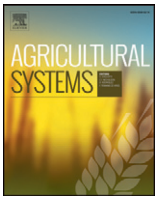
Agricultural Systems 147 (2016) 51–64

Contents lists available at ScienceDirect

Agricultural Systems

journal homepage: www.elsevier.com/locate/agsy



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

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ARTICLE INFO

Article history:
Received 11 April 2015
Received in revised form 7 May 2016
Accepted 9 May 2016
Available online xxxx

Keywords:
Climate change
Climate variability
Water resources
Food security
Positive mathematical programming

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

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http://dx.doi.org/10.1016/j.agsy.2016.05.008
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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.

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

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 each of the sets of climate assumptions, as shown in Eq. (1a).

$$RHS_{cst} = \sum_{l}\sum_{k} hectare_{lkcst} \times \Pr_{lkcst} \tag{1a}$$

3.2.2. Water consumption

Among other factors, actual evapotranspiration ET depends on available precipitation, soil type and properties, plant type, and other climatic parameters. The direct relationship between precipitation intensity and a plant's actual evapotranspiration has not received very much research interest. Increasing precipitation intensity could increase the runoff and ET, but at different rates (Pandey and Ramasastri, 2001; Fay et al., 2003). For instance, Garbrecht et al. (2004) found that in Oklahoma State, increasing precipitation intensity by 12% would increase the stream flow by 64% while it increased ET by 5% only. Increasing plant ET will reach a maximum point, maximum ET, and at that point any extra water from precipitation will runoff. Up to the maximum ET, the soil reaches the saturation stage and water will either evaporate or runoff or infiltrate to the aquifer. Therefore, the relationship between the precipitation intensity and actual ET could be described in quadratic form. This relationship is shown by the following equation:

$$ET_{jkcst} = \beta 1_{jk} * \Pr_{jkcst} - \beta 2_{jk} * (\Pr_{jkcst})^2. \tag{2}$$

Variable (ET_{jkcst}) is the evapotranspiration for any land unit (hectare) covered by plants and is conditioned by the application technique (rainfed or irrigation), climate assumption, subsidy, and time period. (j) is a subscript that includes land use of economic crops and non-economic land use such as grass or forest. ($\beta 1$) and ($\beta 2$) are parameters estimated internally by solving two equations that represent the total observed water depleted (TET_{jk}) and marginal water depletion (MET_{jk}) by different land use (j) and irrigation technology (k), and ($\overline{\Pr}_{jk}$) is the observed water (ET) for each land use and irrigation technology.

$$TET_{jk} = \beta 1_{jk} * \overline{\Pr}_{jk} + \beta 2 * (\overline{\Pr}_{jk})^2 \tag{2a}$$

$$(MET_{jk} = \beta 1 + 2 * \beta 2_{jk} * (\overline{\Pr}_{jk}) \tag{2b}$$

Solving the two above equations for two unknowns ($\beta 1$) and ($\beta 2$) produces the following estimations for those parameters used in Eq. (2):

$$\beta 1_{jk} = MET_{jk} - 2\beta 2_{jk}(\overline{\Pr}_{jk}) \tag{2c}$$

$$\beta 2_{jk} = \frac{MET_{jk} - TET_{jk}}{(\overline{\Pr}_{jk})^2}. \tag{2d}$$

In cases where new irrigation technology is introduced (e.g. drip irrigation during drought), crops are assumed to obtain adequate or maximum evapotranspiration by switching the drip system on or off based on precipitation level. Therefore, the evapotranspiration provided by the drip irrigation system (ET^d) subscribes by the following equation:

$$ET^{d}_{idcst} = \overline{\Pr}_{idcst} - ET_{idcst}. \tag{3}$$

where subscript (d) denotes drip irrigation technology only. In this case (i) refers to all crops that drip irrigation technology could be used to cultivate. These crops only include vegetable and root crops, drip irrigation is not to be applied to sugarcane. In other words, the ET for sugarcane is obtained only from one source, which is rainfall. Parameter ($\overline{\Pr}_{idcst}$) refers to maximum ET required to produce maximum yield for crops under drip irrigation. Part of the rainfall recharges the aquifer; some is lost through direct evaporation and runoff. In this model, run-off does not contribute to aquifer recharge and is described by the following equation:

$$SW_{ucst} = \Pr_{ucst} - Dep_{ucst}. \tag{4}$$

The above equation gives run-off per hectare (SW_{ucst}) from urban and road area (u), under any climate assumption, subsidies scheme, and time analysis span, where ($\Pr_{ucst}$) is the variable of average precipitation on road network, and (Dep_{ucst}) is the water depletion that is assumed to be zero. In contrast, infiltration is modeled as the difference between precipitation and plants' ET plus evaporation. The total infiltration to groundwater is described as follows:

$$Seep_{cst} = \sum_{j}\sum_{k} \Pr_{jkcst} - ET_{jkcst}. \tag{5}$$

3.2.3. Crop yield and production

In addition to ET as a major determinant for crop yield, other factors such as soil type and properties, temperature, humidity, crop variety and water availability all have a significant impact on crop yield. Several researchers have concluded that the relationship between ET and a plant's yield can be described as a linear or curvilinear function. Examples include Al-Jamal et al. (2000), Barros and Hanks (1993), Gonzalez-Dugo and Mateos (2006), Zhang et al. (2006), Tolk and Howell (2008), Garcia-Tejero et al. (2012) and Irmak et al. (2013). However, other researchers have pointed that the crop yield increases by decreasing rate at the water deficit condition, where the plant tends toward early maturation. Having enough water will increase the plant biomass growth and therefore a higher yield can be achieved. Up to the maximum ET stage, no gain in yield could be achieved (Orgaz et al., 1992).

Moreover, the quadratic form for the relationship between crop yield and evapotranspiration was found to be more representative for crops such as sugarcane, cotton, wheat, and barley (Grimes et al., 1969; Gulati and Murty, 1979; Zhang et al., 1999). A detailed explanation for using the quadratic form for the yield–ET relationship is given by Liu et al. (2002). Using field experiment data, they found that the quadratic form is statistically more robust compared to the linear form, where extra water application after maximum ET will not increase the crop yield. That is, the yield–ET relationship can be expressed as a quadratic function where the yield for any given crop increases as more water is made available up the point of maximum ET and extra water after that stage will not improve the yield (Liu et al., 2002). Under flood condition or extreme rainfall, plants could die and drive the yield to zero.

In our framework, the yield function ($Yield_{akcst}$) is modeled as a quadratic function of depleted water from precipitation (ET_{akcst}). The equation's intercept and slope ($\alpha 1_{ak}$ and$\alpha 2_{ak}$) parameters are derived in similar methods used to derive the evapotranspiration parameters in Eq. (2) above. Furthermore, the total production (TP_{akcst}) from each crop, for any given irrigation technology, climate assumption, subsidies scheme, and time period are calculated through multiplying the yield by cultivated area as shown in Eq. (7).

$$Yield_{akcst} = \alpha 1_{ak} * ET_{akcst} + \alpha 2_{ak} * (ET_{akcst})^2 \tag{6}$$

$$TP_{akcst} = hectare_{akcst} * Yield_{akcst} \tag{7}$$

3.2.4. Groundwater hydrology

The groundwater system is simplified, as shown by Eq. (8). The aquifer storage volume available under a climate assumption, subsidy scheme, and any time period is a function of storage volume from previous year (SV_{cst1}), recharge from precipitation ($Seep_{jkcst}$), summed over crops and irrigation technology in the current year, minus the groundwater pumping activities for drip irrigation (GP_{idcst}) and other pumping activities for domestic and urban uses ($\bar{U}r_{cst}$). Other pumping activities are assumed to increase overtime by the same percentage as population growth.

$$SV_{cst} = SV_{cst-1} + \sum_j \sum_k Seep_{jkcst} - \sum_i \sum_d GP_{idcst} - \bar{U}r_{cst} \tag{8}$$

3.2.5. Economics

The optimization framework evaluates the impact of different climatic assumptions and irrigation technology (rainfed and drip irrigation) on water storage capacity and economic welfare derived from crop production. Each crop is associated with different production costs. It is assumed that farmers will seek to maximize their net farm income by using different sources of water. Decreasing water availability reduces crop yield and therefore reduces total production. In the absence of alternatives, several economic consequences occur under the climate variability and change assumptions. A farmer could experience a decline in farm income as a result of yield decline. For food consumers, an incremental increase in crop prices will take place and negatively affect consumer surplus. To offset this, a farmer could adopt more water efficient forms of irrigation to maximize the use of available water, such as drip irrigation. This however, comes at a cost that has to be accounted for. The effects of adoption of irrigation technologies are investigated within the framework.

