	2.3	1.6
G-Nuts	−10.0	−13.4	−2.1	−4.1
Cotton	6.2	3.5	0.9	1.7
Sorghum	−11.5	−17.1	−3.6	−6.7
Millet	−6.3	−11.5	3.4	5.6
Cowpea	−8.4	−12.2	6.8	9.7

Note. HADCM: Hadley coupled model; CGCM: Canadian coupled model.

$$\text{Coefficient of variation} = 100 \times \frac{\text{Standard deviation}}{\text{mean}}$$

sorghum yield decreased by up to 18%, while in sub-humid areas of Sikasso sorghum yield were projected to modest decrease (5–7%).

The loss in yield is higher under the CGCM projected climate change than under HADCM due to relative harsher climate change projections of the CGCM model. CGCM exhibited lower yields in 42 of the 48 cases. Yield increases were found in 11 cases, compared with 15 under the HADCM case. Yield of cotton increased, while sorghum the most sensitive. High losses were found for sorghum, with yield decreases up to 30% in Segou and Koulikoro. Simulation of rice yield could not be conducted using EPIC for want of necessary information. To fill the gap, yield changes for HADCM are used from Mohandass et al. (1995) for summer rice in India.[7] A yield decrease of 14.5%, based on the reported average yield decreases across 9 experiment stations, was applied to base yield in the sector model. Loss in rice yield for CGCM projections was adjusted by the average of CGCM and HADCM differences in the yield losses of the other six crops simulated by EPIC.

The projected climate had mixed effects on variation in yield as shown in Table I. The variation in some of the crops increased, while for others it decreased, which is attributable to a complex mix of temperature, rainfall, CO_2 fertilization effect, plant physiology, and soil characteristics.

EPIC was also used to estimate the rate of degradation in cropland productivity, where rate of degradation was measured in terms of loss of crop yield due to continuous planting. Forty years of simulated yield under a given farming practice and low input application were used to estimate a trend regression for the simulated yields, as shown in the following equation[8]:

$$Y_{ijst} = a_{ijst} + b_{ijst}\, T + \varepsilon_{ijst},$$

TABLE II
Decrease in crop yield by 2030 as a result of projected cropland degradation in three Sikasso regions (% decrease from base)

	North	Central	West
Maize	23	22	25
G-Nuts	23	21	22
Cotton	19	19	19
Sorghum	21	21	24
Millet	21	20	18
Cowpea	24	22	23

where Y_{ijst} is the EPIC simulated yield of crop i, in simulation zone j, on soil type s, for technology t; and T is the trend variable. The intercept a in this regression shows the base year's yield, while the coefficient b shows how yields change over time, and ε_{ijst} shows the error term in regression. The coefficient b was generally found negative—showing degradation over time. Yield for year 2030 was estimated by setting $T = 34$ in the estimated regression. The rate of degradation thus estimated varied between 19 to 25% compared with the base conditions. Table II shows estimated yield losses due to the degradation in three sub-regions in Sikasso by year 2030.

5.1.2. *The Impact on Forage Yields*

Forage yields were estimated using PHYGROW model. Table III shows forage yield sensitivity to the projected climate change. Forage yields are projected to decrease in the range of 5 to 36%. The primary reason is the combined loss of grass basal area due to over grazing and reduced woody plant cover due to fuelwood harvesting coupled with increased temperatures during the growing season.

5.1.3. *The Impact on Livestock*

Changes in livestock performance were assessed using NUTBAL model. The results are shown in Table IV. Livestock impact is caused by increased maintenance

TABLE III
Percentage changes in forage yields under the projected climate in Sikasso region (% change from base)

	Global circulation models	
Region	HADCM	CGCM
North	−18	−26
Central	−5	−12
West	−26	−36

Note. HADCM: Hadley coupled model; CGCM: Canadian coupled model.

