MEASURING THE IMPACT OF CLIMATE CHANGE ON SOUTH AFRICAN AGRICULTURE: THE CASE OF SUGAR-CANE GROWING REGIONS

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Abstract

This study employed a Ricardian model that captures farmers' adaptation to analyze the impact of climate change on South African Sugarcane production under irrigation and dryland conditions. The study utilized time series data for the period 1977 to 1998 pooled over 11 districts. Results showed that climate change has significant nonlinear impacts on net revenue per hectare of sugarcane in South Africa with higher sensitivity to future increases in temperature than precipitation. Irrigation did not prove to provide an effective option for mitigating climate change damages on sugarcane production in South Africa. The study suggests that adaptation strategies should focus special attention on technologies and management regimes that will enhance sugarcane tolerance to warmer temperatures during winter and especially the harvesting phases.

1. INTRODUCTION

It is generally recognized that, among all sectors, agricultural production activities are the most sensitive and vulnerable to climate change (IPCC, 1990). However, studies conducted at the global level indicated small net impacts of climate change (CC) on world agriculture as production losses in negatively affected areas are offset by gains in areas enjoying positive impacts (Kane *et al*, 1991). Clearly, global assessments hide important spatial variations in severity of CC impacts. There is evidence that tropical regions are more likely to be negatively affected whereas, temperate climates are likely to gain in productivity from global warming (IPCC, 1996).

Many efforts have been made to measure the economic impact of CC on agriculture focusing mainly on the United States and other developed countries (Adams, 1989; Rosenzweig, 1989; Mendelson *et al*, 1994; Kaiser *et al*, 1993). Agricultural production systems in developing countries and especially

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in Africa are more vulnerable to CC because they have lower capital intensity and technological flexibility to adapt and most are in already hot climates that are likely to get hotter (Mendelsohn *et al*, 2000).

The relatively higher risk cropping environment (frequent droughts and erratic rainfall patterns) and energy intensive economic system of South Africa (SA) makes the country even more vulnerable to CC damages. This in turn, is expected to have important implications for the welfare of the people of SA given the importance of agricultural production activities for the national economy and the livelihoods of people, especially the poor. While some studies have been conducted to assess the impact of CC on agriculture in developing countries (Winter *et al*, 1996; Dinar *et al*, 1998; Kumar & Parikh, 1998; Mendelson *et al*, 2000), very little research was carried in SA to study CC impacts on agriculture.

Sugarcane production is an important activity in the South African agriculture (Hassan & Olbrich, 2001). Based on the actual sales and selling prices in 2000/2001, it is estimated that the South African Sugar industry contributed R 1.9 billion to the country's foreign exchange earnings. Employment within the sugar industry is approximately 85,000 jobs, direct and indirect employment is estimated at 35,0000 people & there are approximately one million people dependent on the sugar industry (SASA, 2001). Given these contributions, any factor affecting the industry has an impact on its contribution to the total GDP of agriculture and hence to the overall economy.

Like other agricultural sectors, sugarcane farming is expected to be significantly influenced by climate Change. Studies have been conducted to analyze the impact of climate change on maize production (Schulze, 1993; Du Toit *et al*, 2001), the farming sector of the Western Cape (Erasmus *et al,* 2000) and sugarcane farming (Kiker, 2002; Kiker *et al*, 2002) in South Africa. All of these studies adopted the production function approach, which does not include farmers' adaptations. So far there has not been any study to address the economic impact of climate change on sugarcane farming and farm level adaptations that sugar farmers make to mitigate the potential impact of climate change.

The objective of this study is to analyze and measure the economic impact of climate change on sugarcane farming in South Africa by making use of the Ricardian approach. The Ricardian approach is a cross-section regression approach to modeling the response of land value or net revenue to changes in environmental attributes, which allows measuring the marginal contribution of such factors to net farm income capitalized in land value. This paper is organized as follows: section two discusses the climate change modeling which includes the approach adopted, specification of the empirical model variables and data including the estimation procedures. Results of the empirical analysis are presented in section three. Finally, section four gives summary and conclusions.

2. APPROACH AND METHODS OF THE STUDY

As this study deals with one crop, a partial equilibrium analytical approach was adopted. Two main classes of partial equilibrium models are generally employed to analyze impacts of CC on agriculture: the crop growth simulation and the econometric approaches[3]. One common crop modelling method is the crop suitability/agro-ecological zoning approach, which combines with land resource inventories to determine potential yield (FAO, 2002). While this method can handle adaptation to CC, it is data intensive as it is not possible to predict final outcomes without explicitly modelling all relevant components. The other common crop modelling method is known as the production function approach, which is based on experimental or empirical analysis of the relationships between yield and environmental factors (Chang, 2002). This method generates more accurate yield responses as it relies on relatively more reliable data in terms of the relationship between yield and climatic variables, but it does not take adaptation into account and is also more data intensive and thus costly (Mendelson *et al*, 1994; Dinar *et al*, 1998). Kiker (2002) and Kiker *et al* (2002) developed sugarcane growth models to simulate growth factors and sucrose yields and indicated that climatic factors (rainfall and temperature) affect different sites differently across the sugarcane producing regions. In addition to the failure to present the level of damage induced by climate change across production regions, the cited studies adopted the production function method, which does not control for farmers' adaptations.

This study used an econometric approach known as the Ricardian method to assess economic impacts of CC, which allows for capturing adaptations farmers make in response to CC. One of the weaknesses of the Ricardian method studies is the assumption of constant prices, but it is practically even more difficult to properly handle price effects in any of the other methods (Mendelson *et al*, 2000). The Ricardian method is successfully adopted and used to analyse the climate sensitivity of agriculture in different countries (Brazil, India, and USA). It can be used with lesser cost than the other methods and equally important information can be gained for policy purpose in

[3] *For a comprehensive review of climate change impacts assessment models see Kurukulasuriya and Rosenthal (2003).*

countries where time series data on climate, price of land and production data are found. The sugar cane producing regions of South Africa are one of the places where these kinds of data can be obtained from the well-organised database of the South African Sugar Association (SASA).

