Agricultural Drought Impacts on Crops Sector and Adaptation Options in Mali: a Macroeconomic Computable General Equilibrium Analysis

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Abstract

In Mali's current context where the crops sector is particularly exposed and vulnerable to agricultural drought, this study assesses the economy-wide impacts of such events and the potential effectiveness of some adaptation strategies. Using a dynamic computable general equilibrium model, we conduct counterfactual simulations of various scenarios accounting for different levels of intensity and frequency of droughts over a 15-year period. We first show how mild, moderate, and intense droughts currently experienced by the country affect its economic performances and considerably degrade its households' welfare. We also show how these negative impacts could be aggravated in the future by the likely increased number of intense droughts threatened by global climate change. However, we finally show that there appears to be some room for Mali to manoeuvre in terms of drought-risk management policies, such as fostering the use of drought-tolerant crop varieties, improving drought early warning systems or extending irrigation capacities.

Keywords: Climate variability, General Equilibrium, Agriculture, Food Security, Mali

JEL classification: C68, O13, Q54

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1. Introduction

The Malian climate in recent years has been characterised by changing conditions and a growing number of drought events with varying degrees of severity (Masih et al. 2014). Although droughts are not extraordinary events in Mali but are a natural part of the Western Sahel ecosystem, this low-income country is particularly vulnerable to such one-off climatic hazards. It is heavily reliant on its crop production sector which represents a main source of the livelihoods and food available to households. But this mainly rain-fed agriculture is relatively unproductive and finds it difficult to meet the needs of the rapidly growing population. Living conditions are therefore highly precarious, especially in rural areas, characterised by endemic poverty, chronic food insecurity, and poor adaptive capacities (Eozenou et al., 2013).

In this context of substantial exposure together with high economic and social vulnerabilities, where any drought event may turn into a disaster with immediate but potentially long-lasting consequences for the economy and households' welfare (De Sherbinin et al., 2014; Shiferaw et al. 2014; Gautier et al, 2016), this study seeks to assess the risk of droughts hazards in Mali and the potential benefits of some coping strategies. To our knowledge, such assessments have not been conducted previously for this country; extant studies mainly investigate the adverse consequences of projected long-run average temperature or precipitation trends and their associated impacts on yields or land or water availability (for example, Butt et al., 2005; FAO, 2012; Giannini et al. 2017). But focussing on such mean shifts probably leads to underestimate Mali's vulnerability to changing climatic conditions, which also depends on questions of variability and, in particular, of drought events.

We use a dynamic recursive computable general equilibrium (DRCGE) model including various specifications of the potential effects of droughts on the Malian crops sector. Such a framework seems indeed better adapted to an economy-wide analysis of agro-climatic shocks than other frameworks (for example Ricardian or partial equilibrium analyses). Grounded on the Walrassian theory, it does not restrict the effects of shocks to agriculture alone but also captures their influences in the overall economy, through linkages among prices, income, supply, and demand. Moreover, with a dynamic specification, it also can generate time paths of the effects of successive shocks on economic and social variables. In economic literature, a growing number of CGE studies assess the vulnerability of low income countries, where agricultural production is weather sensitive and adaptive capacities are low. Most of them adopt a deterministic approach to long-run climate change–related conditions (for example, Bezabih et al., 2011; Calzadilla et al., 2013; Gebreegziabher et al., 2016); others try to include variability features using stochastic or probabilistic scenarios (for example, Arndt et al., 2011; Arndt et al., 2014; Arndt and Thurlow, 2015). But very few studies focus on the risks that one-off climatic events represent for a country, by adopting either ex post historical approaches (for example, Al-Riffai and Breisinger, 2012) or ex ante hypothetical future approaches (for example, Pauw et al., 2011; Sassi and Cardacci, 2013). We chose here these last approaches and simulate the impacts of various sequences of drought events in Mali over a 15-year period. We first focus on the effects of different categories of drought (mild, moderate, or intense) when they occur, as observed in past years in the country. But, because global warming threatens increases in intense droughts in the Sahel (Dai, 2011; Zhao and Dai, 2016), we also investigate the effects of such potential changes for Mali. Finally, we explore some risk management strategies to determine how they might contribute to reducing the adverse consequences of droughts.

Section 2 details Mali's current vulnerability to drought hazards. Section 3 describes the main features of the DRCGE model and our hypotheses pertaining to defining the drought scenarios. Section 4 contains the results of the simulations, and Section 5 outlines some effective coping policies that could be implemented in the country.

2. Background

Located on the southern edge of the Sahara desert, Mali is a land-locked country listed amongst the least developed economies and ranked near the bottom of the UN's human development index. The agricultural sector is the backbone of its economy, accounting for 41% of the national gross domestic product (GDP) and employing 75% of the workforce. But this sector suffers many handicaps (FAO, 2012). Crop production is geographically highly concentrated in limited arable lands where climatic conditions are the most favourable, mainly in the Southern Sudanic zone and the inlet delta of the river Niger. It is also poorly diversified (see Table 1). Cash-crop cultivates focus on cotton and rice. Subsistence crop production, by far the most important sector, is mainly devoted to millet, rice, sorghum, and maize, which represent nearly 80% of total production and are the basic staples of the Malian diet. But with its rain-fed, small-scale, traditional farming techniques, this subsistence sector provides particularly low yields. The livestock sector, which includes millions of cattle, sheep, and goats, is also of key importance, accounting for 14% of Malian GDP. But most of this sector relies on small-scale, nomadic, pastoral systems with a low average rate of herd utilization and low productivity levels. In this context, living conditions of the fast-growing Malian population are particularly poor. Although Mali experienced an overall drop in poverty in the 2000s, it remains endemic, especially in rural areas, where 77% of the overall population lives and which contribute 90% to the national poverty rate. These rural areas are also affected by chronic malnutrition representing 84% of the overall malnourished population of the country (Eozenou et al., 2013).

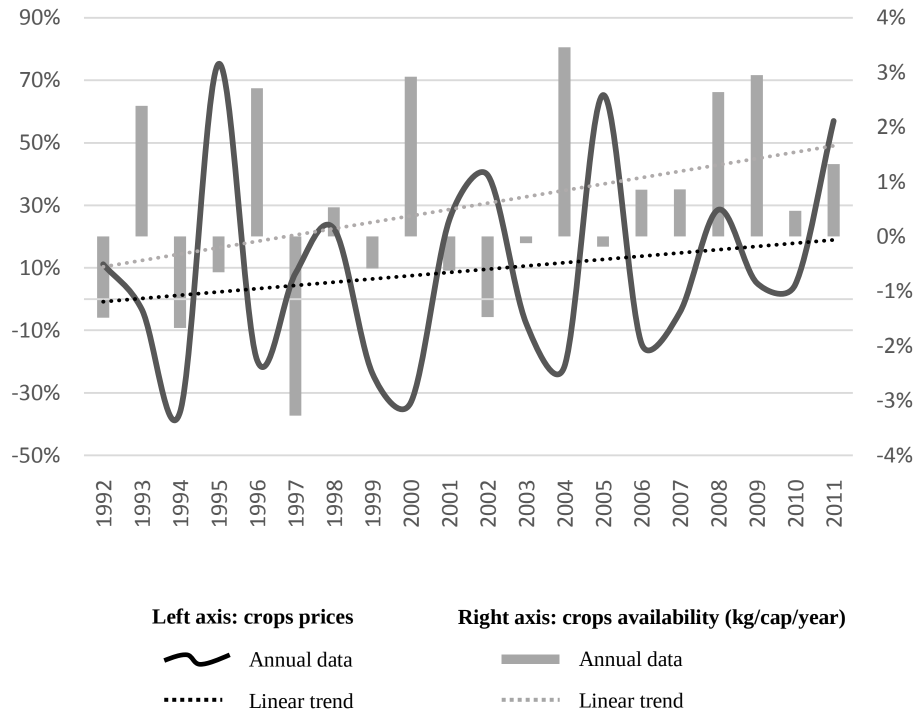
TABLE 1 – Share of different cultivars in total crop production in Mali (average values for 2001-2010)