TABLE IV
Changes in animal intake and the rate of weight gain (% change from base)

	Intake		Weight	
Animal	HADCM	CGCM	HADCM	CGCM
Cattle	−12.8	−13.3	−13.6	−15.7
Sheep	−3.4	−5.9	0.0	0.0
Goats	−4.1	−4.7	0.0	0.0

Note. HADCM: Hadley coupled model; CGCM: Canadian coupled model.

requirements and loss of appetite as a result of increase in thermal stress (Adams et al., 1999), where loss of appetite causes reduced intake and loss of animal weight and lower growth rates. The results show that small ruminants may be more resilient to climate change compared with cattle.

5.2. INCORPORATING ADAPTATIONS

While climate change may adversely impact agriculture, human adaptations are almost certain to mitigate impacts. Ignoring the adaptations may over/under estimate climate change damage estimates (Adams et al., 1999; Rosenzweig and Hillel, 1998; Kaiser et al., 1993). Adaptations may be categorized as biophysical adaptations (Adams et al., 1999; Rosenzweig and Hillel, 1998; Kaiser et al., 1993), changes in policy, and adjustments in market conditions (Adams et al., 1999; Reilly et al., 2002). We will consider an array of biophysical and policy based adaptations and examine climate change impact with and without adaptations.

5.2.1. *Biophysical Adaptations*

Three types of biophysical adaptations are considered. The first involved alteration of cropping patterns to adapt to changing regional climatology (Adams et al., 1999; Reilly et al., 2002). The base solution required MASM to choose regional crop mixes from an array of historically observed regional crop mixes. We relaxed this requirement and allowed the model to choose crop mixes for a region from those of warmer, northern regions' in addition to its own historically observed crop mixes (Reilly et al., 2002; Adams et al., 1999).

The second involved adjustments in planting and harvesting dates to adapt crop schedule to changes in temperature and precipitation (Rosenzweig and Hillel, 1998; Kaiser et al., 1993). EPIC simulations under the changed temperature and precipitation did not show adjusting planting and harvesting dates to be an effective adaptation. In Mali, planting schedules are heavily dependent on when the rainy season begins. EPIC simulations under early planting to mitigate the impact of warming, before the beginning of rain, resulted in further lowering of yield. Hence, in the final analysis changes in planting and harvesting dates was not considered.

The third biophysical adaptation involved simulating heat-resistant varieties that are more tolerant to higher temperatures and, hence, may mitigate climate change impact (Kaiser et al., 1993; Reilly and Schimmelpfenning, 1999), for which we used EPIC. Technically, a plant has a biological life that is determined by the number of Heat Units (HUs) that it accumulates during the growing season until it reaches its full maturity.[9] The optimal adaptive response to the temperature increase in dry areas, where irrigation is not available and adjusting planting and harvesting dates does not shield from the negative effects of higher temperature, would be to develop varieties that would not mature as fast as the existing varieties when the temperature increases. Thus, we adjusted the HUs parameter of EPIC increasing it, however, by keeping an eye on its effect on yield and on the length of the growing season. The HU was increased as long as there was a gain in yields and the length of the growing season increased to match that of the base climate. The simulation was performed with base level input use. Hence, we simulated a heat resistant variety that, under the existing input level, would offset some of the yield loss due to climate change. As shown in Table V, heat-resistant varieties can significantly reduce heat related yield losses.[10]

5.2.2. *Economic Adaptation*

Climate change impact on yields would alter market environment affecting prices, production, consumption, and trade of various commodities. For example, relative profitability of various crops would change in response to yield changes, which in turn, would affect farmers' area allocation decisions. As a result, crop production would change leading to changes in market prices, which affect consumers' spending decision.

