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A methodology to assess the impact of climate variability and change on water resources, food security and economic welfare

Abdelaziz A. Gohar [a,b,*], Adrian Cashman [b,1]

[a] Department of Agricultural Economics and Extension, College of Agriculture, South Valley University, Qena, Egypt
[b] Centre for Resource Management and Environmental Studies, The University of the West Indies, Cave Hill Campus, PO Box 64, Bridgetown, St. Michael, Barbados

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ABSTRACT

The potential impacts of climate variability and change on water resources and food security are receiving growing attention especially in regions that face growing challenges meeting water demands for agricultural, domestic and environmental uses. Rainfed agriculture regions exhibit higher vulnerability to climate variability and change, where aquifer storage and food security are under stress. Little research has attempted to investigate the consequences of climate variability and change on water availability and social livelihoods jointly. Employing available data on precipitation, farm budget data, and aquifer characteristics, a dynamic nonlinear optimization framework that maximizes the economic likelihoods of irrigation activities and food security under several climatic assumptions is developed and applied for Barbados as a numerical example. Our framework accounts for technological adaptation measure, drip irrigation, with the context of variable yield and cost of water demand under governmental subsidy schemes. Results indicate significant negative impacts of climate variability, change, and double exposure on future water resources and food security. However, some climate assumptions provide opportunity for some food producers who respond positively to technological adaptation programs, while consumers could face the major negative consequences by experiencing higher food prices. Our findings provide policymakers and stakeholders a comprehensive tool for economically efficient and sustainably reliant policy design, implementation, and evaluation facing the potential climate variability and change impacts.

1. Introduction

Understanding how climate variability and change might impact agricultural production and food security is a challenge. Firstly, the economic consequences of climate variability and change on regional economies are not fully understood, especially the economic impact on different sections of society. Secondly, little attention has been paid to differentiate between the economic impacts due to climate change and those due to climate variability. While the physical impact of these two climatic events has been investigated, their economic consequences are treated as being the same, whereas they are dissimilar and give rise to different consequences. This study seeks to address this situation first separately and then jointly by investigating the potential impact of climate variability and change on farm income, food security, land use, and future water availability. It also considers the potential impact of adaptation measures. The mathematical framework that achieves this goal is developed and applied to Barbados as a numerical implementation example. The major components are described in the following sections.

2. Background

Social and economic development depends on the availability and the sustainable management of water resources. Food production also relies on the availability of water at a given place and time, and this availability is also influenced by climatic conditions (Hammer et al., 2001). Over the last several years, the potential effects of climate variability and change on water availability have received increasing political, social, and economic attention. Despite the levels of uncertainty associated with the magnitude and direction of climate variability and change, they are expected to have impacts on water resources availability, agricultural activities, and human, and ecosystem functions, including tropical regions (Cashman, 2014; Wang, 2014; Rasmussen et al., 2014). The anticipated climate variability and change are likely to impact water resources by altering precipitation patterns and intensity, duration and frequency of rainfall events. Such changes in the pattern and nature of rainfall regimes will have effects on surface water and groundwater availability (Vicuña et al., 2012; Ramirez-Villegas and

* Corresponding author at: Department of Agricultural Economics and Extension, College of Agriculture, South Valley University, Qena, Egypt.
E-mail addresses: abdelaziz.gohar@cavehill.uwi.edu, agohar@agr.svu.edu.eg (A.A. Gohar), adrian.cashman@cavehill.uwi.edu (A. Cashman).
[1] Co-author.

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Challinor, 2012; Wangchuk and Siebert, 2013). The expected increased variability in water resources would give rise to impacts on agriculture and food security, particularly where rainfed agriculture is the predominant mode of agricultural production.

Some researchers have suggested that climate change would adversely affect groundwater recharge and therefore irrigation uses (Varela-Ortega et al., 2011). Other researchers have concluded that climate change will also increase agricultural water demand and hence water application over and above crop evapotranspiration requirements, which will impose further stress on groundwater supplies (Lehmann et al., 2013; Shahid, 2011). Apart from the effects on water availability, climate variability and change is expected to adversely affect crop productivity, reducing yields from rainfed agriculture through increased crop water stress (Sarker et al., 2012; Barnett et al., 2007; Tao et al., 2008; Rowhani et al., 2011; Ahmed et al., 2011; Ramirez-Villegas and Challinor, 2012; Palazzoli et al., 2015).

Another important impact of climate variability and change is its impact on food security and food producers' income. Variability and changes in precipitation could affect the four pillars of food security; food availability, access, utilization, and stability. Food production could be affected leading to higher prices, as commodities become scarcer (Schneider et al., 2011; Batisani, 2012; Ahmed et al., 2011; Wheeler and von Braun, 2013). Access to food could be affected through a reduction in farmers' income as production costs rise (Mushtaq et al., 2013). The impact on farm profit and food security depends on the scale of climate impact and agricultural sector (Jiang and Grafton, 2012). Moreover, the food supply stability could be affected through the changes in precipitation induced by the climate variability and change where increases in the prevalence and severity of droughts and floods give rise to swings in food availability and prices. For instance, in the Caribbean Region, the future projection of climate change and variability has been seen as posing an increasing food security challenge for the region (Junk, 2013).