	All crops
Millet	23,9%
Rice Paddy	21,6%
Sorghum	17,9%
Maïze	14,8%
Cotton	8,5%
Sugar cane	5,6%
Peanuts	4,6%
Legumes	1,8%
Fonio	0,6%
Wheat	0,2%
Gombo	0,2%
Bambara pea	0,3%
Total	100,0%
Top 4	78,2%

Sources: own calculation from FAOSTAT data

In such a fragile situation, any shock to the agricultural sector thus can have serious implications for economic performance and households' welfare. Figure 1 indicates for instance how prices and quantities of the main cereals cultivated and consumed in the country (Millet, Rice-Paddy, Maize and Sorghum) have been particularly instable over the last decades. Across a wide range of shocks (for example, locust invasions, livestock and plant diseases, price instability, political instability and insecurity, etc.), the risk related to climatic conditions may be the most severe (De Sherbinin et al., 2014; Birkel and Mayewski, 2015; Padgham et al. 2015; Sultan and Gaetani, 2016). Mali's climate is indeed changing, along with the whole Western Sahel—one of the world's climate change hotspots (Turco et al., 2015). In the past 50 years, Mali has experienced an increase in mean temperatures, changes in rainfall patterns, and variations in the onset and end of the growing season in many parts of the country (McSweeney et al., 2010), with direct, adverse impacts on its yields, production, land dryness, and water availability. Furthermore, Mali's climate has also been characterised by significant high annual variability, particularly noteworthy with regard to the steep increase of drought events (Dai, 2011; Kotir, 2011; Masih et al., 2014). The primary effects of such events are well identified in economic literature (for example, lower yields, harvest failures, water scarcity, epizootic diseases, rises in food prices, food scarcity, exacerbated conflicts, rural-to-urban migrations; Thornton et al. 2014; Gautier et al., 2016), yet producing reliable estimations of past direct or indirect impacts in Mali is difficult. First, drought has a creeping nature, and its onset and end sometimes are difficult to determine. Second, each event is unique, depending on its location within the country, its period of occurrence and duration, and the potential co-occurrence of associated risks that increase its impact (for example, locust invasions). Third, there is a general lack of updated and accurate data on agricultural production or on long-run series of households' living conditions indicators which makes it even more difficult to evaluate the impacts of droughts on Malian households' welfare. However, such events and the resulting year-to-year variations of agricultural production and prices clearly seem to be closely intertwined with poverty and food security issues. Eozenou et al. (2013) show for instance that, following the 2011 drought, the number of food poor people in Mali increased by 610,000 (from 22% to 26% of the population), due to both price increases and diminished cereal production.

Figure 1 - Annual variation of prices and of availability of main crops in Mali [(1)]



Note: [(1)] Sorghum, Millet, Maize and Rice paddy
Sources: own calculations from FAOSTAT database

3. Methodology

3.1 DRCGE model

We adapt here the standard PEP-1-t model proposed by Decaluwé et al. (2013). These authors offer a full description of their model; therefore, we simply outline its main characteristics and the changes we introduced to reflect the Malian economy and some specific one-off effects of drought on agricultural activities. Our model features two groups of households (*rural* and *urban*), one government agent, one firm agent, three agricultural activities (*subsistence agriculture, cash-crop agriculture,* and *livestock*), five industrial activities, and two service activities. Its within-period specifications rely on fairly standard general equilibrium assumptions for low income countries. On the supply side, each producer maximises its profit by combining labour with capital (assumed to be fixed for each given period), which for agricultural activities is specific to land stock or herds. On the income side, each agent receives factor revenues on the basis of its initial endowments and secondary revenues from government or other agents. With regard to demand, households' consumption follows a linear expenditure system function and government's consumption is exogenous. On the markets side, the prices and wages are determined endogenously (the numeraire is the nominal exchange rate) and the nominal investments are saving driven in the capital market. The between-period specifications of the model are recursive with a main assignment pertaining to the accumulation of capital in each activity as determined in the preceding period.

The first modification of the standard model involves the potential effects of drought on the crop activities. In the latter, for a given period *t*, we assume first that the total factor productivity parameter ($\beta_{j,t}^{VA}$) depends on an exogenous annual growth rate (β_{yields}), reflecting a Hicks-neutral technical change in the production process (equation 1). FAOSTAT database shows indeed that, in the past decades, average crop yields have increased in Mali (because of land use rationalization, better use of organic or chemical input, improvement of farming techniques, better institutional environment, etc.). We moreover assume that it depends on a random negative annual effect ($dyields_{j,t}$) when a drought occurs. Such random drought impacts is also introduced on land stock reflecting deterioration or higher depreciation rates. Crop land expansion in a normal year (β_K) thus would be reduced in a drought year ($d_{Kj,t}$), with a two-year post-drought recovery period (equations 2a, 2b and 2c).

$\forall j \in \{Crop\ activities\}$

(1) $B^{VA}_{j,t} = B^{VA}_{j,t-1} \cdot \left(1 + \beta_{yields_j} + dyields_{j,t}\right)$

With dyields <0 for a year of drought occurrence and =0 for other years

(2a) $Land_{j,t} = Land_{j,t-1} \cdot \left(1 + \beta_{Land} + d_{Land\ j,t}\right)$

(2b) $Land_{j,t+1} = Land_{j,t} \cdot \left(1 + \beta_{Land} - d_{Land\ j,t} / 2\right)$

(2c) $Land_{j,t+2} = Land_{j,t+1} \cdot \left(1 + \beta_{Land} - d_{Land\ j,t} / 2\right)$

With d_{Land}*<0 for a year of drought occurrence and =0 for other years*

The second modification pertains to the labour market. First, we chose to capture the urban–rural dualism of this underdeveloped economy by including two distinct segments with two different wage rates. Disguised unemployment exists in the rural segment (75% of the labour force), such that the wage earned by agricultural workers (mainly family workers) is lower than the urban wage at the initial equilibrium. For a given period *t*, rural and urban labour supplies are exogenously predetermined, and workers flow freely across all activities in each area but not among areas. The labour force supplies in urban ($LSurb_t$) and rural ($LSrur_t$) areas grow over time, given an exogenous population growth rate (n_t), but also depend on rural-to-urban migrations ($Migr_t$) that may occur between periods (equations 3a, 3b and 3c). An implicit assumption is that such migrations take place after a harvest failure and are a way to cope with drought (for example Marchiori et al. 2012; Gautier et al. 2016). We thus consider a one-period lag, assuming that it takes some time for workers to decide to migrate and that the adjustments are not instantaneous, as is conventionally assumed in other CGE models. The incentives to migrate then should be determined by the ratio of the respective average purchasing powers that prevail in urban and rural areas in the previous period, which depend on the respective households' nominal income ($YHurb_t$ and $YHrur_t$) and index prices ($Purb_t$ and $Prur_t$). The latter reflect the typical basket of goods consumed by rural or urban households, respectively, at the initial equilibrium.