2.1 The Ricardian method

The Ricardian method is an empirical approach developed by Mendelson *et al* (1994) to measure the value of climate in the United States agriculture. The technique has been named the Ricardian method because it is based on the observation made by Ricardo (1817), that land values would reflect land productivity at a site under perfect competition. It is possible to account for the direct impact of climate on yields of different crops as well as the indirect substitution among different inputs including the introduction of different activities, and other potential adaptations to different climates by directly measuring farm prices or revenues by using the Ricardian model.

The value of land reflects the sum of discounted future profits, which may be derived from its use. Any factor, which influences the productivity of land, will consequently affect land values or net revenue. Therefore the value of land or net revenue contains information on the value of climate as one attribute of land productivity. By regressing land values (or net revenue) on environmental and other factors, one can then determine the marginal contribution of each input to farm income as capitalized in land value.

The Ricardian model is based on a set of well-behaved (twice continuously differentiable, strictly quasi-concave with positive marginal products) production functions of the form:

$$Q_i = Q_i(K_i, E) \tag{1}$$

Where, Q_i is quantity produced of good i, K_{ij} is a vector of production inputs j used to produce Qi and E defines a vector of exogenous environmental factors such as temperature, precipitation, and soil, characterizing production sites.

Given a set of factor prices w_j , E and Q, cost minimization gives the cost function:

$$C_i = C_i(Q_i, W, E) \tag{2}$$

Where C_i is the cost of production of good *i* and $W\,(w_1, w_2 \ldots w_n)$ is the vector of factor prices. Using the cost function C_i at given market prices, profit maximization by farmers on a given site can be specified as:

$$Max.\pi = \left[P_i Q_i - C_i(Q_i, W, E) - P_L L_i\right] \quad (3)$$

Where P_L is annual cost or rent of land at that site, such that under perfect competition all profits in excess of normal returns to all factors (rents) are driven to zero

$$P_i Q_i^* - C_i^* = (Q_i^*, W, E) - P_L L^*{}_i = 0 \quad (4)$$

If the production of good *i* is the best use of the land given *E*, the observed market rent on the land will be equal to the annual net profits from the production of the good. Solving for P_L from the above equation gives land rent per hectare to be equal to net revenue per hectare.

$$P_L = (P_i Q_i^* - C_i(Q_i^*, W, E)) / L_i \quad (5)$$

The present value of the stream of current and future revenues gives the land value V_L:

$$V_L = \int_0^\infty P_L e^{-rt} dt = \int_0^\infty \left[(P_i Q^*{}_i - C_i(Q^*, W, E) / L_i\right] e^{-rt} dt \quad (6)$$

The issue to be analyzed is the impact of exogenous changes in environmental variables on net economic welfare (ΔW). The net economic welfare is the change in welfare induced or caused by the changing environment from a given state to the other. Economic welfare change is measured in terms of change in the capitalized value of the land or alternatively in net farm income. Consider an environmental change from the environmental state *A* to *B*, which causes environmental inputs to change from E_A to E_B. The change in annual welfare from this environmental change is given by:

$$\Delta W = W(E_B) - W(E_A) = \int_0^{Q_B} \left[(P_i Q_i - C_i(Q_i, W, E_B) / L_i\right] e^{-rt} dQ - \int_0^{Q_A} \left[(P_i Q_i - C_i(Q_i, W, E_A) / L_i\right] e^{-rt} dQ$$

If market prices do not change as a result of the change in E, then the above equation reduces to:

$$\Delta W = W(E_B) - W(E_A) = \left[PQ_B - \sum_{i=1}^{n} C_i(Q_i, W, E_B) \right] - \left[PQ_A - \sum_{i=1}^{n} C_i(Q_i, W, E_A) \right] \quad (7)$$

Substituting for $P_L L = P_i Q_i^* - C_i (Q_i^*, W, E)$ from (5)

$$\Delta W = W(E_B) - W(E_A) = \sum_{i=1}^{n} (P_{LB} L_{Bi} - P_{LA} L_{Ai}) \quad (8)$$

Where P_{LA} and L_A are at E_A and P_{LB} and L_B are at E_B

The present value of the welfare change is thus:

$$\int_0^{Q_B} \Delta W e^{-rt} dt = \sum_{i=1}^{n} (V_{LB} LB_{Bi} - V_{LA} L_{Ai}) \quad (9)$$

The Ricardian model takes either (8) or (9) depending on whether data are available on annual net revenues or capitalized net revenues (land values V_L). The model in (8) was employed for this research, as data on land prices for the selected samples were not available. This is the same approach followed by Sanghi *et al* (1998) and Kumar and Parikh (1998) for India.

2.2 The empirical sugarcane model and data

Sugarcane producing regions in SA extend from the Eastern Cape Province through Mpumalanga Province in the north. Over these areas, sugarcane is produced under two main climatic conditions: the stepped (arid) zones in the north where sugarcane is irrigated and the sub-tropical wet climate areas of KwaZulu-Natal, where sugarcane production is rain fed. A total of 11 districts were selected for this study: two districts from the irrigated region and nine districts from the rain fed sub-tropical climate in KwaZulu-Natal.

Farm-level data on determinants of net-revenue were obtained from the South African Sugar Association. Those included, price per ton, production per hectare, cost of labour, chemicals, fertilizer, fuels and lubricants, mechanical and fixture maintenance, and irrigation per ton of sugarcane produced. The net revenue per hectare was deflated using the agricultural GDP deflator and is in 1995 prices (Deressa, 2003).