Changes in domestic market also impact trade of various agricultural commodities. The economic model used in this study by its very nature, takes account of these adaptations by including cost and return data of agricultural commodities, producers' and consumers' responses to market changes, and trade. As changes in trade are considered an important adaptation to climate change (Reilly et al., 1994;

TABLE V
Yield losses with and without heat-resistant varieties (% change from base)

	Without adaptation		With adaptation	
	HADCM	CGCM	HADCM	CGCM
Maize	−11.2	−13.5	−8.6	−10.3
G-Nuts	−10.0	−13.4	−6.6	−9.1
Cotton	6.2	3.5	12.5	9.6
Sorghum	−11.5	−17.1	−4.3	−7.7
Millet	−6.3	−11.5	−0.7	−8.3
Cowpea	−8.4	−12.2	−1.4	−3.9

Note. HADCM: Hadley coupled model; CGCM: Canadian coupled model.

Rosenzweig et al., 1995; Rosenzweig and Hillel, 1998; Reilly and Schimmelpfenning, 1999; Kates, 2000), we, therefore, take a closer look at the role of trade adaptation in reducing climate change impact.

Trade adaptations are modeled by exploiting the constrained optimization structure of the economic model used in this study. The climate change impact without the trade adaptation is projected by imposing climate change, while restricting changes in import/export of various commodities. To project the benefits of trade under climate change, we then relaxed the restriction and allowed import/export to adapt to new climatic conditions. The economic gains accrued by relaxing the trade restriction are attributed to trade adaptations.

To implement the trade adaptations, an estimate of changes in international prices of various crops due to climate change was needed. We adapted for use herein the impact of climate change on international prices of agricultural products from the international market component of the U.S. National Assessment study of climate change impact (Reilly et al., 2002, 2003). Using climate change projections made by HADCM and CGCM models, the study projected international prices of various agricultural commodities for year 2030. We used percent changes in prices between the base and year 2030 for various crops from Reilly et al. (2002, 2003) and applied them as adjustment in the cost of imports for Mali; the change varied between 1 to 5% increase in prices.

5.2.3. *Policy Based Adaptations*

Adaptations to climate change may also come about through expansion of cropland and a wider adoption of improved cultivars (Evenson, 1999). We call these policy based adaptation as the government can play a role in promoting these adaptations (e.g. adoption of improved cultivars might require improving agricultural extension services).

Kuyvenhoven et al. (1998) and Benjaminsen (2001) observe that due to population growth and resource degradation, traditional grazingland were under pressure from arable farming. Following their observation, we simulated expansion of cropland adaptation showing increase in cropland at the expense of rangeland. We assumed that the additional cultivable land would come from an increase in crop use intensity (CUI), which is the ratio of cropped area to total cultivable area. The soils information used in this study was collected by US Geological Survey, which classified land into two categories. First, the soils differed based on the CUI, which was the ratio of cropped area to total cultivable area. Second, the soils differed based on their landscape reflecting land productivity. Seven classes were specified for soils by their landscape. These were: alluvial, hilly broken, sandy, wetlands, developed irrigated, and recessional agriculture classes. We assumed that additional cropland would come from alluvial soils that were considered more productive than the other soil types. Table VI presents the base CUI, assumed increases in the CUI, and the potential increase in land available for cultivation with the assumed increase in the CUI.

TABLE VI
Potential for increase in cropland through increase in crop unit intensity in Mali

	CUI-1		CUI-2		CUI-3		CUI-4		CUI-5	
	CL	RL	CL	RL	CL	RL	CL	RL	CL	RL
Base	70–100	0–30	50–69	31–50	30–49	51–70	5–29	71–95	0–4	96–100
Adapt	100	0	69	31	49	51	29	71	4	96
Land	136	−136	10628	−10628	88932	−88932	87150	−87150	37388	−37388

Note. CR: Cropland; RL: Rangeland.
Base: CUI as reported by USGS. For example, CL:70–100 shows classification where the land had been 70–100% under crop, while RL:0–30 classification has been under no rangeland to 30% rangeland.
Adapt: Assumed increase in the CUI; Land: Acres of land available under the assumed increase in the CUI.

As shown in Table VI, the increase in cropland followed a reduction in rangeland. To simulate adaptations through increase in the available cropland, MASM parameters for the maximum available cropland and rangeland were adjusted using the estimates shown in Table VI. Following our assumed increases in the crop use intensity, a total of 224 thousand acres of rangeland were potentially available for cultivation.