3.2.5.1. Cost of production. Agricultural production involves different types of production expenses. In our framework, total average cost per hectare (ATC_{akcst}) of cultivated land is classified into three types of costs, as shown in Eq. (9). The costs are; non-water cost (NWC_{akcst}), capital costs of irrigation system (CC_{adcst}), and energy pumping related costs (PC_{adcst}). The non-water costs of production includes land rent, field preparation, planting, weed control, fertilizing, pest and disease control, harvesting, and transporting and marketing. The irrigation system capital cost refers to the cost of purchasing, installing, and maintaining drip irrigation systems. Energy pumping costs are those charges associated with pumping. Direct water costs refer to the water tariff charge by the government for the water used in drip irrigation (WC_{adcst}).

$$ATC_{akcst} = NWC_{akcst} + CC_{adcst} + PC_{adcst} \tag{9}$$

The non-water cost per unit of land is specified to increase as more land is added to production from specific crops, where additional expense is required to maintain land productivity. Thus, the non-water cost function can be expressed as the incremental increase in the marginal cost of new added land in production:

$$NWC_{akcst} = C0_{ak} + C1_{ak} * hectare_{akcst}. \tag{9a}$$

where the ($C0_{ak}$) is the non-water fixed cost of the first unit of land brought into the production and ($C1_{ak}$) represents the marginal impact of additional land on the average cost function. The average cost of installing the drip irrigation system (CC_{adcst}) has the same trend, whereas a yearly average cost of installing a drip irrigation system depends on the purchase cost (CCS), interest rate (r), life span (SL), and subsidy incentive provided by the government ($Subsidy$). The interest rate used is 10%, while a 10 year life system is standard for drip systems, and the government repays 50% of the total cost of the system, Eq. (9b).

$$CC_{ads} = \left\{ \frac{CCS * r}{1 - \left[\frac{1}{(1+r)^{SL}} \right]} \right\} * (1 - Subsidy_s) \tag{9b}$$

Drip irrigation systems have associated with them additional costs; the capital cost to install the system, energy cost of pumping water, and water tariff charged by cubic meter pumped. Increasing the pumping depth will raise the energy cost of pumping a cubic meter of water, assuming constant pumping efficiency. Eq. (9c) gives the pumping cost per hectare at any given time (PC_{akcst}) for crops under drip irrigation. The influence of the climate assumption on pumping cost is calculated by multiplying a variable pumping cost coefficient (Kp_{akcst}) by varying pumping depth ($P.depth_{cst}$).

$$PC_{akcst} = Kp_{akcst} * P.depth_{cst} \tag{9c}$$

3.2.5.2. Farm income. The net revenue per hectare is equal to crop yield multiplied by crop price (P_{acst}) minus average costs of production (ATC_{akcst}) and cost of water used (WC_{adcst}). Total net revenue (TNB_{akcst}) for each crop is equal to the net revenue per hectare multiplied by total irrigated land from that crop. Greater crop production should reduce market prices, and therefore the farm income could decline as most agricultural products have low elasticity values. The variability of a crop's price is linked to the market forces of demand and supply. For the different assumptions, crop price is taken as an unknown to be solved by the model.

$$TNB_{akcst} = (P_{acst} * Yield_{akcst} - ATC_{akcst}) * hectare_{akcst} - WC_{adcst} \tag{10}$$

The discounted total net farm income under the different climate assumptions and subsidy schemes is examined by summing net farm income over crops, irrigation technology, and time span. The present value ($PTNB_{cs}$), at discount rate (r), of total net farm benefits, by climate assumption and subsidy level can be stated as:

$$PTNB_{cs} = \sum_a \sum_k \sum_t \frac{TNB_{akcst}}{(1+r)^t}. \tag{11}$$

3.2.5.3. Consumer surplus and food security. Consumer surplus is an important part of the consequences of food policies on economic welfare, especially when those policies directly influence food prices. It can be used to estimate the economic gain or loss on the consumer benefits resulting from a price change at a specific period of time (Svoboda, 2008; Vanhems, 2010; Ferreira et al., 2013). Consumer surplus can be used to investigate problems associated with the availability of natural resources such as water (Banzhaf, 2010). Measuring changes in consumer welfare associated with an irrigation water policy or drought assumption requires information on the crop price elasticity and the existing production level, both of which can be used to specify a demand function and its parameters. For each crop, the standard relationship between the demand curve and the price elasticity of demand can be used to calculate consumer surplus. The inverse demand function can be expressed as:

$$P_{acst} = \theta 0_a + \theta 1_a * \sum_k TP_{akcst}. \tag{12}$$

The consumer surplus in Eq. (13) is calculated for each climate assumption and subsidy scheme summed over irrigated crops, irrigation technology, and time periods. The consumer surplus equals half the difference between the maximum (reservation) price and the actual (endogenous) price multiplied by the total quantity produced from a specific crop summed over irrigation technologies. The actual price increases with decreases in water availability for irrigation, which will occur under climate variability and drought assumptions.

$$CS_{cs} = \sum_{a}\sum_{t}\frac{0.5 * \left[(\theta 0_a - P_{acst}) * \sum_{k} TP_{akcst}\right]}{(1+r)^t} \tag{13}$$

3.2.5.4. Economic welfare. Total economic welfare is defined as the sum of consumer surplus plus farm income. For a given demand curve, increases in consumer surplus require lower crop prices, while higher crop prices give rise to a rising farm income. Therefore, farm income could be said to conflict with food security. In our analysis, the trade-off between consumers and producers is investigated by setting the model to maximize the algebraic sum of consumer surplus and farm income. Discounted consumer surplus is defined in Eq. (13), while discounted farm income is defined in Eq. (11). The analysis examines allocations of available water and land that maximize the sum of those two algebraic terms in present value terms.

While the sum of consumer surplus and farm income has been recognized as a classic welfare measure, little research has attempted to integrate its two components into a unified model that could especially inform policy debates around the impacts of climate variability and change. The current work builds on previous work by the Gohar et al. (2015) paper by adding the variable cost dimension and integrates climate variability and change with groundwater hydrology.

3.2.6. Model calibration

Mathematical programs required calibration to ensure reliable results. Several methodologies have been used in the few past decades to calibrate optimization frameworks. The Positive Mathematical Programming approach "PMP" (Howitt, 1995) has been widely used recently to calibrate water resource allocation problems; examples include He et al. (2006) for Egypt and Morocco, the Murray–Darling Basin in Australia (Qureshi et al., 2013), Rio Grande–Rio Bravo Basin (Medellin-Azuara et al., 2012), the Upper Rio Grande (Dagnino and Ward, 2012), and the province of Palencia in Spain (Gallego-Ayala, 2012), and the Balkh Basin in Afghanistan (Gohar et al., 2015). Other examples include investigating farmers' adoption of irrigation techniques (Cortignani and Severini, 2009, 2011, 2012), and assessing farming design under climate variability (Gohar et al., 2015). The major advantage of adopting PMP is its capability of producing smooth change resulting from new policy implementation in the face of climate variability(Gohar et al., 2015), while ensuring optimized outcomes that match observed outcomes for a base set of historical conditions with minimal data requirements (Nakashima, 2011; Preckel et al., 2002; Medellin-Azuara et al., 2010).