Data on climatic (rainfall & temperature) and geographic (altitude and latitude) variables were collected from experiment stations compiled for each of the cane producing districts. The soil data were collected from the Institute for Soil, Climate and Water of the Council for Scientific and Industrial Research (CSIR). The climatic variables included were the monthly average temperature and rainfall for each district over the period 1976/77 to 1997/98. As the net revenue per hectare is expected to be influenced by factors other than climatic variables, control variables like soil type and altitude were also included. The soil type, which varies across the sample districts, was included as it affects yield. Altitude was included to proxy solar energy. In addition, irrigation dummies were used to control for and compare the impact of climatic variables on irrigated and dryland farming. Finally, time trends were included to observe the net revenue per hectare over time for both regions. Table one gives a description of the variables included in the empirical model.

The study employed the Ricardian approach using net revenue per hectare for each district as the dependent variable. Net revenues were regressed on the climatic and other control variables listed in Appendix 1. A non-linear (quadratic) model was chosen, as it is easy to interpret (Mendelson *et al*, 1994).

The data were pooled over districts and one equation for all districts was estimated. In the preliminary runs, district dummies were included to capture the variability among districts, but most of the district dummies were statistically insignificant. In the second run, regional dummies (for the 5 agro-ecological sub-regions) were included and again found insignificant except for the irrigated regions. This is an indication that location effects were adequately captured by other physical conditions or factors (climate and soil) rendering regional location dummies redundant except for irrigation. Accordingly, an irrigation dummy was included to measure the effect of irrigation on CC impacts. Additionally, the trend of net revenue per hectare for both irrigated and non-irrigated regions were captured by including a time trend for both regions.

The independent variables include the linear and quadratic temperature and precipitation terms for the three seasons (winter, summer and harvesting), the temperature precipitation interaction terms, edific and geographic variables (soil type and altitude), the irrigation dummy and time trends. The quadratic climate terms were included to capture second order effects of climate on net revenues and e_i is the error term. Initially, the planting season temperature, and precipitation were included but were found statistically insignificant and hence omitted. Population density as a proxy for urbanization and hence its influence on the price of land (net revenue) was also included in the initial run but was also found insignificant and consequently dropped.

3. RESULTS AND DISCUSSION

The regression results indicated that climate variables, altitude, the soil and irrigation dummies and the time trend have significant impacts on net revenue from sugar farming. The estimated coefficients of most of the linear, quadratic and interaction terms of the climate variables (temperature and rainfall) were statistically significant (Table 1).

Table 1: Parameter estimates of the sugarcane net revenue model for South Africa

Dependent Variable: Net revenue per hectare		
Independent variable	**Parameter**	**t value**
Winter growing temperature (WT_i)	3729.67	3.08**
Winter growing temperature square ($WTSQ_i$)	-108.94	-3.17**
Summer growing temperature (STi)	-4460.22	-2.43**
Summer growing temperature square ($STSQ_i$)	89.47	2.28*
Harvesting temperature (HT_i)	-1633.84	-1.34
Harvesting temperature square ($HTSQ_i$)	37.92	1.10
Winter growing precipitation (WP_i)	20.76	0.85
Winter growing precipitation square ($WPSQ_i$)	-0.04	-1.14
Summer growing precipitation (SP_i)	-79.92	-2.49*
Summer growing precipitation square ($SPSQ_i$)	0.01	0.23
Harvesting precipitation (HP_i)	-65.59	-2.65**
Harvesting precipitation Square ($HPSQ_i$)	-0.05	-1.38
Winter temperature* Winter precipitation ($WTWP_i$)	-0.76	-0.53
Summer temperature * Summer precipitation ($STSP_i$)	3.24	2.5*
Harvesting Temp * Harvesting precipitation ($HTHP_i$)	3.96	2.78**
Soil type1	375.78	1.38
Altitude	-1.41	-1.43
Irrigation dummy	44877	2.5*
Dryland dummy	43830	2.45*
Time trend for irrigated land	-43.15	-1.8
Time trend for dryland	-70.90	-5.82**
Adjusted R^2 = 0.99; DW statistic = 0.873; F value = 8048		
Model Degree of freedom = 21; Error Degrees of freedom = 232; Number of observations = 253		

Note: *Indicate significance at the 5% level of probability and ** refers to significance at the 1% level of probability.

As expected, temperature and precipitation were found to significantly affect net revenue per hectare across production seasons. The dummies for both irrigated and non-irrigated regions were also statistically significant. The parameter estimate for the irrigated region is greater than that of the dryland region indicating higher yields and hence net revenue as irrigation controls for rain fluctuations. The estimated parameters of the time trend for both irrigated and dryland farming were negative and statistically significant. The negative time trend parameter values indicate the general trend of decline in net revenue per hectare in both regions. This could be attributed to a number of factors including unfavorable price trends and patterns of technological change. The results further indicated that net revenue per hectare in the dryland farming areas was decreasing at a higher rate than that in the irrigated region. This is again an indication of reduced damages to net revenue made possible through irrigation.

Altitude, which was included to proxy solar radiation, was negatively related to net revenue per hectare, this could be attributed to the fact that at higher altitudes, temperature is cooler and makes sugarcane production period longer before maturity. The soil type (drained sandy soil) positively affected sugarcane production compared to the shallow and high lime content soils. This suggests that sugarcane grows better on sandy-loam soils compared to shallow and high lime soils (Smith, 1994).