For the wider adoption of existing improved cultivars, we considered improved cultivars for sorghum, millet, cotton, maize, cowpeas, and rice. The data used for these cultivars was based on the experience with cultivars that had already been developed and were in experiment phase. The yield, cost, and returns data for these varieties was made available by Institute d'Economie Rurale, Government of Mali with collaboration of SANREM project. Table VII shows the yield of traditional (those used in the base model) and improved cultivars.

An important consideration in the wider adoption of improved cultivars is the adoption rate that shows the percentage of area under a crop using the improved cultivars. MASM has the ability to consider production of a crop with more than one technologies simultaneously (Chen et al., 1999; Butt, 2002). Being an optimization model, it would, if not restricted, shift 100% of the land under a crop from existing cultivars of the crop to its improved cultivars, which may not be real as not all farmers would adopt the improved cultivars due to various socio-economic considerations (Vitale, 2000). We, therefore, restricted the adoption rate in MASM to a maximum of 50% for each of the crops considered for this purpose (Kergna, 2000).[11]

5.3. IMPLEMENTING BIOPHYSICAL IMPACTS IN THE ECONOMIC MODEL

The results of climate change impact on the biophysical environment were incorporated in the Mali agriculture sector model (MASM). Changes in crop and forage yields, estimated from EPIC and PHYGROW, and animal weight, estimated from NUTBAL, were used to adjust relevant parameters in MASM so that the model

TABLE VII
Yields of existing and new cultivars (Kg./hectare)

	Improved cultivars	
Crop	Traditional	Improved
Maize	2531	6500
Rice	1600	7000
Cowpeas	1294	1900
Cotton	1386	2000
Sorghum	1500	1995
Millet	1325	1650

Source: Institute d'Economie Rurale, Ministère du Développement Rural, Govt. of Mali.

reflected the biophysical environment under the projected climate change. The procedure to implement crop yield changes in MASM, however, needs an explanation.

MASM base yields across the 12 yrs of weather history were adjusted to reflect changes in both the mean and the dispersion of yields using the procedure used in Lambert et al. (1995). Therein, the new yields became

$$\text{Yield}_i^{cc} = \text{MeanYld}^b \left(\frac{\mu^{cc}}{\mu^b}\right) + \left(\text{Yield}_i^b - \text{MeanYld}^b\right)\left(\frac{\sigma^{cc}}{\sigma^b}\right)$$

where superscripts *cc* and *b*, respectively, are for with climate change and without (base) parameters; MeanYld^b is the mean of the yields in the MASM base model; Yield_i^b and Yield_i^{cc} are yields for the *i*-th uncertain weather year under base (*b*) and climate change (*cc*) conditions; μ^{cc},μ^{bb},$\sigma^{cc}$and$\sigma^{bb}$are the mean and standard deviation of the simulated biophysical yields under base (*b*) and climate change (*cc*) conditions.

The procedure alters the mean yields by the ratio of means of simulated yields under base and climate change scenarios, while the dispersion around the mean is altered by the ratio of standard deviations of simulated yields under base and climate change scenarios.

To assess the economic and food security potential of various adaptive measures, we set up several scenarios; these were based on (1) regional shifts in crop mix, (2) trade adaptations, (3) adoption of heat-resistant cultivars, (4) cropland expansion, (5) adoption of improved cultivars, and combinations of scenarios 1 through 5.

To model regional shift in crop mix, we considered a southward migration of cropping pattern in Mali. For example, the cropping patterns in Tombouctou are applied to Segou (in the south), while those in Segou are applied to Sikasso (in the south).[12]

6. Economic and Food Security Implications

The collective effect of the changes in crop yields, forage yields and animal weight is an overall decrease in production resulting in an overall increase in price level. We provide cost of climate change impact in terms of changes in welfare as measured in terms of consumers' surplus (CS), producers' surplus (PS), and foreign surplus (FS). The CS measures welfare of consumers in terms of dollar value of utility derived from consumption at a given market price. As the market price increases, the consumption and utility levels fall so does the CS. The PS measures welfare of producers in terms of rent to (or value of) fixed resources used in production, which in our case were land and labor. As the market price increases, the rent to land and labor used in production increases so does the PS. The FS is a measure of trade surplus and is directly related to net export receipts (export receipt minus import payments). Within the limitations discussed in Just et al. (1982), the sum of CS, PS, and FS represents total welfare to the society for engaging in production of commodities included in the analysis.