Previous works implemented PMP to calibrate the observed yield function representing heterogeneous land quality in such a way that added land from any crop expected to reduce the yield. This represents an application for Ricardian rent. In the current work, the yield function is already varying based on the available water supply from precipitation. That is, we implemented the PMP through the cost function; non-water related cost, in such way that scaling up land in production is a linear function with increasing cost in the face of expanded land and associated increases in water use for production. Increasing costs with scale expansion for any given crop reflects heterogeneous land quality in a different way. Farmers should increase their cost to maintain the land yield at any specific yield condition. PMP was implemented in this work by assuming that the total water (W_{jk}) used for any specific crop is the total land use multiplied by the water crop requirement (ET_{jk}), Eq. (14).

$$hectare_{jk} = \frac{W_{jk}}{ET_{jk}} \tag{14}$$

Substituting for the value of the land in Eqs. (9) and (10) produces a total net farm income function that can be maximized by differentiation to solve for the two unknown parameters ($C0$) and ($C1$), where the unknown parameters in each crop's cost function is based on farmer behavior reflecting constrained income optimization. The intercept parameter is the minimum cost for the first unit of land planted, and the slope represents the marginal cost from additional land brought to production, and (P^w) is the water tariff. The new equation can be expressed as follows:

$$TNB_{akcst} = \left[P_{acst} * Yield_{akcst} - C0_{jk} - \frac{C1_{jk}}{ET_{jk}} W_{jk} - CC_{ads} - PC_{aks}\right] * \frac{W_{jk}}{ET_{jk}} - P^w * W_{jk}. \tag{15}$$

Solving the above equation by taking the first derivative with respect to the total water (W) will produce the two unknown parameters ($C0$) and ($C1$) as follows:

$$C0_{akcst} = ATC_{akcst} - C1_{akcst} * hectare_{akcst} - CC_{akcst} - PC_{akcst} \tag{15a}$$

$$C1 = \frac{P_{acst} * Yield_{akcst} - ATC_{akcst} - P^w * W_{adcst}}{hectare_{akcst}}. \tag{15b}$$

4. Numerical example

4.1. Overview

This section presents a numerical implementation of the developed framework, using Barbados as an example. Barbados is located in the Eastern Caribbean and has a land area of 430 km^2 and a population of 278,000 according to the 2010 Population Census (BSS, 2013). Of the total land area, some 44% has been classified as agricultural, the majority of which is used to grow sugarcane. Approximately 10% of the working age population makes their living from agriculture though it only contributes 3% to Gross Domestic Product. In recent years the area of land actually under cultivation has declined while more land is being left fallow, reforested or given over to housing developments.

Barbados is predominantly a coral limestone island, which covers some 86% of the land area. The coral cap lies on top of sediments of oceanic origin, which make up the remaining 14% of the land area. In comparison to the limestone, the oceanic sediments are relatively impermeable. As a consequence of its geology, Barbados has no significant perennial surface water resources. Groundwater is the only significant source of water on the island. It is augmented by water supplied from a desalination plant, for domestic purposes. Although located in the Tropics, Barbados is ranked among the top 15 most water scarce countries (GoB, 2010), where water scarcity is defined as having total renewable water resources of less than 1000 m^3/person/year (Falkenmark and Rockstrom, 2005). One of the anticipated effects of climate change in the Caribbean is greater variability of climate with more extreme events such as droughts and intense rainfall events (Campbell et al., 2011). Studies have shown rainfall variability to be a significant factor affecting economic growth and development (Brown and Lall, 2006; Grey and Sadoff, 2006). Water scarcity can be addressed through 'soft water' approaches (Brown and Lall, 2006) such as water management, economic and institutional measures, policy and the promotion of more efficient and effective water use.

The production of sugarcane provided the foundation of much of the development of the Caribbean Region in the years following European settlement, and for several centuries formed the basis of the region's economy. In the post-colonial era, tourism has supplanted sugar and agriculture as the foundation of many of the region's economies. Since the mid twentieth century, nearly all of the countries of the region have moved from being predominantly self-sufficient in terms of food supply to a situation where food imports are now essential, particularly for the tourism sector. Since the global concern created by the spike in food prices in 2007–08 there has been renewed interest in food security and sufficiency in the Caribbean with efforts to encourage the greater production of local food crops. Most Caribbean agriculture is rain-fed, particularly in the insular Caribbean. The projected decrease of precipitation under various climate change scenarios has given rise to concerns with respect to stream and aquifer recharge, water availability as well as what the effects on food production might be.

The data required for the framework has been collected from different sources. The available monthly precipitation data for a period of 24 years from 1989 to 2012 from different rainfall stations across Barbados was obtained from the Barbados Water Authority (BWA). Thus, the total annual average precipitation was calculated for this time period. This average annual precipitation for Barbados was calculated to be 13.268 thousand CM per hectare. Yet, available data on precipitation for the period between 1989 and 2012 shows a yearly variability in the average annual precipitation. This variability ranges between 18.93 thousand CM per hectare in 2009 and 9.79 thousand CM per hectare in 2002. Using this figure as a starting point, three different synthetic climates were generated. This was done by using a normal distribution technique to generate the three future precipitation assumptions; climate change, climate variability, and double exposure assumption in addition to the normal climate assumption that represents the base assumption. For example, a normally distributed precipitation is generated with a mean of 13.268 thousand cubic meters per hectare with an annual variance of ± 3.98 thousand cubic meters to generate the precipitation for the climate variability assumption.

Farm budget data for the year of 2012 was sourced from the Ministry of Agriculture. This includes crops' water application, crop yields, production cost, crop wholesale prices and groundwater pumping cost. From the Ministry's data, twelve major crops were identified as well as other forms of land use such as grasslands, golf courses, vacant areas, residential and commercial land, transportation network land, gullies, and forested areas. The crops identified include; sugarcane, cabbage, cassava, cucumber, okra, onion, pigeon peas, pumpkin, squash, sweet pepper, sweet potato, and tomato. This research employed the available data for crop water requirements provided by the FAO's Irrigation Water Management Manual No. 3, which available online by the Natural Resources Management and Environmental Department (FAO, 1986). Information on groundwater characteristics such as aquifer depth, aquifer area, aquifer storativity, and pumping depth were also obtained from the (BWA).

5. Results

5.1. Overview

In this section, the impacts of different climate assumptions on water availability, land reallocation, food security, and farm benefits for the numerical example of Barbados are presented. Water availability includes precipitation, crop evapotranspiration, aquifer storage capacity, and groundwater pumping. The reallocation of land used by the agricultural sector and major non-agricultural sectors are shown as well. Finally, the economic impact of climate assumptions on national welfare is described.

5.2. Water availability

One of the major consequences of climate variability and change is the altering of the annual average precipitation and therefore the water availability in the future. Table 1 illustrates the annual total average precipitation for Barbados, crops' water consumption, aquifer recharge, water losses through evaporation, and water collected at sewage systems during a 20 year analysis in million cubic meters (MCM). Under the normal climate assumption, small variability in precipitation

Table 1
Annual total precipitation, crop ET, aquifer recharge, sewage and evaporation loses by climate assumption, Barbados (million cubic meter).