3.1 Simulation of climate change impacts

Following Sanghi *et al* (1998), and Kumar and Parikh (1998) in analyzing the impact of climate change on Indian agriculture, this section used estimated coefficients of the regression model to simulate the impacts of changing temperature and precipitation on net revenue per hectare of sugarcane. In this approach, the change in the response variable (net revenue per hectare) is simulated utilizing estimated regression coefficients from the pooled analysis (Table 1) for both the irrigated and dryland farming for the 1976/77 to 1997/98 period.

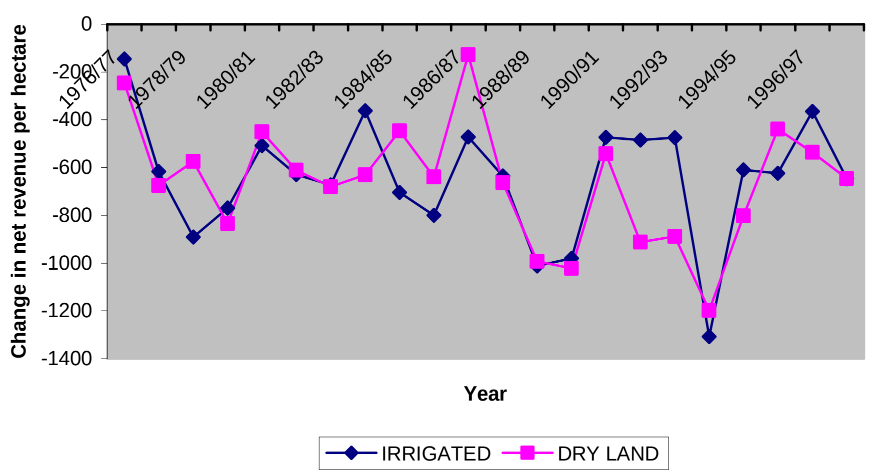

Figure 1: Impact of 2°C and 7% rise in temperature and precipitation, respectively, on net revenue per hectare of dryland and irrigated sugar

The change (i.e. difference between actual trend and scenario levels) in net revenue per hectare was calculated for the benchmark[4] warming scenario of 2^0C rise in mean temperature and a 7% increase in mean precipitation levels for both irrigated and dryland farming (Figure 1). Increasing temperature by 2^0C and precipitation by 7% (Doubling of CO_2) has negative impacts on sugarcane production in all zones. As expected, this impact is not equally distributed between the irrigated and dryland farming regions. The difference however, is negligible as the reduction in average net revenue per hectare was 26% under irrigation compared to 27% under dryland farming. This is an indication that irrigation is not a very effective adaptation measure for mitigating climate change damage on sugar farming in South Africa.

3.2 Synthesis of the likely impacts of climate change on sugar farming in South Africa

The likely impact of changing climate conditions will depend on current temperature and rainfall levels in the various seasons and where those levels are compared to critical damage points. Using the estimated net revenue function, critical damage points were determined for the three seasons (winter, summer and harvesting) based on the first order conditions of optimization (the point at which the effect of climate factors is optimized, at a minimum or a maximum):

$$\delta(NR)/\delta X_j = 0$$

Where, NR is net revenue and X_j is the level of climate variable j (temperature and rainfall). All levels of climate variables beyond these critical levels are sub-optimal. The critical damage points shown in Figures 2 - 7 were calculated by changing only a specific season's temperature or rainfall in the estimated net revenue function while keeping all other factors constant at mean values[5].

Increasing winter temperature was found to increase net revenue per hectare for temperature levels lower than the critical point 18ºC (Figure 2). Due to the quadratic form of the relationship however, increasing winter temperature beyond 18ºC reduces net revenue. The decline in net revenue for winter temperatures higher than 18ºC could be associated with the incidence of pests and insects due to favorable conditions created by warmer winter, which reduce growth. Summer temperature less than 23ºC decreases net revenue per hectare whereas temperature levels more than 23ºC were found to increase net revenue (Figure 3).

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[4] *The level of climate change associated with the doubling of carbon dioxide (IPCC, 1990).*

[5] *The impact on net revenue, of say winter temperature, was calculated by changing only winter season temperature in the net revenue function, by keeping other factors constant at mean values.*