The results of climate change impact without any adaptation to it are presented in Table VIII. As we imposed climate change on year 2030 conditions, which included degradation of cropland and rangeland, the results are presented considering 2030 conditions as base. We estimated an overall loss of welfare to be \$70 and \$142 million, respectively, under HADCM and CGCM projected climate changes, producers gain while consumers lose. The risk of hunger (ROH) increased from 44% of the population to 64 and 72% of population, respectively, under the HADCM and CGCM projected climate. The price index, which has a value of 100 in the Base (1996) conditions, is projected to increase by 76 and 145% under HADCM and CGCM. The results are presented in Table VIII.

TABLE VIII
Economic and food security indicators under the projected climate change

	Base		Climate change 2030		% Change from 2030	
	1996	2030	HAD	CG	HAD	CG
Price index (1996 = 100)	100	127	224	311	76	145
CS (\$ million)	655	568	401	315	−29	−45
PS (\$ million)	738	734	834	844	14	15
FS (\$ million)	14	6	2	6	−59	11
TS (\$ million)	1406	1308	1238	1166	−5	−11
ROH (% of population)	34	44	64	72	45	65

Note. Base (1996): Existing conditions.
Base (2030): Productivity loss due to land degradation.
HAD: Hadley coupled model projections for 2030.
CG: Canadian coupled model.
CS: Consumer surplus; PS: Producer surplus; FS: Foreign surplus; TS:CS + PS + FS.

6.1. EFFECTS OF ECONOMIC AND BIOPHYSICAL ADAPTATION

To examine the potential of economic and biophysical adaptations, we considered trade adaptation, shifts in regional crop mix, and heat-resistant cultivars. These adaptations were imposed on climate change impact as presented in Table VIII. Table IX shows improvements in the overall economic surplus and ROH, when different levels of adaptations were considered. Column TS(Rec%) shows the percentage of total loss recovered by adaptations, while column ROH(%) shows the percentage point reduction in the ROH. As Table IX shows, a significant amount of loss is reduced when adaptations are considered. More than 90% of the loss in total surplus is mitigated, while ROH is brought down to below 2030 base conditions. The benefits from adaptations through trade adjustments, crop mix migration, and adoption of heat-resistant varieties mitigated most the losses from climate change, which highlights the importance of these adaptations. Next, we examine the effect of cropland expansion and a wider adoption of existing improved varieties on mitigating climate change impact.

6.2. EFFECTS OF POLICY BASED ADAPTATIONS

The implications of climate change were also considered under cropland expansion (at the expense of rangeland) and adoption of new cultivars. Food security conditions showed a considerable improvement under scenarios for cropland expansion and adoption of high yielding cultivars, as the ROH is projected to decrease substantially. The ROH level reduced from 64 to 32% under HADCM and from 72 to 34 % under CGCM with increase in cropland, while in response to improve cultivars adaptation the ROH reduced to 31 and 32% under the HADCM and CGCM projections. The overall economic welfare also shows considerable gain under land expansion and adoption of improved cultivars. Table X shows the results of land expansion and adoption of improved cultivars.

TABLE IX
Potential of economic and biophysical adaptations

	HADCM (2030)		CGCM (2030)	
Adaptation type	TS(% Rec)	ROH (%)	TS (% Rec)	ROH(%)
Crop mix	33	−11	29	−7
Heat-resistant var.	33	−1	34	0
Economic	58	−7	58	−14
Full adaptation	107	−30	90	−35

Note. TS(% Rec): Percentage of total welfare loss recovered from 2030 base conditions.
ROH(%): Percentage point reduction in Risk of Hunger from 2030 base conditions.
HADCM (2030): Hadley coupled model projections for 2030.
CGCM (2030): Canadian coupled model projections for 2030.