Years	Precipitation				Water consumption[a]				Aquifer recharge				Sewage and evaporation losses			
	Normal climate	Climate variability	Climate change	Double exposure	Normal climate	Climate variability	Climate change	Double exposure	Normal climate	Climate variability	Climate change	Double exposure	Normal climate	Climate variability	Climate change	Double exposure
1	514	336	257	334	223	177	146	176	49	23	14	23	241	136	97	135
2	530	643	265	205	225	236	149	122	52	75	15	10	253	333	101	73
3	534	697	267	328	226	236	150	174	53	87	15	22	255	374	101	132
4	474	371	237	322	215	189	137	172	43	27	13	21	216	155	88	129
5	503	352	251	315	221	182	143	169	48	25	14	21	234	145	94	125
6	497	497	248	142	220	220	142	89	46	47	14	6	230	231	93	48
7	512	359	256	417	222	185	145	201	49	26	14	34	240	149	96	182
8	546	398	273	328	228	197	153	173	55	31	16	22	263	170	104	133
9	502	602	251	264	221	233	143	148	47	66	14	15	234	302	94	100
10	522	768	261	390	224	231	148	193	51	104	15	30	247	432	99	166
11	498	829	249	344	220	223	142	179	47	121	14	24	231	485	93	141
12	531	431	265	409	226	206	149	199	53	36	15	33	253	190	101	177
13	505	472	252	158	221	215	144	97	48	42	14	7	236	214	95	54
14	509	362	255	133	222	186	145	83	49	26	14	5	239	150	96	44
15	571	553	286	216	231	228	158	126	60	57	17	11	280	268	110	79
16	503	463	252	191	221	213	143	114	48	41	14	9	235	209	94	68
17	488	411	244	204	218	200	140	121	45	33	13	10	225	178	91	73
18	486	335	243	337	218	176	140	176	45	23	13	23	224	136	90	137
19	530	846	265	235	225	221	149	135	52	125	15	13	252	500	101	87
20	553	690	276	217	229	236	154	127	57	85	16	11	268	369	106	79

[a] Consumption by crops, natural forests, grass and other crops.

is expected, which results in smooth fluctuation in water consumption by agricultural crops and non-economic plants such as grass and forest. The climate variability assumption results in yearly variation in average annual precipitation where a sequence of flood and drought years can be observed. On the other hand, the climate change assumption produces a steady decline in long run average precipitation. However, water consumed by crops and plants under this climate assumption will decline by a smaller percentage and with less variation as the plants' ability to consume water from rains increases under drought condition, while less water will infiltrate into the aquifer. The joint impact of climate variability and change (double exposure) results in the most severe precipitation condition when compared to the other separate climate assumptions.

Moreover, greater fluctuations in aquifer recharge takes place under the climate variability assumption. During flood periods, more water is expected to recharge the aquifer while during drought years there is significantly less infiltration. Less variability in aquifer recharge occurs under the climate change assumption compared to the normal climate assumption. Yet, the reduction aquifer recharge is higher than the reduction in precipitation. This could result in increasing plants' ET proportionally under lower precipitation density. Under the double exposure effect, it seems that the climate variability impact reduces the negative impact of the climate change impact, where more water infiltrates during 'flood' years while the situation is worse in drought periods as the recharge sharply declines. Despite that, the country could experience more severe drought years under the double exposure assumption. More precipitation can be noticed in some years such as years 9–12. The higher precipitation density improves the groundwater recharge in some years of the above average precipitation like years 9, 10, 11, and 12, while deep declines in the groundwater recharge occurred in years 6, 13, 14, 15, 16, and 20.

The same trends are observed in the run-off water; Table 1 indicates that the climate variability assumption produces variable water losses, dependent on the density of precipitation. The climate change assumption indicates a reduction in evaporation and run-off while fluctuation in those losses can be observed under double exposure assumption.

The absolute change in groundwater storage volume, agricultural groundwater pumping, and pumping depth by climate assumptions are shown in Table 2. A general decline in groundwater availability occurs over time across all climate assumptions. Under the normal climate, a small accumulation of shortages in groundwater storage occurs as a result of increasing water demand from the urban and domestic sectors. Climate variability mitigates the decline in aquifer volume due to increased recharge during wet years. The only noticeable change between the two assumptions is that under the climate variability, a fluctuation in yearly storage availability occurred compared to small steady increases in groundwater storage under normal climatic assumption. The change in aquifer storage will affect the water table and the aquifer thickness (i.e. stored water) will decrease over time resulting in increased pumping depth.

Under the climate change and double exposure assumptions, a significant increase in water shortages over time occurs, as shown in Fig. 1. While climate change creates a steady decline in precipitation, the storage volumes decline as a result of the higher capability of crops and plants to deplete more water under drought conditions. The water shortage intensifies under the climate change assumption but with small improvements in water storage under a double exposure assumption. The improvement in aquifer storage under double exposure leads to slight decreases in pumping depths compared to climate change assumption. Two explanations could account for this; first, the precipitation variability involved in the double exposure climate assumption alleviates the decline in precipitation from the climate change affect and therefore higher average rainfall would improve the storage volume. Second, a dramatic redistribution in land use has a major impact on the water use from the aquifer system and on recharge.

The diminishing trend in water availability, under all climate assumptions for the case study of Barbados is consistent with previous research regarding the impact of climate change. However, while the climate change reduces water availability, climate variability tends to even out the negative impact of absolute climate change, due to more water stored during peak rainfall seasons. The extent of mitigating the negative impacts of climate change will depend on the degree of climate change and variability in precipitation.

Table 2 illustrates the total groundwater pumping used for irrigation activities by year and climate assumptions. Results shown in this table demonstrate a high level of variability in groundwater usage under different climate assumptions. In the case of the normal climate assumption, less yearly variation in pumped groundwater is observed as it is more profitable for farmers to rely on rainfall. Drip irrigation is used only to fill the gap between direct evapotranspiration from rains and the maximum ET required to maintain the crop maximum yield. Under climate variability assumption, more groundwater will be used, 12% to 135%, to cover the shortage in ET induced by the climate variability during dry years. However, in some years, less groundwater is

Table 2
Optimized annual groundwater storage, aquifer depth and pumping depth by climate assumption, Barbados.

	Absolute change in aquifer storage (MCM)				Groundwater pumping (MCM)				Groundwater pumping depth (meter)			
Year	Normal climate	Climate variability	Climate change	Double exposure	Normal climate	Climate variability	Climate change	Double exposure	Normal climate	Climate variability	Climate change	Double exposure
1	0	0	0	0	0.131	0.308	0.427	0.315	46.0	46.0	46.0	46.0
2	−4	18	−42	−47	0.119	0.060	0.415	0.506	46.0	45.9	46.1	46.1
3	−7	49	−83	−82	0.117	0.044	0.412	0.325	46.0	45.9	46.2	46.2
4	−22	19	−128	−118	0.163	0.266	0.458	0.332	46.1	45.9	46.3	46.3
5	−31	−13	−172	−155	0.139	0.289	0.436	0.342	46.1	46.0	46.4	46.4
6	−42	−24	−216	−207	0.144	0.144	0.441	0.617	46.1	46.1	46.5	46.5
7	−51	−56	−259	−230	0.133	0.280	0.429	0.221	46.1	46.1	46.7	46.6
8	−53	−83	−301	−266	0.109	0.237	0.404	0.324	46.1	46.2	46.8	46.7
9	−64	−74	−346	−309	0.140	0.078	0.437	0.414	46.2	46.2	46.9	46.8
10	−71	−28	−389	−337	0.125	0.036	0.422	0.250	46.2	46.1	47.0	46.9
11	−82	35	−434	−371	0.143	0.041	0.440	0.305	46.2	45.9	47.1	46.9
12	−88	12	−478	−397	0.119	0.202	0.415	0.229	46.2	46.0	47.2	47.0
13	−99	−4	−523	−449	0.138	0.166	0.435	0.599	46.2	46.0	47.3	47.1
14	−109	−37	−568	−504	0.135	0.277	0.431	0.646	46.3	46.1	47.4	47.3
15	−108	−40	−610	−552	0.094	0.105	0.386	0.498	46.3	46.1	47.5	47.4
16	−120	−58	−655	−603	0.139	0.173	0.436	0.540	46.3	46.1	47.7	47.5
17	−134	−85	−702	−653	0.151	0.223	0.448	0.518	46.3	46.2	47.8	47.7
18	−149	−121	−749	−689	0.153	0.310	0.449	0.320	46.4	46.3	47.9	47.7
19	−157	−56	−794	−737	0.119	0.044	0.416	0.467	46.4	46.1	48.0	47.9
20	−160	−31	−838	−786	0.105	0.046	0.399	0.496	46.4	46.1	48.1	48.0