(3a) $LSrur_{t+1} = LSrur_t.(1+n_t) - Migr_t$

(3b) $LSurb_{t+1} = LSurb_t.(1+n_t) + Migr_t$

(3c) $Migr_{t+1} = \Psi^{MIGR}.\ln\left[{YH_{Hurb,t}}/{Purb_t} \Big/ {YH_{Hrur,t}}/{Prur_t} \right]$

Finally, we have also included two food security indicators in the model for each area: a *food access index* measures the food purchasing power of households, depending on both their nominal income per capita and the food price index, and a *food availability index* measures the volume of overall food supply per capita.

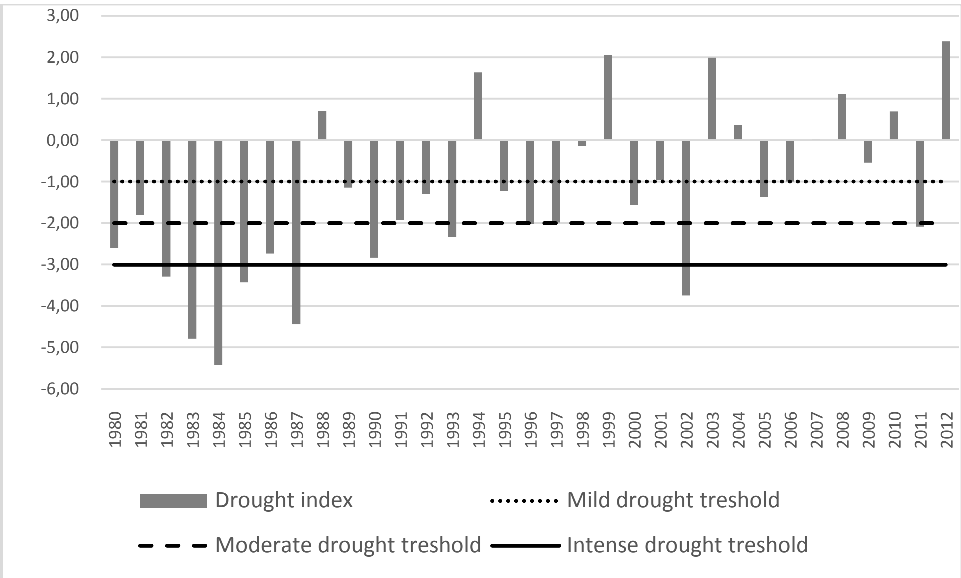
The DRCGE model will be used to generate time paths for the evolution of Malian economy by simulating numerically successive general equilibriums that is, for a given period *t*, the vector of prices and wages for which demand equals supply in all markets simultaneously. For that purpose, we first define an initial equilibrium of the model on the basis of the last social accounting matrix (SAM) built for Mali, which depicts the observed structure of the economic system and the monetary flows associated with all transactions that have taken place between agents in the economy in 2013. This SAM is also used to calibrate different parameters in the within-period specifications of the model. If such calibrations are not possible, we obtain parameters from extant CGE literature. Second, as is common for dynamic CGE modelling, we define a business as usual (BAU) scenario by updating, from one period to the next, some constants and exogenous variables of the model. Most updates refer to the annual medium population growth rate (n_t), which the United Nations projects to be close to 3.1% for Mali. For crop yields and land stock expansion (β_{yields} and β_{land}), we use historical data from FAO over the period 1980–2013, which indicate rates of 0.8% and

3.5%, respectively. For the between-period migration function parameter (ψ^{MIGR}), in the absence of better information, we use the last Population Census, conducted in 1998. It shows that migrations within Mali are mainly from rural towards urban areas, with a migration rate close to 1%. This BAU scenario will be therefore taken as a benchmark scenario for all other simulations of drought-scenarios. At this point, it should be however outlined that these simulations are here *ex-ante* counterfactual experiments whereby the impacts of droughts are evaluated *ceteris paribus* by comparing between what happen *with* and *without* the events. Within this framework, these results should not thus be understood as forecasts but only as differences of the evolution of the economic system that can be attributed to droughts.

3.2 Definition of drought scenarios

We deliberately set the time horizon for the different drought scenarios relatively short (15-year period), to exclude the potential effects of significant structural changes in the economy and thus maintain the consistency of the initial calibration of the model. Each scenario is defined according to two key parameters: the intensity of each annual drought-related shock on the crop sector and the frequency of occurrence of events over the simulation period. We first started with what has been observed in the country in recent decades. In scientific literature, drought can refer to deficits of precipitation (meteorological drought), negative anomalies in water levels (hydrological drought) or deficits of soil moisture (agricultural drought). Given the objective of this study, we focus on the latter and build a weighted National Agricultural Drought Index using the Palmer Drought Severity Index (PDSI) improved with the Penman-Monteith (pm) equation. PDSI is indeed a common measure of agricultural drought using temperature data and physical water balance model to estimate relative dryness. Improved with the Penman-Monteith equation (PDSI-pm), it also accounts for the potential evapotranspiration (see for instance Dai, 2011). In last decades, PDSI-pm have been calculated monthly at a regional level for Mali. But, given that a drought affects agriculture mainly during growing seasons, we only retained relevant months for each region, according to their respective crop calendars. Moreover, given that the regions do not account for the same weight in the nation's overall crop production, our National Agricultural Drought Index is a weighted average of the regional PDSI-pm. Results show that, between 1982 and 2011, Mali has experienced six intense (three extreme and three severe), four moderate, and nine mild agricultural droughts (Figure 2).

FIGURE 2 - Estimated historical weighted national agricultural drought index for Mali



Source: Own calculation, based on data provided by the Climatic Research Unit of the University of East Anglia, the NCAR for PDSI-pm (http://tools.harvestchoice.org/rainfall/), and the FAOSTAT database for regional considerations.