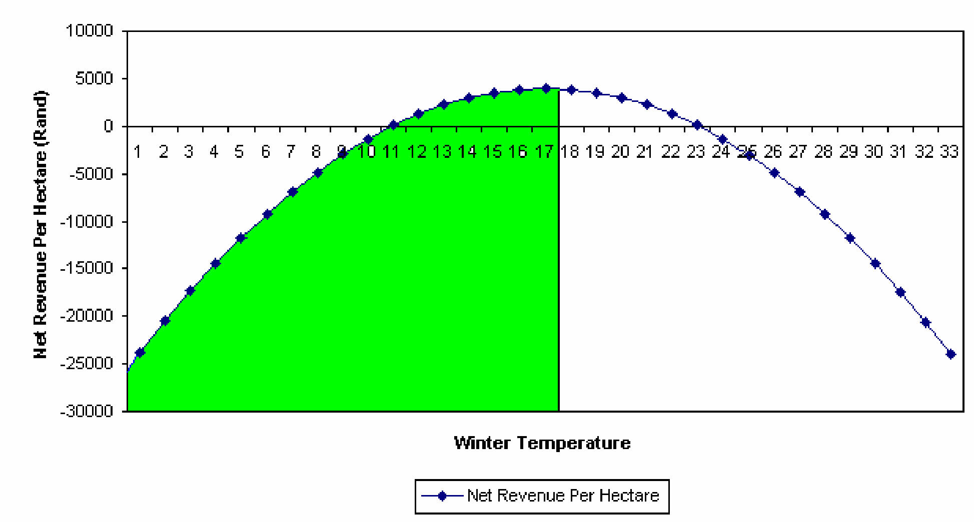

Figure 2: Impact of increasing winter temperature on net revenue per hectare

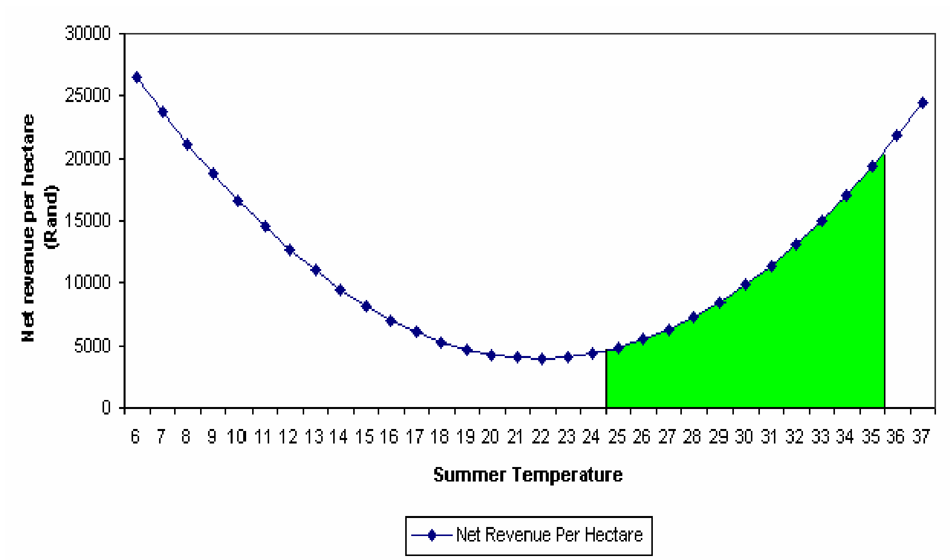

Figure 3: Impact of increasing summer temperature on net revenue per hectare

This positive response of net revenue per hectare to increased summer temperatures beyond 23ºC may be attributed to the fact that sugarcane requires high temperature 30-32ºC (Hunsgi, 1993) during the main growing season (the summer season in the case of South Africa). Even though higher temperature is recommended for cane growth, increasing temperature beyond 35ºC curtails growth irrespective of water supply (Blackburn, 1984).

Additionally, net revenue per hectare was found to decrease for harvesting temperature levels less than 19ºC (Figure 4).

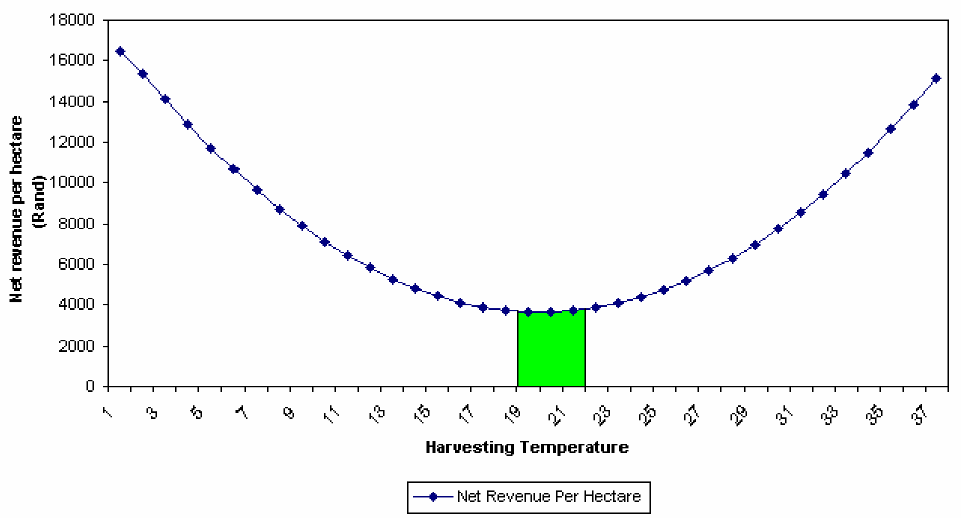

Figure 4: Impact of increasing harvesting temperature on net revenue per hectare

Ripening requires low temperature levels to allow for sucrose accumulation, but very low temperature, below 10ºC rupture cells and cause irrevocable deterioration (Humbert, 1968). The result of increasing net revenue with increased harvesting temperature should be seen with caution, because high temperature is not recommended as it initiates growth and reduces sucrose accumulation during the harvesting season (Hunsgi, 1993).

Comparing the critical point analyses using the estimated model with optimal ranges of temperature and rainfall for sugar production based on agronomic research knowledge revealed interesting findings on the sensitivity of sugarcane production to CC in SA. The shaded areas in each of Figures 2 - 7 indicate the areas of overlap between the results of this study (critical damage points) and optimum agronomic values. Based on the optimum agronomic values, winter temperature should optimally be less than 22ºC (Table 2).

Table 2: Average, agronomic optimal ranges and the estimated critical damage points of temperature for South African sugarcane production

Production seasons	Average temperature (˚C) for 1976/77-1997/98	Critical damage points (˚C)	Agronomic optimal ranges of Temperature[1] (˚C)
Winter	17.38	18	<22
Summer	22.48	23	25-35
Harvesting	16.66	19	<22

Source: Based on personal communication with SASA agronomist, Smit (2002).

This is consistent with the results of this study in which increasing temperature beyond the critical value of 18ºC reduced net revenue (Figure 2). Increasing summer temperature beyond 23ºC was found to increase net revenue per hectare. This result is again in line with optimum agronomic values, which range from 25 to 35ºC (Table 3).

Table 3: Average, agronomic optimal ranges and the estimated critical damage points of precipitation for South African sugarcane production

Production seasons	Average precipitation (mm) (1976/77-1997/98)	Critical damage points (mm)	Agronomic optimal ranges of precipitation[1] (mm)
Winter	37.12	94	60 -120
Summer	113.3	354	270-1200
Harvesting	37.2	4	<60

Source: Based on personal communication with SASA agronomist, Smit (2002).