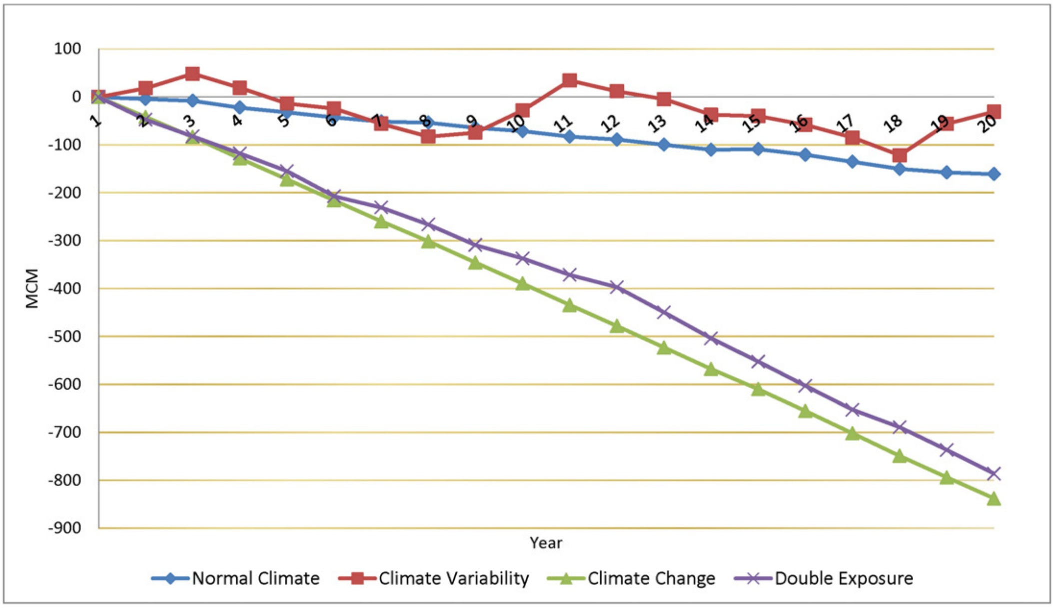

Fig. 1. Absolute annual change in aquifer storage volume by climate assumption, Barbados (MCM).

pumped due to the high level of precipitation. During wet years under this climate assumption, farmers switch off the drip system. With the climate change assumption, groundwater abstraction will increase significantly for all years. Another difference is that under the climate assumption, the higher water abstraction results from increases in land brought under drip irrigation rather than the increased demand from existing land under the drip system.

Groundwater abstraction under the double exposure assumption is always higher than water abstracted under normal and climate variability assumptions. Adding climate variability to climate change shifts the precipitation above and below the individual climate change assumption. Therefore, when the average precipitation under double exposure assumption is above the average, more groundwater will be pumped and vice versa. In severe drought years, adopting the drip system will be vital to maintaining crop yields and more land would be expected to be under drip irrigation.

5.3. Land allocation

Climate variability and change has a major impact on water availability as well as the land use and distribution. Based on the degree of change in the precipitation, a redistribution of land use can be observed, as shown in Fig. 2. Under all climate assumptions, urban and non-agricultural lands are taken as being constant each year, at 15.19 thousand hectares. Cultivation of agricultural land is taken as being motivated by the generation of income from the production of crops, where farmers will attempt to maximize the net economic value of irrigated land under available water resources. It is expected that declining crop

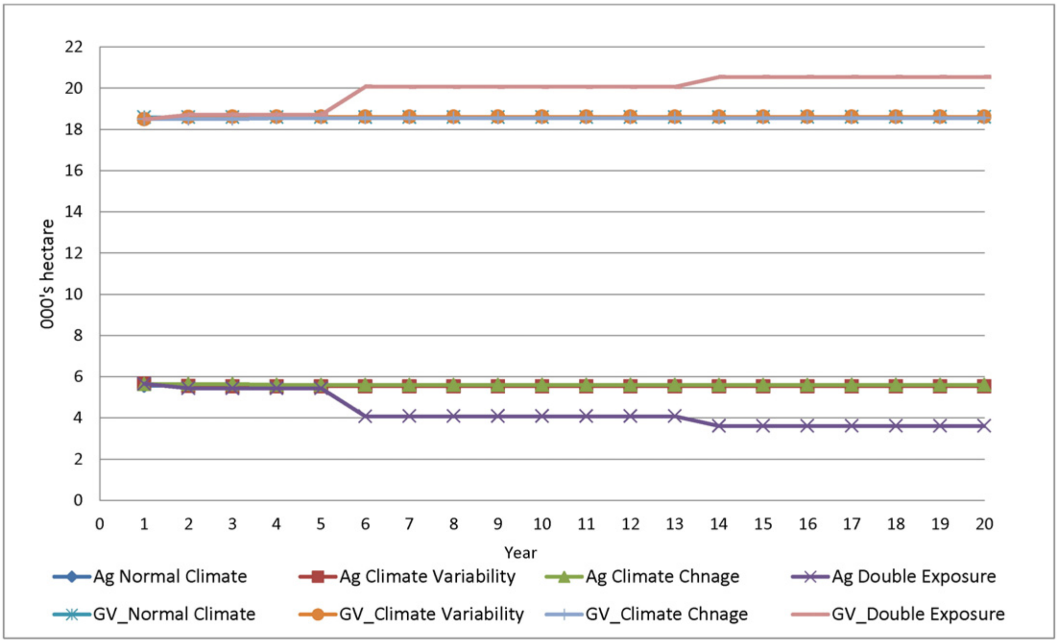

Fig. 2. Total agricultural land in production vs. grass and vacant land by climate assumption, Barbados (000's of hectares).

yields, a result of water supply shortage will encourage farmers to take some actions to maintain land yield through the adoption of irrigation technology or by switching to higher value crops. Under all circumstances, moving toward higher value crops or new technology adds additional costs.

Up to a point, moving to higher valued crops has a positive impact on farmers' income for a limited period of time, as increasing aggregate production from any crop will lead to higher supply in the market and result in a reduction in overall market price and reducing farmers' profitability. Therefore, farmers would choose to abandon production if the associated costs exceed total revenue in the long run, leaving the land unused.

Fig. 2 provides information about total redistribution of agricultural land use versus non-occupied land uses, summed by irrigation technologies under different climate assumptions. Under a normal climate assumption, a very small decline in agricultural land is observed over time. Climate variability would add a further slight reduction in agricultural land uses. Surprisingly, a small increase in agricultural land is observed under the climate change assumption, attributed to increasing food prices. Despite that fact that the climate change assumption has the largest negative impact on the aquifer storage volume and pumping depth, it seems that other factors play a more important role, encouraging farmers to bring more land into production. Those factors are non-physical variables, which are related to the supply and demand on food that drives the food market price.

Under the double exposure climate assumption, a sharp decline in agricultural land occurs and an increase in non-agricultural land takes place. The reduction grows gradually over time, moving from 28% in the first stage to 36% at the end of the analysis period. This explains the incremental increases in the aquifer storage volume under this climate assumption shown earlier. Grasslands have less evapotranspiration capacity compared to other land uses and hence more water infiltrates, due to the reduction in agricultural activities. While it is not shown in this figure, the severe reduction in precipitation will negatively affect the crops' yield, especially rainfed agriculture crops, such as sugarcane, making it less profitable to be cultivated.

In addition to the redistribution of land between agriculture cultivated and non-cultivated land, shown in Fig. 2, another type of land use redistribution occurs; between rainfed and drip irrigation. Drip irrigation works as a back-up system that can be used during drought periods to provide sufficient water to maintain crop yields. Farmers would be willing to install the system if the change in total revenue of that action exceeds the total average cost of the adapted system. Fig. 3 sums up all rainfed agricultural land and demonstrates a decline in rainfed land under all climate assumptions, except absolute climate change. The magnitude of that reduction varies, a small decline can be observed under climate variability compared to a relatively higher level of reduction with double exposure assumption.