On these bases, we use a two-pronged approach to define our drought scenarios. In a first step, we will run the model to evaluate the effects generated by each category of events when they occur as observed in past years. Regarding their respective annual impacts, the FAO data indicate that in the past ten years, intense, moderate, and mild droughts have been characterised by annual average deviations from agricultural crop yields ($dyield_{j,t}$) close to -27%, -18%, and -11%, respectively, as well as by annual average losses of harvested lands

($dland_{j,t}$) close to -20%, -4%, and 0%. Regarding the frequency of occurrence of each category, we have no choice but to develop a subjective prior distribution. We consider a binomial distribution with a probability p. As observed in Figure 1, this probability has been close to p=0.2, p=0.13, and p=0.30 for intense, moderate, and mild droughts, respectively. For each category, we will use these historical levels to generate a significant number (100) of annual weather sequences, including drought events at random over the next 15 years. We will simulate each sequence with the DRCGE model and compare it against the BAU scenario. The mean of these 100 simulations thus will provide an average of the representative impacts of a "normal" occurrence of each category of drought in Mali.

In a second step, we will consider the impacts of increased frequencies of intense agricultural droughts. At this stage, we focus on these intense events because they are those for which farmers cannot really adapt, such that they represent greater risks for Malian agriculture. Furthermore, such events are the threats most likely to increase due to on-going global climate change (IPCC, 2012). However, climate models are not really able to predict them accurately because the factors that influence a drought in the Western Sahel are complex (see for example, Burke and Brown, 2008 or Zhao and Dai, 2016). In such an uncertain context, we thus will rely on a conservative approach with distinct hypotheses about the future higher occurrence of intense droughts: *optimistic* (p = 0.27, n ≈ 4), *medium* (p = 0.33, n ≈ 5), and *pessimistic* (p = 0.40, n ≈ 6). Here again, we will simulate 100 annual weather sequences, generated at random, for each probability level.

4. Results

4.1. Scenarios with "normal" occurrences of mild, moderate and intense droughts

Table 2 presents selected results of the simulations for the scenarios where mild, moderate and intense droughts occur at random as observed in past years. These results are comparable to what has been observed in Mali during the last decades. Though we obtained them with a different framework and methodology, they also align with the results of other CGE studies that have focused on extreme events (for example, Pauw *et al.*, 2011 for Malawi; Al-Riffai *et al.*, 2012 for Syria). We first note that, when it occurs, one mild, moderate, and intense event causes an average one-off reduction from the BAU in the agricultural GDP of -5.4%, -10.3%, and -22.4%, respectively, along with an increase in agricultural prices of 11.8%, 24.2%, and as much as 58.9% in the intense drought scenario. Given the importance of the crop sector and its direct and indirect links with other sectors these effects cascade down through the entire national economy. In a drought year, the real GDP deviates from the BAU by -2.8%, -5.6%, and -13.1%, and the price index shifts by 5.1%, 10.6%, and 25.9% in the three respective scenarios. In this new general context, social indicators also degrade sharply. Drought events have strong impacts on real income per capita for all households, and this decrease is logically greater in rural than in urban areas. The effects on food security are particularly striking: Due to decreased agricultural production, according to the food availability index, per capita supplies of foodstuffs fall by -4.4%, -8.0%, and -16.7%, depending on the drought intensity. Similarly, as a result of food price increases and income per capita decreases, the food access index signals the decrease in per capita food consumption, especially in rural areas (-6.3%, -11.9%, and -25.3%) relative to urban areas (-2.5%, -5.2%, and -12.5%). Finally, each drought event exerts a strong impact on annual migration processes (15.8%, 30.9%, and 66.9%), because lower purchasing power in rural areas (cf. urban areas) induces households to migrate to cope with the drought.

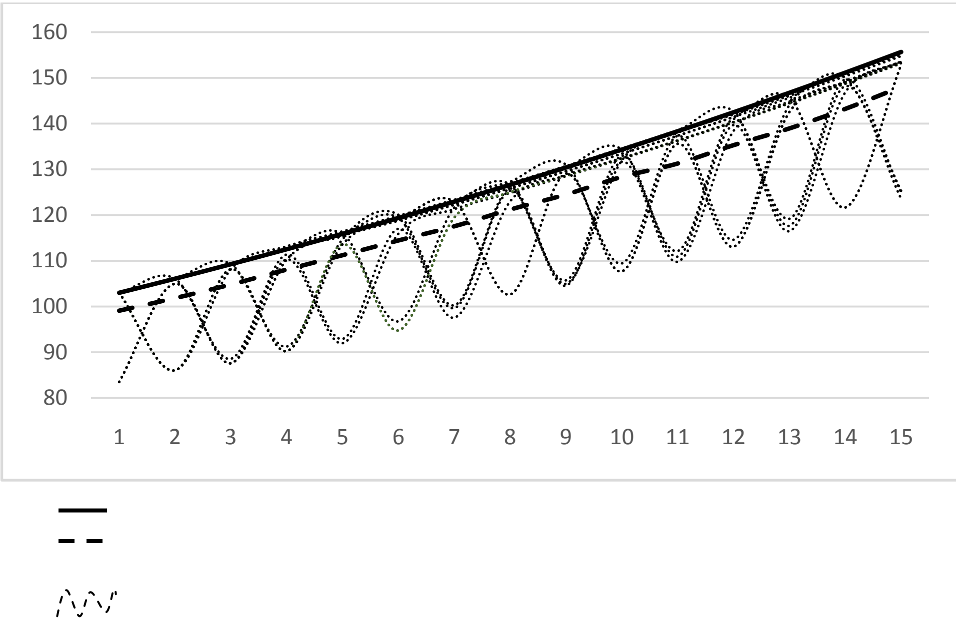
If we focus now on the average deviation from the BAU scenario that each sequence of drought generates over the period, it should be noted that, although they have lesser one-off annual impacts than moderate droughts, mild droughts generate higher mean impacts over the period, because they are more numerous. For example, relative to the BAU scenario, successive events cause an average decrease in the national GDP of -0.8%, -0.7%, and -2.6% and in the agricultural GDP of -1.6%, -1.4%, and -4.5%, for mild, moderate, and intense drought scenarios, respectively. Such average effects are for instance illustrated in Figure 3 for the agricultural GDP under the intense drought scenario. The impacts on prices are also powerful; on average, each sequence of events prompts relative average increases in national prices (1.5%, 1.4%, and 5.2%) and agricultural prices (3.5%, 3.2%, and 11.8%). In this context, households' welfare degrades sharply, with strong average decreases of real income per capita for rural households (-1.2%, -1.1%, and -3.6%) and urban households (-0.3%, -0.3%, and -1.2%), as well as degraded food security indicators and increased migration flows.