This study further showed that increasing harvesting temperature beyond 19ºC is optimal for sugarcane production, which coincides with the agronomic optimum harvesting temperature levels varying between 19 and 22ºC (Figure 4).

Table 2 also shows that currently average values of winter and summer temperature are close to the critical damage points. This implies that both seasons are sensitive to marginal changes in temperature as the remaining range of tolerance to increased temperature levels is narrow, especially for winter season temperature, i.e. current levels are very close to critical damage points. The cumulative impact of increasing temperature marginally across all seasons should further be agronomically evaluated to give a better picture of the likely impact of climate change on South African Sugarcane production.

Precipitation, like temperature, also significantly and differently affected sugarcane production across the production seasons. Critical damage point analysis indicated that increasing winter precipitation levels up to 94mm increases net revenue per hectare, whereas precipitation level beyond 94mm decreases net revenue (Figure 5). This negative relationship between increased precipitation beyond 94mm and net revenue could again be due to the possible outbreak of pests and insects, which are depressed under low precipitation but start reproducing under the conducive environment created by high precipitation. Increasing summer precipitation more than 354 mm was found favorable to sugarcane production (Figure 6).

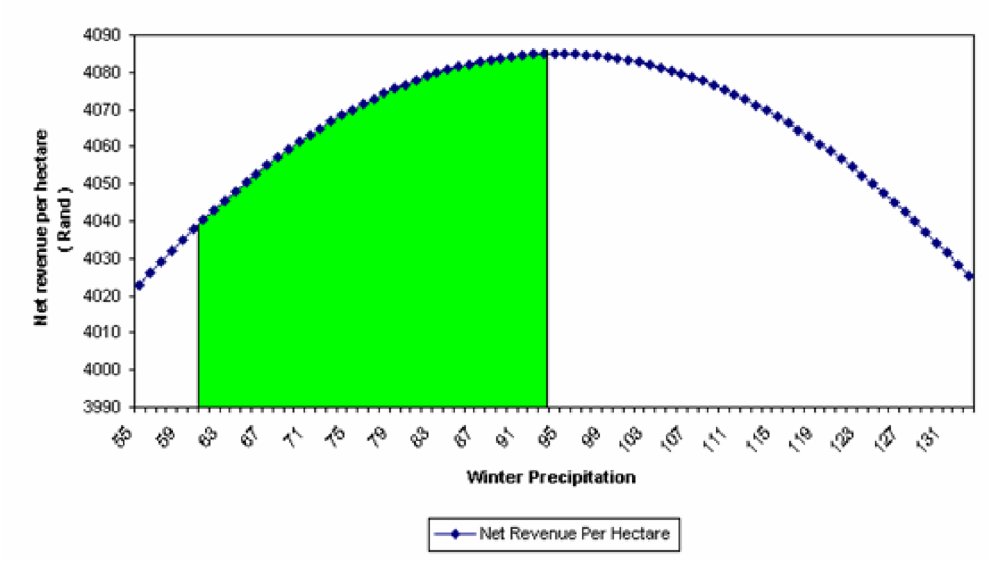

Figure 5: Impact of increasing winter precipitation on net revenue per hectare

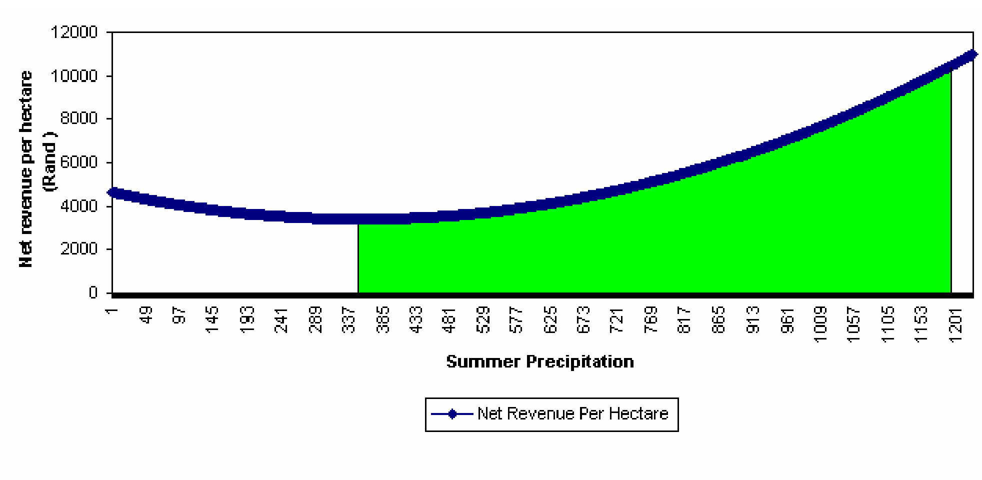

Figure 6: Impact of increasing summer precipitation on net revenue per hectare

During the main growing season (the summer season in the case of South Africa) sugarcane requires high level of precipitation to facilitate growth (Mangelsdorf, 1950; Humbert, 1968; Smith, 1994), and the results of this study are in line with this fact. Finally, increasing harvesting precipitation beyond 4mm (Figure 7) was found to be damaging to sugarcane production. This finding is in line with the fact that sugarcane production requires a very low precipitation level during ripening and harvesting, as increasing precipitation initiates growth and reduces sucrose accumulation (Hunsgi, 1993).