Fig. 4 shows changes in cultivated land under a drip irrigation system by climate assumption. A general trend of increasing land under drip irrigation is indicated with all climate assumptions, as compared to the normal climate assumption. Climate variability shifts drip irrigated land slightly, by 0.5% as compared to the normal climate assumption. Water shortages in drought years encourage farmers to adopt the irrigation technology to maintain farm incomes. The impact of lower average pumping costs per cubic meter of abstracted groundwater as a result of increased aquifer storage volumes is shown in Fig. 1. The increases in land area under drip irrigation reach 3.4% under the climate change assumption as a result of declining precipitation.

5.4. Food security

Table 3 shows the impact of climate assumptions on total average crop prices. Annual variability in water supply generates a similar variability in annual prices for all crops. During wet years, production from rainfed irrigated land rises due to the improvement in crop yields resulting in falls in market price. In contrast, during dry periods, a significant reduction in rainfed-irrigated land productivities occurs and less food is supplied to the market causing price escalation. Despite farmers' willingness to add more land under drip irrigation under the new climate condition, about 0.5%, the increased production does not compensate for the reduction in rainfed land productivity. In other words, increased prices during drought years outweigh the decline in prices

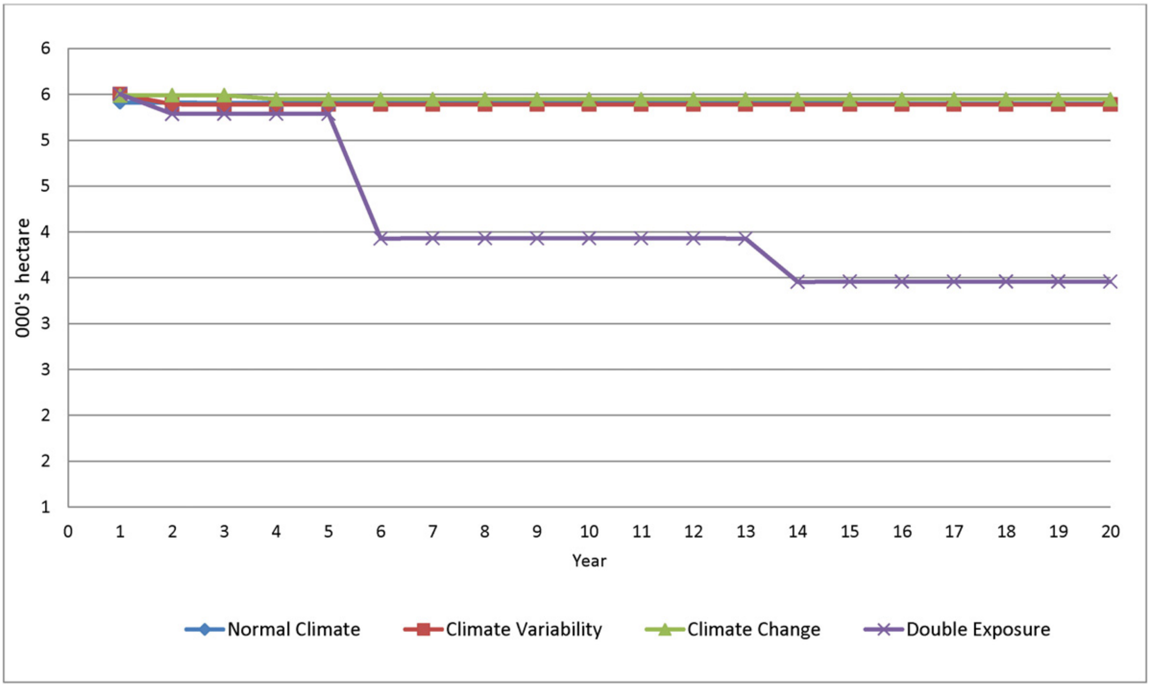

Fig. 3. Total annual rainfed agriculture land in production by climate assumptions, Barbados (000's of hectares).

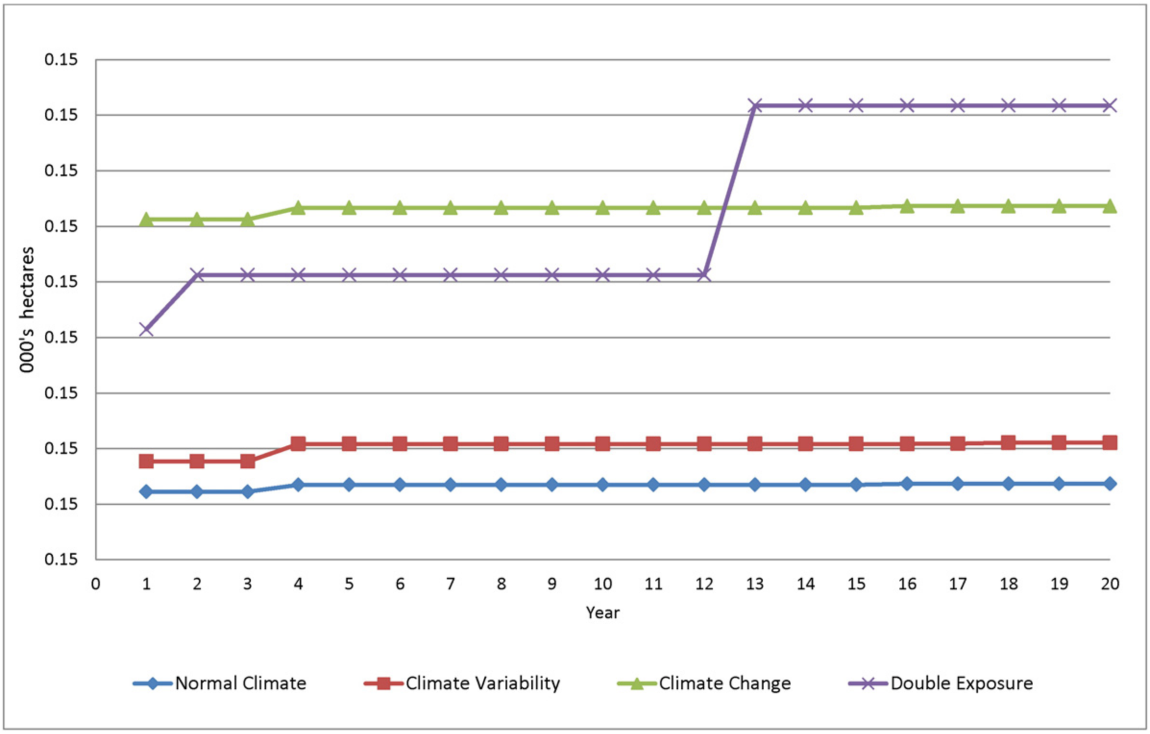

Fig. 4. Total annual agricultural land in production under drip irrigation technology by climate assumption, Barbados (000's a hectare).

during the wetter years, resulting in small increases in prices under climate variability assumptions.

Under climate change, rainfed farming experiences an increased reduction in crop yields and total production falls sharply. Although more farmers would decide to adopt drip irrigation technology, almost 4% comparing to normal climate assumption, increased total production brought about by land added to production will be less than the reduction in total production caused by declines in crop yield. Under the double exposure impact, a severe reduction in crop yields induces more farmers to adopt drip irrigation. As more farmers adopt irrigation technology, supply from vegetable and root crops will increase causing significant decreases in prices compared to the climate change assumption. For sugarcane, where drip technology would not apply, the significant decline in sugarcane productivity together with a massive decline in cultivated sugarcane land reduces the total supply and further shifts up the price. Overall, the limited ability to apply modern irrigation technologies makes sugarcane highly vulnerable to climate change.