TABLE 2 - Selected average impacts of different categories of drought occurring with a "normal" frequency over a 15-year period
(Deviation in % from the BAU scenario)

	Average effects of droughts over the period			**Average one-off effects of a drought when it occurs**		
	Mild	***Moderate***	***Intense***	***Mild***	***Moderate***	***Intense***
Annual probability of occurrence of drought	***p=0.30*** *(n ≈ 4.5)*	***p=0.13*** *(n ≈ 2)*	***p=0.20*** *(n ≈ 3)*	***p=0.30*** *(n ≈ 4.5)*	***p=0.13*** *(n ≈ 2)*	***p=0.20*** *(n ≈ 3)*
Economic indicators						
National real GDP	-0,8	-0,7	-2,6	-2,8	-5,6	-13,1
Agricultural real GDP	-1,6	-1,4	-4,5	-5,4	-10,3	-22,4
National prices index	1,5	1,4	5,2	5,1	10,6	25,9
Agricultural prices index	3,5	3,2	11,8	11,8	24,2	58,9
Households'welfare indicators						
Real Income per capita						
Rural households	-1,2	-1,1	-3,6	-4,1	-8,1	-17,9
Urban households	-0,3	-0,3	-1,2	-1,0	-2,2	-5,8
Food access per capita						
Rural households	-1,9	-1,6	-5,1	-6,3	-11,9	-25,3
Urban households	-0,8	-0,7	-2,5	-2,5	-5,2	-12,5
Food availability per capita						
Rural households	-1,3	-1,1	-3,3	-4,4	-8,0	-16,7
Urban households	-1,3	-1,1	-3,4	-4,5	-8,2	-17,2
Rural to urban migration flows	4,8	4,1	13,4	15,8	30,9	66,9

Source: Own calculations with GAMS software (results computed from the simulations of 100 randomised drought sequences for each category of drought)

FIGURE 3 – Evolution of real agricultural GDP for the BAU and 30 randomised sequences of intense droughts with "normal" frequency
(Base of 100 at initial equilibrium)



Source: Own calculations with GAMS software

4.2 Scenarios with increased frequency of intense droughts

Table 3 presents selected results of the simulations for the scenarios assuming different increases in the number of intense droughts. To separate out the effects due to changing climatic conditions from the effects due to "normal" occurrences of intense droughts, we now compare the simulations' results with the *representative normal intense drought scenario* estimated in the previous section. These results show how the higher than "normal" number of intense droughts would increase their average impacts on the macroeconomic and welfare indicators, according to the level of climate variability considered. In the most unfavourable scenario, an average number of six events over the next 15 years (p = 0.40) would cause mean deviations of -2.4% in the national GDP (-4.5% for agricultural GDP) and 4.6% for national prices (9.0% for agricultural prices). Similar shifts would emerge among the social indicators. Rural households would suffer an average decrease in their income per capita of -3.5% and diminished food security indicators (-5.1% for food access index, -2.3% for food availability), along with increased migration flows (9.9%).

TABLE 3 - Selected average impacts of intense drought sequences over a 15-year period under different hypotheses for events' frequency
(Deviation in % from the *Representative normal intense drought* scenario)

	Average effects of droughts over the period			**Average one-off effects of a drought when it occurs**		
	Optimistic Scenario	***Medium Scenario***	***Pessimistic Scenario***	***Optimistic Scenario***	***Medium Scenario***	***Pessimistic Scenario***
Annual probability of occurrence of drought	***p=0.27 (n≈4)***	***p=0.33 (n≈5)***	***p=0.40 (n≈6)***	***p=0.27 (n≈4)***	***p=0.33 (n≈5)***	***p=0.40 (n≈6)***
Economic indicators						
National real GDP	-0,8	-1,8	-2,4	-2,9	-6,7	-9,1
Agricultural real GDP	-1,3	-3,2	-4,5	-5,0	-11,8	-16,7
National prices index	1,4	3,2	4,4	5,2	11,8	16,4
Agricultural prices index	2,9	6,5	9,0	11,0	24,4	33,7
Households'welfare indicators						
Real Income per capita						
Rural households	-1,1	-2,5	-3,5	-4,0	-9,3	-13,0
Urban households	-0,3	-0,8	-1,0	-1,3	-2,9	-3,8
Food access per capita						
Rural households	-1,5	-3,6	-5,1	-5,7	-13,5	-19,2
Urban households	-0,7	-1,7	-2,3	-2,7	-6,4	-8,7
Food availability per capita						
Rural households	-1,0	-2,3	-3,3	-3,7	-8,7	-12,2
Urban households	-1,0	-2,4	-3,3	-3,8	-9,0	-12,5
Rural to urban migration flows	3,3	7,2	9,9	12,2	26,9	37,1

Source: Own calculations with GAMS software (results computed from the simulations of 100 randomised drought sequences for each probability of occurrence *p*)

5. Exploring drought adaptation strategy options

There is little Malian farmers can do to alter their drought exposure, yet some coping strategies aimed at reducing their vulnerability could help minimise, over time, the adverse consequences of the events. In agro-economic literature, a broad spectrum of options has been identified as efficient in drought-prone areas: adopting suitable farming practices enables to restore degraded drylands and increase soil fertility (Zaï pit technique for instance), adjusting cropping patterns and planting date, intercropping different crops species, selecting drought tolerant varieties of crops, improving water management, using weather forecasts or early warning systems, etc. Most of these strategies are already used by farmers in places to deal with drought hazards. But, in a context of an increase of occurrence of droughts, these strategies would deserve to be fostered for enhancing resilience and strengthening adaptive capacities of farmers (see for instance, Rhodes et al., 2014; Shiferaw et al., 2014; Wilhite et al., 2014; USAID, 2014; Giannini et al., 2017). In this spirit, following the Climate-Smart Agriculture Framework (see for instance Lipper et al., 2014 or Campbell et al., 2016), a prioritization process has recently been led in Mali (from October 2014 to October 2015) in order to identify the best practices that could transform and reorient Malian agricultural systems in the face of climate change (Andrieu et al., 2017). We choose here to focus on three promising options which are also part of the Malian National Policy on Climate Change (AEDD, 2011) and of the Malian National Adaptation Programme of Action (NAPA) submitted to the United Nations Framework Convention on Climate Change in 2011 (see République du Mali, 2007 or Padgham et al., 2015): a wider use of drought-tolerant crop varieties, an improvement of drought early warning systems and an extension of irrigation capacities.

5.1. Fostering the use of drought-tolerant crop varieties

For a long time, selecting crop varieties better adapted to drier conditions and to shorter agricultural calendar, has been a strategy used by West-African farmers to manage drought risk. Such traditional breeding has provided over time a lot of varieties with higher drought tolerance and stable productivity. However, with the ongoing higher climate variability, a more systematic use of new varieties appears now necessary (see for instance, Shiferaw et al, 2014, USAID, 2014, ODI, 2015). Recently, new agronomical technologies based on genetic improvement (for instance marker-assisted breeding or genetic engeneering) have opened great opportunities for plant selection and, in many parts of Africa, several national and international research institutions have scored important gains in improving the drought tolerance of major crops (for an overview, see Xoconostle-Cazares et al 2010, Shiferaw et al 2014 or Sultan and Gaetani, 2016). In Mali, a lot of early and resilient varieties of main crops (millet, sorghum, cotton, sesame, rice, maize, corn, cowpea, groundnut or market gardening) have for instance already been identified by the Institute of Rural Economics for different agro-ecological areas of the country (FAO, 2017). But, although they demonstrate a certain tolerance compared to climatic variations, they are still currently little used by farmers (CGIAR, 2015).