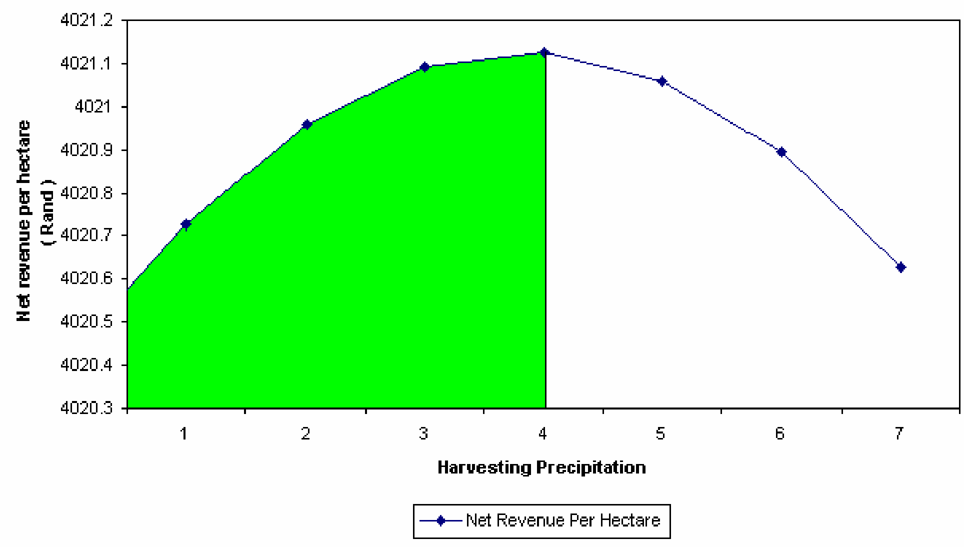

Figure 7: Impact of increasing harvesting precipitation on net revenue per hectare

As depicted in Figures 5 - 7, the critical damage point for winter, summer and harvesting precipitation levels fall within the optimum agronomic optimum range. Fortunately, current rainfall levels are far from estimated critical damage points, e.g. wider range of remaining tolerance to higher rainfall (Table 4). This suggests that, sugarcane production in SA will be less sensitive to future increases in precipitation than in temperature.

4. CONCLUSIONS AND IMPLICATIONS OF THE STUDY

This study employed the Ricardian model to measure and evaluate likely impacts of CC on sugarcane production in SA under dry land and irrigated systems. Results of the Ricardian analyses indicated that sugarcane production in SA is highly sensitive to CC. The impact of an IPCC Scenario of doubling CO_2 (which will lead rises in temperature by 2ºC and precipitation by 7% was negative on sugarcane production in all zones under both irrigation and dry land conditions. The small margin of difference between reduction in average net revenue per hectare for irrigated systems (26%) and dry land conditions (27%) have important implications for the efficacy of irrigation as a strategy for mitigating impacts of CC. This result suggests that production of sugarcane under irrigation does not provide an effective option for reducing CC damages in SA.

Results of a critical damage point analyses combined with agronomic knowledge about optimal climatic conditions for sugarcane production indicated that sugarcane production in SA will be less sensitive to increases in rainfall levels than temperature. These results suggest a priority to intervention and adaptation strategies that target mitigation of increased temperature impacts. Therefore, future research has to focus on cost-effective methods of controlling yield-reducing factors associated with increased temperature especially during the winter growing season and the availability of sugarcane varieties, which are relatively not sensitive to increased temperature during ripening and harvesting.

One should note that the results of this study are based on only one crop and hence generalizations to the entire agricultural sector in the whole country cannot be made. More research on multiple crops and other sub-sectors like livestock are needed to get better understanding of the net impact of CC on agriculture and inform the design of improved and more effective mitigation strategies. Moreover, the exclusion of carbondioxide fertilization and price movements' effects is another limitation of this study.

REFERENCES

Adams RM (1989). Global climate change and agriculture: An economic perspective. *American Journal of Agricultural Economics* 71(5):1272-1279.

Blackburn F (1984). *Sugar Cane*. Longman Inc, New York.

Chang C (2002). The potential impact of climate change on Taiwan's agriculture. *Agricultural Economics* 27:51-64.

Deressa T (2003). *Measuring the impact of climate change on South African agriculture: The case of sugarcane producing regions*. Unpublished MSc Thesis, University of Pretoria, South Africa.

Dinar A, Mendelsohn R, Evenson R, Parkih J, Sanghi A, Kumar K, Mckinsey J & Lonergan S (1998). *Measuring the impact of climate change on Indian agriculture*. World Bank Technical Paper No 402, World Bank, Washington, DC.

Du Toit M, Prinsloo, S & Marthinus A (2001). *El Nino-Southern Oscillation effects on maize production in South Africa: A preliminary methodology study*. In Rosenzweig C, Boote K, Hollinger S, Iglesias A & Phillips J (eds), Impacts of El Niño and climate variability on agriculture. ASA Special Publication No 63, American Society of Agronomy, Madison, Wisconsin, USA, pp 77-86.

Erasmus B, Van Jaarsveld A, Van Zyl J & Vink N (2000). The effect of climate change on the farm sector in the Western Cape. *Agrekon* 39(4):559-573.

FAO (Food and Agriculture Organization) (2002). *Global agro-ecological zones assessment: Provisional methodology and results*. Available online at http://www.fao.org/ag/agl/agll/gaezmeth.htm.

Hassan R & Olbrich B (2000). *A comparison of the economic efficiency of water use of plantations, irrigated sugarcane and sub-tropical fruits: A case study of the Crocodile Catchments, Mpumulanga Province*. WRC Report No 666/1/99, Water Research Commission, Pretoria.

Humbert PH (1968). *The growing of sugarcane*. Elsevier Publishing Co, New York.

HUNSGI G (1993). *Production of sugarcane: Theory and practice*. McMillan India Ltd, Bangalore.