5.5. Economic welfare

In our analysis, economic welfare refers to the discounted net farm benefit plus consumer surplus generated by allocating resources such as land, water, and capital to produce different crops. It is important to note that in this analysis, the economic impacts of climate variability and climate change assumptions on land use, farm income, and consumer surplus are averages estimated over the sector. The changes in land use and farm income will depend on aspects such as the farm size and operation efficiency, which required more concrete information for them to be incorporated into the framework. Determining the beneficiaries and losers of climate variability and change assumption is beyond the scope of this research. It would also require a different type of framework such as an agent based model. Table 3 demonstrates the total average discounted net farm benefits by crops and climate assumptions in thousand US dollars. Sugarcane is the dominant cultivated crop but it generates the least discounted farm income even under normal climate assumption. Sugarcane is a low value crop that is associated

Table 3
Optimized average discounted net farm income, consumer surplus and crop prices, Barbados (Ave. 20 years, 000's $ US).

	Discounted farm income				Discounted consumer surplus				Crops prices			
Crops	Normal climate	Climate variability	Climate change	Double exposure	Normal climate	Climate variability	Climate change	Double exposure	Normal climate	Climate variability	Climate change	Double exposure
Sugarcane	51	230	134	3148	16,399	15,539	11,014	6914	0.083	0.086	0.102	0.124
Cabbage	133	134	140	140	402	399	383	383	1.725	1.748	1.905	1.902
Cassava	187	188	193	192	624	622	609	610	1.139	1.148	1.212	1.209
Cucumber	226	227	231	231	792	789	768	770	0.862	0.868	0.918	0.915
Okra	159	159	159	159	561	560	554	554	1.986	1.993	2.043	2.040
Onion	268	269	274	274	1113	1111	1095	1096	1.138	1.144	1.187	1.185
Pigeon peas	53	54	56	56	187	186	176	176	3.448	3.508	3.893	3.894
Pumpkin	140	142	156	155	373	368	333	335	1.204	1.239	1.479	1.480
Squash	521	522	530	529	1820	1815	1778	1780	1.145	1.152	1.204	1.202
Sweet pepper	264	266	272	272	899	895	876	876	2.255	2.279	2.387	2.390
Sweet potato	844	849	882	879	2867	2854	2781	2784	2.286	2.313	2.474	2.469
Tomato	205	205	208	208	1290	1287	1271	1272	1.414	1.422	1.470	1.468

with high yield sensitivity to precipitation. For other crops, farmers make positive net farm income, especially crops such as sweet potato, sweet pepper, and onion.

Climate variability produces a small overall increase in farm profitability for most crops, while no significant change can be observed for other crops. Growers of crops such as sugarcane, pumpkin, sweet potato, and sweet pepper are better off under climate variability while cultivators of crops such as tomato and okra achieve no additional net benefits in the long run. The improvement in net farm income for those crops results from higher prices during the drought periods. Under the climate change assumption, a steady reduction in crop yields reduces the overall total supply from all crops resulting in much higher prices and thus additional net farm income that can be generated by farmers. The reduction in food supply due to climate change will raise the prices to a higher level and improve the net farm income for all crops by different fractions. Crops such as pumpkin, sweet potato, pigeon peas, and cabbage will achieve the highest increases in net farm income, while sugarcane continues to increase by a smaller rate.

With the double exposure assumption, enormous increases in sugarcane cultivators' farm income happened as a direct result of a massive decline in sugarcane production. Concurrent with a decline in sugarcane yields, a large portion of cultivated sugarcane lands would be abandoned, scaling down the supply to the market and resulting in higher prices. In the extreme case, this would increase these farmers' incomes. Given the fact that cultivating sugarcane is a 6 year decision, sugarcane cultivators who decide to give up sugarcane production will find it hard to switch back to cultivate due to the high initial capital cost in the first year of cultivation. For other crops, however, larger areas of land would be reallocated to the drip irrigation system increasing production and lowering crop prices, thus farm income from those crops fall slightly.

Table 3 shows changes in consumer wellbeing under the climate assumptions. Consumer surplus is the other side of the economic welfare analysis coin, and is expected to show an inverse trend compared to the farm income. Integrating the farm income and consumer surplus in this way demonstrates the competitive nature between the consumers' and the producers' willingness and interests. Table 3 demonstrates that under the climate variability assumption, a small reduction in consumers' welfare occurs as a result of increased prices. However, the highest decline happens for sugarcane consumption, which drops by almost 5%. The climate change assumption on other hand, adversely affects consumers through higher prices and less food availability. Some crops that contribute to higher net farm income would now contribute to a reduction in consumers' surplus. Under the double exposure assumption, small improvements in the consumer surplus take place as result of lower prices for all crops except the sugarcane compared to the climate change assumption. It is important to note that the magnitude of consumer surplus reduction is close to the magnitude of increased farm income for most crops except sugarcane, whereas the increase in farm income is proportionally higher than the reduction in consumer surplus under all climate assumptions.

Climate variability and change have differing impacts on farmers and consumers. The impact will be uneven among farmers themselves based on their irrigation technology choices. Net gains or losses per hectare under different climate assumptions are determined by the level of precipitation induced by climate and market prices resulting from changing total food supply in the market. By applying drip irrigation, however, yield per hectare can be maintained and only market prices have the major effect on the net benefit per hectare. The average annual discounted net farm income per hectare, irrigation system, and climate assumptions are shown in Table 4.

Under climate variability, average net benefits per hectare from rainfed crops increases significantly during drought years as compared to the normal climate assumption, where the impact of increased prices outweighs the impact of declining yield. Wetter years increase the total supply due to higher productivity and thus prices fall resulting in less profitability per hectare. For the climate change assumption, an overall decline in per hectare net farm income is detected due to the deep reduction in crop yields. However, increased prices mitigate the negative impact on per hectare net farm income especially in dry years. By contrast, the situation would be the reverse under the impact of double exposure climate where a considerable amount of land is taken out of cultivation causing a massive reduction in total supply to the market leading to a significant increase in crop prices. Despite higher reduction in yield, increased prices will increase net farm income.

Farmers adopting drip irrigation would be able to maintain their yield during drought period under climate variability assumption. The net farm income per hectare is higher compared to that under the normal climate assumption in dry years, but it is less for wet years. During wet years, the total market supply is higher due to higher productivity from rainfed land, which means lower crop prices. Regardless of their ability to achieve a high yield, drip irrigators bear additional cost per hectare, which reduces the net benefit per hectare with low market prices. Under climate change assumption, net farm income for drip irrigation adopters will be higher for the same reasons. Under double

Table 4
Annual average discounted net farm income per hectare by irrigation technology and climate assumption, Barbados (000's $ US/ha).

	Rainfed agriculture				Drip irrigation			
Year	Normal climate	Climate variability	Climate change	Double exposure	Normal climate	Climate variability	Climate change	Double exposure
1	0.09	0.08	0.07	0.07	19.44	21.64	20.34	19.83
2	0.09	0.08	0.07	0.06	19.12	18.19	19.88	22.79
3	0.08	0.08	0.07	0.28	18.90	17.90	19.63	18.86
4	0.11	0.18	0.06	0.28	19.14	20.05	20.21	18.79
5	0.09	0.18	0.09	0.28	18.68	20.21	19.55	18.77
6	0.09	0.11	0.08	0.07	18.55	18.03	19.45	24.60
7	0.09	0.18	0.09	1.73	18.24	19.68	19.03	16.61
8	0.08	0.16	0.11	1.55	17.82	18.83	18.35	17.93
9	0.09	0.08	0.08	1.28	17.96	16.88	18.80	19.34
10	0.09	0.08	0.10	1.65	17.63	16.45	18.33	16.49
11	0.09	0.09	0.08	1.54	17.64	16.36	18.48	17.10
12	0.08	0.13	0.10	1.64	17.22	17.64	17.84	15.91
13	0.09	0.11	0.08	0.30	17.24	17.04	18.03	19.89
14	0.09	0.16	0.08	0.06	17.03	18.30	17.78	20.63
15	0.08	0.09	0.11	1.18	16.49	16.12	16.82	17.46
16	0.09	0.11	0.08	0.92	16.73	16.62	17.50	18.10
17	0.10	0.14	0.07	1.05	16.69	17.03	17.53	17.48
18	0.10	0.16	0.06	1.83	16.54	18.06	17.39	14.10
19	0.08	0.09	0.09	1.29	16.06	15.13	16.63	16.22
20	0.07	0.07	0.10	1.14	15.77	14.91	16.19	16.57

exposure assumption, there are some declines in net farm benefit per hectare in wetter years. However, price reduction caused by higher total supply plays the critical role in determining the hectare's net profitability.