TABLE X
Economic and food security indicators under high yield and area expansion scenarios with adaptations

	HADCM (2030)				CGCM (2030)			
Indicators	2030	Exp	HYld	ExpHYld	2030	Exp	HYld	ExpHYld
Price index	103	100	81	72	114	108	83	76
CS	596	597	604	608	577	583	598	601
PS	715	781	712	770	714	776	695	753
TS	2	3	9	13	3	4	10	19
ROH	34	32	31	28	38	34	32	28

Note. CS: Consumer surplus, PS: Producer surplus, TS: Total surplus, ROH: Risk of Hunger.
HADCM: Hadley coupled model projections for 2030.
CGCM: Canadian coupled model projections for 2030.
2030: Climate change impact with economic and technological adaptation.
Exp: Land expansion scenario, HYld: High yielding cultivars, ExpHYld: Land expansion and high yielding cultivars.

6.3. CLIMATE CHANGE IMPACT ON VARIANCE OF WELFARE MEASURES

As the structure of MASM allowed us to simulate market conditions across 12 yrs of yield history in Mali, we were able to compute the variance of the welfare measures. Table XI summarizes the coefficient of variation for the indicators whose average levels were presented in Table X under different scenarios. The variation in each of the surplus measures increased with climate change, while it decreased as adaptations were considered. For example, the coefficient of variation for consumer surplus increases by more than eight -fold under climate change, which ultimately falls below the base level when full array of adaptations are considered. The results indicate a further increase in risk in the Malian agriculture might be forthcoming with climate change, which might be reduced with appropriate adaptations.

TABLE XI
Change in coefficient of variation in welfare measures (Percentage changes)

		HADCM		CGCM	
	1996 Base	Without adaptation	With adaptation	Without adaptation	With adaptation
Consumer surplus	5	41	4	52	4
Producer surplus	6	15	2	15	2
Foreign surplus	224	390	176	336	350
Total surplus	8	31	6	37	6

Note: HADCM: Hadley coupled model; CGCM: Canadian coupled model.

6.4. EFFECTS OF POPULATION EXPANSION

Population is a critical factor to the future food security conditions in Mali. In the results discussed above, we did not consider any change in population so that the impact of climate change on food insecurity might be assessed separately from that of population. Also, it can be argued that population might not be exogenous to food production in Mali. Hence, linear projections of population based on historical trends might be misleading. However, we examined how sensitive food security conditions might be, if population change were incorporated in the analysis. For this purpose, we used population projections made by FAO for 2030 (FAO, 2002).

Population in Mali is projected to double in urban areas and increase by over 50% in the rural areas. Using these population projections, we set up demand conditions for agricultural commodities in MASM for the year 2030. Results show a quite precarious food security condition in Mali due to population growth. Under the relatively optimistic scenario considered in this study, land expansion along with the adoption of high yielding cultivars, show that the ROH may increase to 81 and 85% under HADCM and CGCM projected climate, respectively. Also, results show a high dependence on import of cereals, as the cereal import index rises by more than 13 fold.

7. Conclusions

The study concludes with the finding that Mali may experience moderate economic losses under the magnitude of climate change as projected by HADCM and CGCM models. The losses may be in the range from 70 to $142 million, under HADCM and CGCM projection. However, when distribution of losses is considered across producers and consumers, producers gain at the expense of consumers due to rise in prices. The risk of hunger in Mali may increase from 34% of the population 44% due to land degradation and further to 64 and 72% due to climate change as projected by HADCM and CGCM models. In terms of the FAOs' ranking of world countries by the risk of hunger, the study found that Mali might move from category 4 to category 5, which was the highest risk category.[13]

Various economic, biophysical, and policy adaptations can be pursued to mitigate climate change impact in Mali. Our results show that the benefits from adaptations through trade adjustments, crop mix migration, and adoption of heat-resistant varieties mitigated most of the losses from climate change. The results highlight the importance of land expansion and the adoption of high yielding varieties in providing higher economic benefits and improving food security conditions in Mali. Our results suggest that investing in reversal of land degradation, developing heat-resistant cultivars, and promoting the adoption of improved cultivars may better equip Mali in meeting the challenges posed by climate change.