In this context, our first drought adaptation scenario considers an extension of the use of such drought-tolerant crop varieties in the country. This scenario relies here on three main hypothesis. First, we chose to consider that the introduction of new cultivars only concerns the main crops which are the basic staples of the Malian diet (millet, rice, sorghum, and maize) that is 80% of total crop production. Second, regarding the yield gains that could be expected with these new varieties we chose here to rely on a conservative approach. Although substantial progress has been made in the assessment of the potential for adaptation of new cultivars in West Africa, their responses to changing climatic conditions remain largely uncertain. Large gaps exist in studies based on process-based crop models because of a lack of sufficient data for accurate validation of models or inappropriate assumptions for low intensive agricultural systems (see for instance Hertel and Lobell, 2014; Sultan and Gaetani, 2016). Moreover, varietal change doesn’t result automatically in substantial average productivity change without complementary good agricultural practices. CGIAR (2015) indicates for instance that, for most African countries, the use of shorter duration varieties that escape drought could lead to potential productivity gains by 30–50% in high production potential environments, where soil fertility is not as constraining and where agriculture is supported by favorable input policies. But in most rainfed environments, where agricultural input (such chemical fertilizers or pesticides) are not readily available, it seems more reasonable to expect relative yields by 10–30%. In the most unassured production zones, such increase could even be as small as 10%. In this context, given the low production potential environment of crops sector in Mali, our scenario assumes a conservative average yield gain attained from using improved varieties by 20%. Third, we also consider different adoption rates by farmers (that is different percentages of land under use for the new cultivars) ranging from 25% to 100% at the end of the 15-year period. The adoption of new crop varieties by farmers depends indeed on various socio-economic and institutional considerations at local and national level. For example, it could not be achieved without a considerable political commitments in awareness campaigns, technical assistance, strengthening of seed systems to ensure an availability and affordability of seeds, improving of access to credit for farmers (see for instance, Thornton et al., 2011).

Table 4-1 depicts some potential buffering effects of such strategy under the different climatic scenarios for intense droughts. For conciseness, we only present the results for rural areas which are the ones most affected by drought events. Results show that, as expected, a wider use of new crop varieties could reduce drought-related impacts according to the extent of land surface considered. In some cases, the average impacts over the period of each drought sequences could even be overcome. Under the normal scenario, the negative impacts of current climate variability on agricultural GDP, rural income and rural food security could be neutralized from a threshold level between 75% and 100% of land area sown with new varieties. Under climate change scenarios, the mean impacts on agricultural GDP of a higher than “normal” number of intense events could be neutralised at land surface thresholds close to 50% under the optimistic scenario and between 75% and 100% under the medium scenario. However, this neutralization threshold cannot be achieved under the pessimistic scenario. In turn, rural households would benefit from the strategy though, with potential offsets of the average negative impacts of additional droughts on their real income and food security for a neutralization threshold of 50% for the optimistic scenario, and between 75% and 100% for the medium scenario. These thresholds would however never be achieved for the pessimistic scenario, even if the adverse impacts of an increased number of droughts diminished substantially compared with the scenario without any cultivar adaptation.

Results in Table 4-2 show that such a strategy could also be worthwhile according to cost-benefit criteria although it should be stressed that estimating this cost is quite difficult. We use here the data from the *Technology needs assessment report* prepared by Mali for UNFCC (République du Mali, 2010) which assessed an average costs of using new varieties; on these basis, an achievement of 100% rate of utilization of new cereals variety could for instance represent an overall investment of 52 USD million. On this basis, whatever the scenarios, the results show that each dollar invested in the use of new crop varieties would generate an average net return close to 100 USD in terms of national GDP.

5.2. Extending the use of drought early warning systems

Drought early warning systems (EWS) are designed to identify climate and water supply trends and thus to detect the emergence or probability of occurrence and the likely severity of a drought event. Multiple studies clearly demonstrate that, by providing to farmers the timely and reliable information necessary to make appropriate decisions regarding the management of water and sowing, EWS could be a key element for reducing drought disaster risk (see for instance, Rhodes et al., 2014, Shiferaw et al., 2014; Pulwarty et al, 2014; Wilhite et al., 2014). In Mali, the national meteorological agency (Mali-Météo) and the Système d'Alerte Précoce (SAP) are the key organizations responsible for such early warning and disaster risk management. SAP monitors the availability food situation, determines areas at risk and identifies vulnerable populations. Mali-Météo (together with AGRHYMET, the regional center of the Permanent Interstates Committee for Drought Control in the Sahel), has the mandate to provide forecasts of seasonal rainfall for different geographical zones as well as other potential

TABLE 4-1– Selected effects of an improved crop variety substitution strategy under various drought scenarios
(% of reduction of drought impacts compared with the same scenario without adaptation strategy)

	Normal scenario [1]				Climate change scenarios [2]											
					Optimistic				Medium				Pessimistic			
Substitution rate achieved at the end of the 15-year period	**25%**	**50%**	**75%**	**100%**	**25%**	**50%**	**75%**	**100%**	**25%**	**50%**	**75%**	**100%**	**25%**	**50%**	**75%**	**100%**
Agricultural GDP	-30	-59	-87	-115	-52	-102	-151	-198	-31	-61	-90	-118	-21	-41	-60	-79
Agricultural prices	-26	-50	-72	-94	-51	-100	-144	-186	-32	-61	-89	-115	-22	-43	-62	-80
Rural income	-26	-51	-75	-98	-51	-100	-147	-191	-31	-60	-88	-115	-21	-41	-60	-79
Rural food access	-30	-59	-86	-114	-53	-104	-154	-202	-31	-62	-91	-120	-21	-40	-61	-80
Rural food availability	-33	-65	-97	-129	-52	-104	-156	-207	-31	-61	-92	-122	-20	-4	-60	-80
Migrations	-28	-55	-80	-103	-58	-112	-164	-213	-34	-67	-98	-127	-24	-43	-67	-87

[1] Results for deviations from the BAU scenario [2] Results for deviations from the Representative normal intense drought scenario
Source: Own calculations with GAMS software (mean results computed from the simulations of 100 randomised drought sequences for each scenario).

TABLE 4-2 – Cost-Benefit analysis of an improved crop variety substitution strategy under various scenarios for intense droughts

	Normal scenario				Climate change scenarios											
					Optimistic				Medium				Pessimistic			
Substitution rate achieved at the end of the 15-year period	**25%**	**50%**	**75%**	**100%**	**25%**	**50%**	**75%**	**100%**	**25%**	**50%**	**75%**	**100%**	**25%**	**50%**	**75%**	**100%**
Cost of the policy (Million USD)	13,0	26,0	39,0	52,0	13,0	26,0	39,0	52,0	13,0	26,0	39,0	52,0	13,0	26,0	39,0	52,0
Benefit of the policy [1] (Billion USD)	1,3	2,6	3,8	4,9	1,4	2,7	3,9	5,1	1,4	2,8	4,1	5,4	1,5	2,9	4,3	5,6
Benefit-cost ratio	100,8	98,5	96,4	94,4	105,4	103,1	101,0	98,8	110,0	107,7	105,1	102,9	115,4	112,3	109,7	107,3

[1] Gains in real GDP over the period compared to the BAU scenario for normal scenario or to the Representative normal intense drought scenario for climate change scenario
Source: Own calculations with GAMS software (mean results computed from the simulations of 100 randomised drought sequences for each scenario).

climate information that are relevant for rainfed agriculture (onset and cessation dates of the rainy season, duration of dry spells during the critical growth stages of the major crops, etc.). But Mali-Météo, currently experiences a precarious financial situation and an obsolescence of its stations network and therefore faces difficulties to fulfill its tasks. In this context, our second adaptation scenario considers an improvement and a wider use of this drought EWS in Mali.