The fluctuation in net farm income induced by climate alterations correlates with variability in consumer livelihoods. Change in total annual consumer surplus summed over all crops by climate assumptions in 1000 $ US is shown in Fig. 5. A declining trend in consumer welfare under all climate assumptions is observed over time. However, with the normal climate assumption, a small, steady reduction in welfare occurs compared to the moderate variability in consumer surplus under the climate variability assumption. Consumer surplus would decrease slightly with a declining supply of food and increased prices. In contrast, a decrease in consumer surplus takes place under the climate change impact, while the double exposure assumption has a significant negative effect on consumer surplus.

As discussed above, climate impacts vary among crops as well as over time. Crops that are vulnerable to climate impacts, such as sugarcane, are associated with greater loss of consumer surplus compared to low vulnerability crops. For instance, greater variability in consumers' surplus occurs for sugarcane than for other crops that could be brought under drip irrigation. Irrigation reduces crop susceptibility by mitigating the impacts on productivity of the crops' water shortage during drought periods. Adopting irrigation technologies not only benefits food producers but also provides some benefits for consumers as well. Drip irrigation would keep the total supply at higher levels, which results in more food at affordable prices for consumers.

6. Conclusion

There has been little research to date that has simultaneously investigated the impact of climate variability and change on agricultural production, water availability and social economic livelihoods. Furthermore, there has been little differentiation between the relative effects of climate variability, climate change, and their combined impact (i.e. variability and change). In this work, we present an integrated framework that differentiates between these different climate assumptions and their impacts on water resources availability, land distribution, farm income, and food security, taking into account adaptation measures and technological boundaries.

Integrating climatic data, aquifer properties, and farm budget information, a dynamic non-linear framework that optimizes the total agricultural economic welfare under four climate assumptions has been developed and as a numerical example applied to Barbados. Several inferences from the results of this work can be made. Climate variability, change, and dual exposure assumptions are shown to have major impacts on water resources and economic wellbeing. However, the magnitude and direction of the impacts vary and it is important not to treat physical and economic aspects separately. While climate variability and change reduce water availability, climate variability could mitigate some of the negative impacts of climate change. Moreover, while climate variability and change each produce undesirable effects on consumer surpluses, their joint impact worsens the consumers' outcomes. On the other hand, climate alteration offers an opportunity for some food producers to gain more benefits, dependent on the type of crops produced and the adoption of irrigation technology.

Adaptation measures such as drip irrigation could bring benefits for both consumers and food producers under different climate alternatives. Food producers would be better off by adopting irrigation technologies that secure higher crop yields, while consumers have access to more food in the market. Yet, under all climate assumptions, some increases in food price take place. Regardless of the fact that the agricultural sector is smaller compared to other water users: the growing demand from other sectors such as urban domestic users and industry create negative externalities on food producers and consumers through increasing the cost of water and pumping costs.

Although the results of this work indicate how different climate assumptions impact water availability and food security it is acknowledged that the framework does require further refinement and development. Aspects that require further elicitation include better spatial representation of rainfall distribution, land use and productivity, groundwater characteristics and costs of production. Seasonality within climate variables such as rainfall, ET, and evaporation are important factors, which could not be better represented due to data availability. Climate projection outputs based on global, regional and downscaled climate will in the future allow for better correlation with other climate

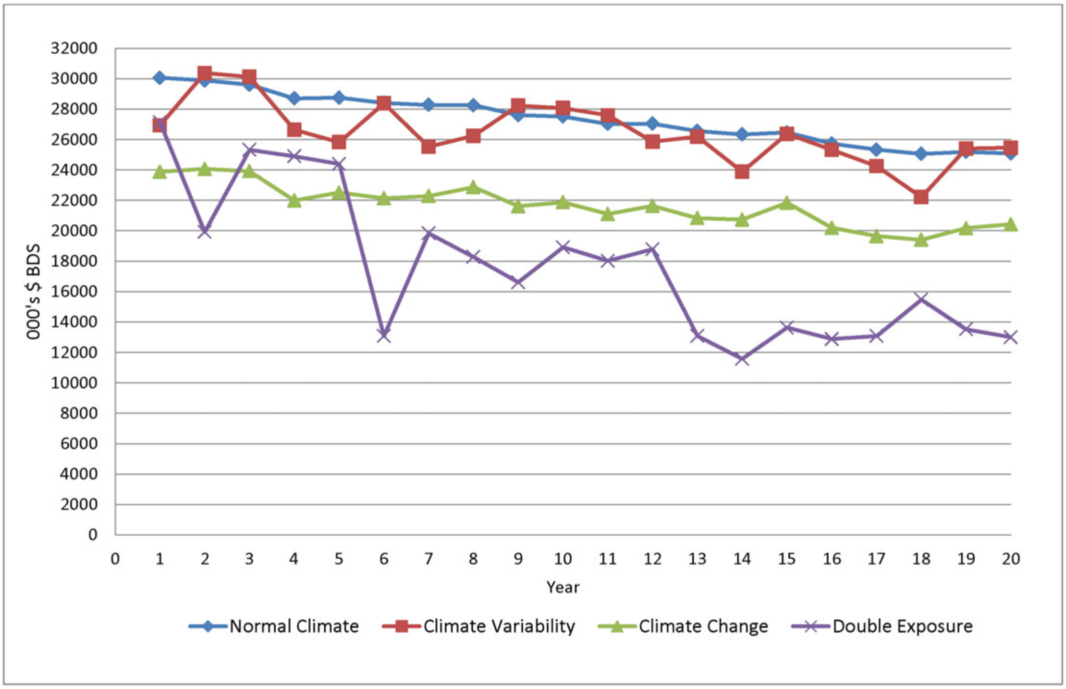

Fig. 5. Average annual consumer surplus (CS) by climate assumption, Barbados (000's $ US).

change research such as impacts on water resources. The investigation of the magnitude of the impacts of different subsidies and taxes on economic welfare, taking into account the other factors mentioned above, would aid better decision-making and policy design. Finally, the environmental impact of different climate assumptions is an important area to be integrated in future analyses. Despite these limitations, the framework presented has been designed in such a way as to enable refinements such as more detailed data and different spatial and temporal scales to be incorporated.

Acknowledgments

The authors are grateful for financial support by Water-aCCSIS project and data support from Barbados Water Authority (BWA), and the Ministry of Agriculture, Barbados.

Appendix A. The mathematical framework's variables list

A.1. Major variables used in the mathematical framework by name and unit of measurements

Variable	Discretion	Unit
Pr	Average annual precipitation	000's CM
RHS	Total water available for the region	000's CM
ET	Actual evapotranspiration	000's CM
ET^d	Potential ET for drip irrigated crops	000's CM
SW	Water run off	000's CM
Dep	Water depletion for road and urban areas	000's CM
Seep	Seepage to groundwater system	000's CM
Yield	Crop yield	Ton
SV	Aquifer storage volume	000's CM
GP	Groundwater pumped for drip irrigation	000's CM
ATC	Average total cost of agricultural production	000's $ US
NWC	Non-water cost of agricultural production	000's $ US
CC	Capital cost of agricultural production	000's $ US
PC	Pumping cost of agricultural production	000's $ US
hectare	Land in use	Hectare
CCS	Drip irrigation system purchase cost	000's $ US
r	Interest rate	No units
Subsidy	Governmental subsidy for drip irrigation system	000's $ US
Kp	Pump cost per meter added to pumping depth	000's $ US
P.depth	Pumping depth	Meter
TNB	Total net benefit (farm income)	000's $ US
P	Crop price	000's $ US/ton
WC	Water tariff	000's $ US/000's CM
PTNB	Present value of total net benefit	000's $ US
TP	Crop total production	Ton
CS	Consumer surplus	000's $ US

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