3. Data and methodology

3.1. Data integration

The development and implementation of the framework such as described in this paper required different sets of data, obtained from different sources. The diverse nature of the data sources needed to implement the developed framework required an extensive investment of time in sourcing, preparing, and integrating data. The framework uses climatology data that could be at daily, monthly or yearly timescales, and over different spatial scales such as watershed, sub-basin, basin or region. Farm budget data from the agricultural sector is essential as well. The farm budget data could include crops' water application, crop yields, production cost, crop wholesale prices and groundwater pumping cost in addition to other agronomic data such as crop water requirements. In addition to agricultural land use, other forms of land usage such as open grassed areas, golf courses, vacant land, residential and commercial land, transportation network land, gullies, and forested areas can be integrated in such frameworks. Information on groundwater characteristics such as aquifer depth, aquifer area, aquifer storativity, and pumping depth were also needed.

3.2. Modeling approach

Mathematical programming techniques have a long history in addressing complex problems associated with multi-objective functions that depend on the values of several variables. The advantage of implementing mathematical programming is in addressing interrelated themes such as hydrology, climate change, economic, environmental, institutional, and policy implications. Data from different sectors can be adjusted and placed in one mathematical framework to provide a comprehensive tool for policymakers and stakeholders that inform policy design, implementation, and evaluation. Several mathematical frameworks addressing water resources and climate change subjects have been published recently (Rosegrant et al., 2000; Ringler, 2001; Mainuddin et al., 2007; Gohar and Ward, 2010; Gohar et al., 2013, 2015).

The framework that has been developed for this work distinguishes between climate variability, climate change, and the 'double exposure assumption', and the associated impact on water availability, food security, land use, and farming livelihoods. Climate variability refers to yearly fluctuations above or below the long run mean of climatic parameters such as precipitation for a specific region (Bugmann and Pfister, 2000; Hulme et al., 1999). In contrast, climate change is defined as a long run shift in average precipitation resulting from natural variability or anthropogenic factors (Katz and Brown, 1992). In our research, the double exposure impact refers to the combined impact of climate variability and climate change assumptions.

An optimized nonlinear dynamic framework is developed to maximize the total economic welfare from agricultural activities under climate variability, climate change, and the double exposure assumptions. The presented framework contains four climatic assumptions; normal climate assumption, climate variability assumption, climate change assumption, and double exposure assumption. It incorporates 12 crops, 5 other land uses, and two irrigation systems; rainfed and drip irrigation. The analyses are carried out over a 20-year period. The major advantage of the current analysis framework is that it investigates the potential impact of climatic assumptions on farm income, food security, land uses, and water availability within a single framework. The following section describes the major components of our framework; the complete mathematical documentation and GAMS code are available from the authors by request.

3.2.1. Climatic assumptions

The climate assumptions in this research refer to projected variability and change in the annual average precipitation. Aggregating the available monthly precipitation data for 24 years from 1989 to 2012, the total annual average precipitation is calculated. Three different hypothetical future climate assumptions have been generated using the normal distribution technique. The fourth climate assumption used is the base climate assumption, which uses the current data without any changes. The average precipitation per unit of land (hectare) is estimated by the following equation where the average precipitation Pr_{lkcst} for any land use classification (l), irrigation technology (k), climate assumption (c), subsidy scheme (s), and time span (t) is a function of the calculated average annual precipitation$(\overline{P}_{ct})$ under climate variability and change assumptions and time period.

$$\text{Pr}_{lksct} = N \sim \left(\overline{P}_{ct}, s_c\right) \tag{1}$$

Parameter $(\overline{P}_{ct})$ refers to the average precipitation in thousand cubic meters (CM) per hectare and (s_c) refers to the variance in annual precipitation under climate assumptions. The first is taken as "normal climate assumption", where no change or variability in precipitation is modeled; the annual average precipitation is normally distributed around that average with a variance of 5% of the average. This is the baseline assumption against which the other three climate assumptions are compared. The second is "climate change assumption", where the normal average precipitation $(\overline{P}_{ct})$ is taken to have declined by 50% but there is no change in variation around the mean average precipitation. The third is "climate variability assumption", where there is 30% variance around the mean average precipitation. The fourth is called "double exposure assumption" that combines the two affects; a decline in average precipitation by 50% and the variance set at 30%. The total water available from precipitation for the entire island is the total land area multiplied by the calculated rainfall per hectare generated by