Here again, we use a conservative approach. First, we assume a progressive geographical coverage of the EWS with different rates of adoption by farmers ranging from 25% to 100% at the end of the 15-year period. Second, using data from the *Technology needs assessment report* for Malian NAPA (République du Mali, 2010), we assume that, during an event, using an EWS provides an average yield gain up to 30% compared to a situation where it is not used.

Table 5-1 presents some potential effects of the strategy under the different climatic scenarios for intense droughts. Here again, these results show that such strategy could reduce the potential adverse consequences of droughts. However, compared to the previous strategy, improving the use of a EWS has lower buffering effects because it is only relevant for a year of occurrence. Under the normal scenario, for a geographical coverage rate of 100%, the average impacts of the drought sequences over the period on agricultural GDP or prices could for instance be reduced by 17% and 22% respectively. Under changing climatic conditions scenarios, they would be reduced by 42% and 58% for the optimistic scenario, by 32% and 43% for the medium scenario and by 26% and 34% for the pessimistic scenario.

Table 5-2 evaluates the effect of the policy in regards to costs-benefits criteria. In absence of better information, the cost of the strategy has been estimated using data from the

Climate Risk and Early Warning System (CREWS) initiative[1]. In 2017, together with the World Bank

[1] CREWS initiative has been launched at COP21 in Paris and is a direct contribution to the target 7 of the Sendai Framework for Disaster Risk Reduction 2015-2030, adopted by UN Member States in 2015. It is operated through multiple partners, including the World Bank, the World Meteorological Organization and the United Nations Office for Disaster Risk Reduction, with the objective to enhance hydro-meteorological observations and to improve early warning services.

TABLE 5-1– Selected effects of a drought early warning system improvement strategy under various drought scenarios
(% of reduction of drought impacts compared with the same scenario without adaptation strategy)

	Normal scenario [1]				Climate change scenarios [2]											
					Optimistic				Medium				Pessimistic			
Substitution rate achieved at the end of the 15-year period	25%	50%	75%	100%	25%	50%	75%	100%	25%	50%	75%	100%	25%	50%	75%	100%
Agricultural GDP	-4	-9	-13	-17	-11	-22	-32	-42	-8	-16	-24	-32	-7	-13	-20	-26
Agricultural prices	-6	-12	-17	-22	-16	-30	-45	-58	-11	-22	-33	-43	-9	-18	-26	-34
Rural income	-5	-10	-14	-19	-13	-26	-38	-50	-10	-19	-28	-37	-8	-15	-23	-30
Rural food access	-4	-9	-13	-17	-11	-22	-33	-43	-8	-16	-24	-32	-7	-13	-20	-26
Rural food availability	-4	-7	-11	-15	-9	-18	-27	-36	-7	-14	-21	-28	-6	-11	-17	-23
Migrations	-5	-10	-15	-20	-14	-29	-42	-55	-10	-21	-31	-40	-8	-17	-25	-32

[1] Results for deviations from the BAU scenario [2] Results for deviations from the Representative normal intense drought scenario
Source: Own calculations with GAMS software (mean results computed from the simulations of 100 randomised drought sequences for each scenario).

TABLE 5-2 – Cost-Benefit analysis of a drought early warning system improvement strategy under various scenarios for intense droughts

	Normal scenario				Climate change scenarios											
					Optimistic				Medium				Pessimistic			
Coverage rate achieved at the end of the 15-year period	25%	50%	75%	100%	25%	50%	75%	100%	25%	50%	75%	100%	25%	50%	75%	100%
Cost of the policy (Million USD)	11,3	22,5	33,8	45,0	11,3	22,5	33,8	45,0	11,3	22,5	33,8	45,0	11,3	22,5	33,8	45,0
Benefit of the policy [1] (Billion USD)	0,3	0,5	0,7	1,0	0,4	0,7	1,1	1,4	0,5	0,9	1,4	1,8	0,6	1,1	1,7	2,2
Benefit-cost ratio	23,1	22,7	21,9	21,6	32,9	32,4	32,0	31,3	41,8	40,9	40,3	39,6	51,6	50,7	49,8	48,9

[1] Gains in real GDP over the period compared to the BAU scenario for normal scenario or to the Representative normal intense drought scenario for climate change scenario
Source: Own calculations with GAMS software (mean results computed from the simulations of 100 randomised drought sequences for each scenario).

and the Green Climate Fund, the CREWS initiative has indeed launched a modernization project of the Malian EWS (including capacity building and development of Malian institutions as well as improvement of hydro-meteorological and warning infrastructures or enhancement of service delivery and warnings to communities at risks) and has estimated that for a full modernization of the Malian EWS system would require USD 45 million (CREWS, 2017). On this basis, results show would the strategy would be potentially worthwhile. Its profitability would be greater as the number of drought events is supposed to increase over the period. For instance, one dollar invested in order to achieve a 100% coverage rate of farmers could generate a national real GDP gain of about 48,9 USD under the pessimistic scenario and 21,6 USD under the normal scenario. These results align with the studies (for instance, Hallegatte, 2012) which argue that, because some of the most expensive components of EWS already exist (e.g., earth observation satellites, global weather forecasting system), the needed investments for an improvement of EWS are relatively modest compared to the expected benefits.

5.3 Extending irrigation capacities

By extending the growing season in normal years, providing a supplemental water supply at critical times in the crop's life cycle during drought periods, or even allowing off-season cultivation, irrigation infrastructures are likely not only to increase mean agricultural yields but also to reduce their fluctuations and to remove the farmers' dependence on precipitations. But irrigation capacities still remain limited in Mali (only 5.3% of lands) despite a huge estimated irrigation potential (about 2.2 million hectares). In this context, our third drought adaptation scenario considers an extension of irrigated land (at the expense of unirrigated land) over the next 15 years. However, the technical and financial difficulties associated with this policy led us to adopt a pragmatic approach. First, we only consider the objective of 560.000 hectares (8.1% of total Malian harvested area) which have been identified to be easily irrigated with persistent surface water resources by the FAO. Second, we consider different levels of achievement of this objective ranging from 25% to 100% at the end of the 15-year period (see for instance Beyene et al., 2013 for a similar approach). In each case, the extension of irrigated lands is here assumed to be progressive over the period. Third, we only consider an extension of rural small-scale irrigation techniques. Currently, a majority of Malian irrigated lands (86%) benefit from large-scale dam-based systems. But such technology needs huge initial investment costs and human resources or equipment for its functioning. In comparison, small-scale village level technologies, including mechanical lifting of water from source (micro-dam, groundwater or run-off-river) as well as distribution systems to plots (gravity irrigation, Californian system, sprinkling system or drip irrigation system)[2], appear relatively easier to finance and to manage by rural communities and have often been showed to be less expensive and more efficient than large-scale irrigation systems (You *et al.*, 2011; Qureshi and Shoaib, 2016). The Malian Small-Scale Irrigation Promotion Programme 2012-2021 provides us the main data for our scenario. It indicates that equipping 1 hectare could generate a threefold average increase of land productivity for an average cost of approximatively USD 8000 (République du Mali, 2012).