Acknowledgement

This project was supported by the USAID SANREM CRSP and the Texas Agricultural Experiment Station.

Notes

[1]The model predictions are available under two scenarios; these are Greenhouse Gas Integrations (GG), and Greenhouse Gas plus Sulphate Aerosol Integrations (GS). In this study, we used GG, as this scenario has captured the observed signal of global-mean temperature changes better than GS scenario for the recent 100 yr record (Data Distribution Center).

[2] Figure 1 shows eight regions in Mali marked by Admin. II level boundaries. In MASM, we disaggregated Sikasso region into three sub-regions and represented Tombouctou and Kidal as one region. See Butt (2002) for detail.

[3] Agriculture sector models are different from their counter part general equilibrium (GE) models as the one used in Winters et al. (1998). In contrast to sector models, GE models may include several sectors of economy. However, GE models are of a rather aggregate nature and do not capture the detailed production environment as do agriculture sector models.

[4] Climatic variability is only modeled for crops. Livestock are modeled as deterministic for want of necessary information to do so.

[5] Information needed to set up EPIC simulation was not available for Tombouctou – the northern most region of Mali. EPIC responses from Segou region, closest to Tombouctou, were used as representative of Tombouctou.

[6] Plants are characterized into C3 and C4 species according to the phases of their photosynthesis. The C3 species are cotton, rice, wheat, barley, soybeans, sunflowers, potatoes, most leguminous and woody plants, most horticultural crops, and many weeds. The C4 species are: maize, sorghum, sugar cane, millet, and many tall tropical grasses, pasture, and forage and weed species. Of the two plant categories, C3 species benefit more from the elevated CO_2 level than do C4 species (Sombroek and Gommes, 1996).

[7] The choice of Mohandass et al. (1995) study was for two reasons. First, the study was conducted under the Hadley model climate change projections, which we used in our study. Second, both Mali and India have a comparable day-length and months of the rice growing season, which affect the overall growing environment for the rice crop.

[8]The information available restricted calibration of EPIC to observed crop yields only in Sikasso region. Hence, the trend regressions were estimated for 43 agro-ecological zones in Sikasso. The degradation estimates averaged across agro-ecological zones in Sikasso-North, a relatively dry area, were applied to other areas in Mali.

[9] For example, sorghum has 1600 HUs. It will take longer for the crop to mature in colder areas as it will take longer to accumulate 1600 HUs compared with the situation in warmer areas. Thus, the length of growing season for a crop is determined by its biological life, which EPIC measures in terms of HUs. As temperature is increased, EPIC simulations show an early maturity of crops, which restricted the size of grain due to hardening of its crust leading to lower crop yields.

[10] The average gain due to heat-resistant varieties adaptation for other crops was used as a surrogate to reduction in rice yield loss.

[11] The adoption rate used in this study is a subjective assessment of a local extension expert based on his experience in the field. Although alternative rates might be used, the rate we used is only to indicate the potential of improved cultivars in reducing climate change impact.

[12] The reader should note that Mali is located in south of the Sahara desert. The climate in Mali becomes mild with southward movement. As temperature increases in the southern regions, one would expect these regions to benefit by adopting the cropping patterns of northern regions.

[13]FAO has developed a ranking of world countries based on the 'risk of hunger' criteria that was used in this study. The ranking ranges from 1 to 5; 1 being the countries that have lowest exposure to hunger, while 5 being those countries that have the highest exposure to hunger.

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(Received 13 March 2003; in revised form 6 April 2004)