IPCC (Intergovernmental Panel on Climate Change) (1990). *Scientific assessment of climate change*. Report prepared by Working Group 1, World Metrological Organization and United Nations Environmental Program, New York.

IPCC (Intergovernmental Panel on Climate Change) (1996). *Impacts, adaptations and mitigation of climate change: Scientific-technical analyses*. Contribution of Working Group II to the IPCC Second Assessment Report, Cambridge University Press, Cambridge, UK.

Kaiser M, Riha J, Wilks S, Rossiter G & Sampath R (1993). A farm-level analysis of economic and agronomic impacts of gradual climate warming. *American Journal of Agricultural Economics* 75:387-398.

Kane D, Hinzman L, Benson C & Liston G (1991). Snow hydrology of a headwater Arctic basin 1. Physical measurements and process studies. *Water Resources Research* 27**:**199-1109.

Kiker GA (2002). *CANEGRO-DSSAT linkages with geographic information systems: Applications in climate change research for South Africa*. Proceedings of International CANGRO Workshop, Mount Edgecombe, South Africa.

Kiker G, Bamber I, Hoogenboom G & Mcgelinchey M (2002). *Further progress in the validation of the CANEGRO-DSSAT model*. Proceedings of International CANGRO Workshop, Mount Edgecombe, South Africa.

Kurukulasuriya P & Rosenthal S (2003). *Climate change and agriculture: A review of impacts and adaptations*. Climate Change Series Paper No 91, Environment Department and Agriculture and Rural Development Department, The World Bank, Washington DC.

Kumar K & Parikh J (1998). *Climate change impacts on Indian agriculture: The Ricardian approach*. In Dinar A, Mendelsohn R, Evenson R, Parikh J, Sangi A, Kumar K, Mckinse J & Lonergan S (eds), Measuring the impact of climate change on Indian agriculture. World Bank Technical Paper No 402, World Bank, Washington, DC.

Mangelsdorf AJ (1950). Sugarcane: As seen from Hawaii. *Journal of the Society for Economic Botany* 4:150-176.

Mendelsohn R, Nardhaus W & Shaw D (1994). The impact of global warming on agriculture. A Ricardian analysis. *American Economic Review* 84(88):753-771.

Mendelson R, Dinar A & Dalfelt A (2000). *Climate change impacts on African agriculture*. http://www.worldbank.org/wbi/sdclimate/pdf.

Ricardo D (1817). *The principles of political economy and taxation*. John Murray, London.

Rosenzweig C (1989). Global climate change: Predictions and observations. *American Journal of Agricultural Economics* 71(5):1265-1271.

Sanghi A, Mendelsohn R & Dinar A (1998). *The climate sensitivity of Indian agriculture*. In Dinar A, Mendelsohn R, Evenson R, Parikh J, Sangi A, Kumar K, Mckinse J & Lonergan S (eds), Measuring the impact of climate change on Indian Agriculture. World Bank Technical Paper No 402, World Bank, Washington, DC.

SASA (South African Sugar Association) (2001). *Industry directory 2000/2001*. South African Sugar Association, Durban.

Schulze RE (1993). *The green house effect and global climate change: An agricultural outlook from Namibia*. Association of Agricultural Economists in Namibia Seminar on Challenges to Agriculture to the year 2000 within the changing environment.

Smit M (2002). *Personal communication with principal crop scientist*. SASEX (South African Sugar Association Experiment Station), P/Bag X02, Mt Edgecombe 4300, South Africa.

Smith JM (1994). *Crop, pasture and timber yield index*. Cedara Report No N/A/94/4, pp 82, Natal Agricultural Research Institute, Cedara.

Winter P, Muragi R, Sadoulet E & De Janvry A (1996). *Climate change, agriculture, and developing economies*. Working paper No 785, Department of Agricultural and Resource economics, University of California at Berkley, California.

Appendix 1: Description of the South Africa sugarcane model variables

Variable Name	Definition and Data (Measurement)
Net revenue (NR_i)	Net revenue for district *i* measured in R/ha.
Winter temperature (WT_i)	Average of the winter growing temperature (May to August) for district *i* measured in degree centigrade.
Winter temperature square ($WTSQ_i$)	
Summer temperature (ST_i)	Average of the summer growing temperature (September to January) for district *i* measured in degree centigrade.
Summer temperature square ($STSQ_i$)	
Harvesting temperature (HT_i)	Average of the harvesting season temperature (May to September of the second cropping year) for district *i* measured in degree centigrade.
Harvesting temperature square ($HTSQ_i$)	
Winter precipitation (WP_i)	Average of the winter growing precipitation (May to August) for district *i* measured in millimeters.
Winter precipitation square ($WPSQ_i$)	
Summer precipitation (SP_i)	Average of the summer growing precipitation (September to January) for district *i* measured in millimeters.
Summer precipitation square ($SPSQ_i$)	
Harvesting precipitation (HP_i)	Average of the harvesting season precipitation (May to September of the second cropping year) for district *i* measured in millimeters.
Harvesting precipitation squared ($HPSQ_i$)	
Winter temperature * winter precipitation (WTP_i)	
Summer temperature * Summer precipitation ($STSP_i$)	
Harvesting temperature * Harvesting precipitation ($HTHP_i$)	
Soil dummy 1 (SD_1)	The type of soil in the sample district. This variable takes the value of one if the soil is red, excessively drained sandy soil and zero other wise.
Altitude (ALT_i)	The distance above sea level measured in meters.
Irrigation dummy (ID_1)	The irrigation dummy, takes the value of one if irrigated and zero if dryland.
Dryland dummy (ID_2)	The dryland dummy, takes the value of one if dryland and zero if irrigated.
Trend (ID_1T)	Time trend for irrigated farming.
Trend (ID_2T)	Time trend for dryland farming.