Table 6-1 presents some potential effects of such a strategy under the different climatic scenarios for intense droughts. They indicate that increasing irrigated land area could not only contribute to improve economic and social indicators but also to compensate entirely for the current effects of intense droughts and potential effects of future increases in the numbers of events. Under the normal scenario, reaching a 75% level of the irrigation objectives would be sufficient to offset almost all the negative effects that droughts currently generate in Mali.

[2] Gravity irrigation system is done through primary and secondary canals and is mainly used for cereals (rice, wheat, maize) and vegetables production. Californian irrigation system distributes water through furrows and is mainly used for vegetable production. Sprinkling system is mainly practiced on commercial farms for high value crops such as fruit trees. Finally, drip low pressure irrigation system is recently taking off in Mali and mainly used for fruits and vegetables cropping in the urban areas.

TABLE 6-1– Selected effects of an irrigation extension strategy under various drought scenarios
(% of reduction of drought impacts compared with the same scenario without adaptation strategy)

	Normal scenario [1]				Climate change scenarios [2]											
					Optimistic				Medium				Pessimistic			
Substitution rate achieved at the end of the 15-year period	**25%**	**50%**	**75%**	**100%**	**25%**	**50%**	**75%**	**100%**	**25%**	**50%**	**75%**	**100%**	**25%**	**50%**	**75%**	**100%**
Agricultural GDP	-39	-76	-112	-147	-69	-131	-188	-241	-41	-81	-119	-156	-28	-55	-80	-105
Agricultural prices	-34	-65	-93	-119	-68	-132	-192	-248	-43	-82	-117	-149	-30	-58	-83	-106
Rural income	-34	-66	-96	-124	-69	-136	-201	-263	-41	-80	-117	-151	-29	-56	-81	-105
Rural food access	-38	-75	-111	-145	-69	-136	-204	-270	-42	-82	-121	-158	-28	-56	-82	-107
Rural food availability	-42	-84	-125	-166	-76	-147	-213	-274	-41	-81	-121	-161	-27	-54	-80	-107
Migrations	-37	-70	-102	-131	-69	-131	-188	-241	-46	-89	-128	-165	-32	-62	-89	-115

[1] Results for deviations from the BAU scenario [2] Results for deviations from the Representative normal intense drought scenario
Source: Own calculations with GAMS software (mean results computed from the simulations of 100 randomised drought sequences for each scenario).

TABLE 6-2 – Cost-Benefit analysis of an irrigation extension strategy under various scenarios for intense droughts

	Normal scenario				Climate change scenarios											
					Optimistic				Medium				Pessimistic			
Irrigation level achieved at the end of the 15-year period	**25%**	**50%**	**75%**	**100%**	**25%**	**50%**	**75%**	**100%**	**25%**	**50%**	**75%**	**100%**	**25%**	**50%**	**75%**	**100%**
Cost of the policy (Billion USD)	1120	2240	3360	4480	1120	2240	3360	4480	1120	2240	3360	4480	1120	2240	3360	4480
Benefit of the policy *[1]* (Billion USD)	1,7	3,3	4,8	6,3	1,8	3,5	5,2	6,7	1,9	3,7	5,4	7,1	2,0	4,0	5,8	7,4
Benefit-cost ratio	1,5	1,5	1,4	1,4	1,6	1,6	1,5	1,5	1,7	1,7	1,6	1,6	1,8	1,8	1,7	1,7

[1] Gains in real GDP over the period compared to the BAU scenario for normal scenario or to the Representative normal intense drought scenario for climate change scenario
Source: Own calculations with GAMS software (mean results computed from the simulations of 100 randomised drought sequences for each scenario).

Similarly, under the optimistic (respectively medium and pessimistic) climate change scenario, reaching a 50% (respectively 75% and 100%) level would neutralise the additional adverse effects generated by an increasing number of events. Table 6-2 shows moreover that, although very expensive, this strategy could remain profitable. Whatever the scenario, the average gain in national GDP would still exceed the costs of the policy, even if this profitability is sharply reduced compared to the two previous adaptation strategies.

6. Conclusion

In Mali's current context, marked by great exposure and vulnerability to agricultural drought, this study uses a DRCGE model to assess the potential risks of such events for this country, as well as to evaluate some adaptation policies. With simulations of various drought scenarios over a 15-year period, we show first how the impact on crop production of each mild, moderate, and intense drought currently experienced by the country contributes to hinder its economic performance and considerably degrade its households' welfare. Furthermore, we depict how these negative impacts likely will be aggravated by the increased number of intense drought events threatened by global climate change. However, we show that there are some options for Mali to cope with these adverse current or future climatic conditions, if it were to implement coping strategies such as adopting drought-tolerant crop varieties, using drought early warning systems or extending irrigated areas.

These results offer some indications of Mali's vulnerability to agricultural drought and its options for adaptation, yet some caution is required in terms of interpreting their estimated absolute magnitudes. First, our economy-wide analysis does not really account for regional differences within the country. Moreover, the low disaggregation of the agricultural sector in our model, which is constrained by the structure of the Malian SAM, prevents us to assess more detailed potential impacts of drought events. Second, our methodology does not fully address uncertainty regarding the nature and amplitude of future climate variability or regarding its effects on agriculture. Third, our modelling framework cannot account for all the effects associated with a drought event; certain collateral effects (for example, health risks, conflict over water resources, external migrations) clearly could alter economic performance and households' welfare. Fourth, though some autonomous responses to drought are endogenously determined in the DRCGE model (accumulation dynamics, inter-sectoral or inter-regional migrations, changes of relative price or patterns of consumption), the reality may be more flexible. For example, in addition to government climate policies, farmers could employ a wide range of autonomous coping strategies (increasing self-consumption, liquidating productive assets, changing crop patterns or agricultural calendars, etc.), which do not appear in our economy-wide model but that are options already available in Mali. Fifth, the coping strategies that we consider include various institutional, social, technological, and financial dimensions that our macro-level economic CGE approach cannot address exhaustively. For instance, we did not examine the critical question of funding which was beyond the objectives of our study although it is an important policy question in the Malian context of reduced fiscal space available for the government, or lack of financial resources of farmers.

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