Available online at www.sciencedirect.com

SCIENCE DIRECT®

Global and Planetary Change 47 (2005) 143–152

GLOBAL AND PLANETARY CHANGE

www.elsevier.com/locate/gloplacha

Measuring the economic impact of climate change on major South African field crops: a Ricardian approach

G.A. Gbetibouo*, R.M. Hassan[1]

Centre for Environmental Economics and Policy in Africa (CEEPA), Department of Agricultural Economics, University of Pretoria, South Africa

Received 1 March 2004; accepted 29 October 2004

Abstract

This study employed a Ricardian model to measure the impact of climate change on South Africa's field crops and analysed potential future impacts of further changes in the climate. A regression of farm net revenue on climate, soil and other socio-economic variables was conducted to capture farmer-adapted responses to climate variations. The analysis was based on agricultural data for seven field crops (maize, wheat, sorghum, sugarcane, groundnut, sunflower and soybean), climate and edaphic data across 300 districts in South Africa. Results indicate that production of field crops was sensitive to marginal changes in temperature as compared to changes in precipitation. Temperature rise positively affects net revenue whereas the effect of reduction in rainfall is negative. The study also highlights the importance of season and location in dealing with climate change showing that the spatial distribution of climate change impact and consequently needed adaptations will not be uniform across the different agro-ecological regions of South Africa. Results of simulations of climate change scenarios indicate many impacts that would induce (or require) very distinct shifts in farming practices and patterns in different regions. Those include major shifts in crop calendars and growing seasons, switching between crops to the possibility of complete disappearance of some field crops from some region.

Keywords: agriculture; climate change; sensitivity; net revenue and adaptations

1. Introduction

The growing literature on climate change and agriculture highlighted some general findings. First, the agricultural sector is vulnerable to climate change physically and economically. Due to climate change, agricultural supply will be affected, especially relative prices of agricultural commodities and consequently reallocation of resources within the agricultural sector, altering the structure of the economies of numerous countries and the international trade pattern (Deke et al., 2001). Secondly, there are numerous empirical studies on climate

* Corresponding author. Fax: +27 12 420 4958.
E-mail addresses: ggbetibouo@postino.up.ac.za (G.A. Gbetibouo), rhassan@postino.up.ac.za (R.M. Hassan).
[1] Fax: +27 12 420 4958.

0921-8181/$ - see front matter © 2004 Elsevier B.V. All rights reserved.
doi:10.1016/j.gloplacha.2004.10.009

change impacts on agriculture across the world, most of them have been conducted in the developed world. The results of those studies suggest that the effects of climate change will not be uniform across the globe. Developed countries will be less affected by climate change whereas in the developing countries where the effects of climate change are predicted to be greater little research was carried on climate change impacts. Accordingly, the picture of what will be the consequences of climate change for the agricultural sector in developing countries remains unclear. Specifically in South Africa, climate impact' studies on agriculture are limited and focused mainly on the maize crop. Evidence from Global Models developed so far suggests that the agricultural sector in the Southern Africa region is highly sensitive to future climate shifts and increased climate variability. Nevertheless, climate change and greenhouse related issues have not yet been given enough attention in the agricultural policies of South Africa. It is therefore necessary to examine the economic impacts of climate change on the South African agricultural sector. The main objective of this study is to develop and apply empirical methods and procedures to assess the economic impact of climate change on the South African field crops' sector. Field crops occupy, on average, 80% of the total cultivated land and contribute about 40% of the gross revenue of the total agricultural sector (AAS, 2002).

Agronomic–economic and cross-sectional methods are two major approaches that have been employed to study the interaction between climate, water and agriculture (Mendelsohn and Dinar, 2003). The agronomic–economic approach begins with calibrated agronomic models that can predict outcomes of economic simulations. The cross-sectional approach compares choices and performance of existing farms that are facing different climate and soil conditions. Although the agronomic–economic approach has the advantage of reliable results in terms of the relationship between yield and climatic variables, the present study will not adopt this methodology due to the complexity and high data requirements and its failure to take into account farmers' adaptation strategies. Alternatively, the present study will use the Ricardian model, one of the models based on the cross-sectional approach to measure the economic impact of climate change on the field crops of South Africa. The analytical framework of the Ricardian approach and the empirical model specification for South Africa are presented in the following section. Section 3 presents the data. The empirical results are reported in Section 4 and Section 5 presents simulation results of climate change scenarios. The final section distils conclusions and implications of the study.

2. Approach and methods of the study

The Ricardian method is an empirical approach to studying sensitivity of agricultural production to climate change based on cross-sectional data. The method was named after Ricardo because of his original observation that land rents would reflect the net productivity of farmland at a site under perfect competition (Ricardo, 1817, 1822). This method has been developed by Mendelsohn et al. (1994) to measure the economic impact of climate on land prices in the USA. The model accounts for the direct impacts of climate on yields of different crops as well as the indirect substitution of different inputs, introduction of different activities and other potential adaptations to different climates. The Ricardian model can be adopted to evaluate country level as well as regional level impact, and with modification it can be used to address many questions that arise such as ones concerning private adoption. However, in the Ricardian analysis, adaptation costs are not considered and since the analysis makes forecasts based on current farming practices, it does not capture future changes affecting agriculture such as technical change. Darwin (1999) also pointed out that this method does not take into account water supply and availability. The problem of water cannot be properly addressed without using a sophisticated hydrological–economic model (Mendelsohn, 2001). Another criticism of the method is that it treats price as constant (Cline, 1996). By holding prices constant, the Ricardian model underestimates damages and overestimates benefits. It is not unreasonable, however, to assume constant prices because due to the predicted moderating effects of climate change on international markets, aggregate world supply is not expected to change by much. Finally, the Ricardian method is criticized for assuming implicitly zero adjustment costs and therefore yields a lower-bound estimate of the costs of climate change (Quiggn and Horowitz, 1999).

Given the market price P_i for good i, and profit maximising farmers, on a given site under perfect competition, land market will drive profits to zero. Put differently, the implication of this is that land rent per hectare will be equal to the discounted sum of future net revenue per hectare P_{Lt}. Consequently land value (V) will reflect the present value of future net productivity:

$$V = \int_0^\infty P_{Lt} e^{-rt} dt = \int_0^\infty \left(\sum_i [P_{it} Q_{it}(K_{it}, E) - C_{it}(Q_{it}, w, E)] / L_{it} \right) \times e^{-rt} dt \quad (1)$$

where Q_i is the quantity produced of good i and K_i is a vector of all purchased inputs in the production of good i. E is a vector of exogenous environmental variables such as climate factors (temperature, precipitation, etc.), soil types and economic factors (market access, etc.), which are common to a production site. P_L is the annual cost or rent of land at that site and L_i is the land under the production of good i. Note that C_i is the cost function for all purchased inputs other than land and w is the vector of factor inputs' prices.

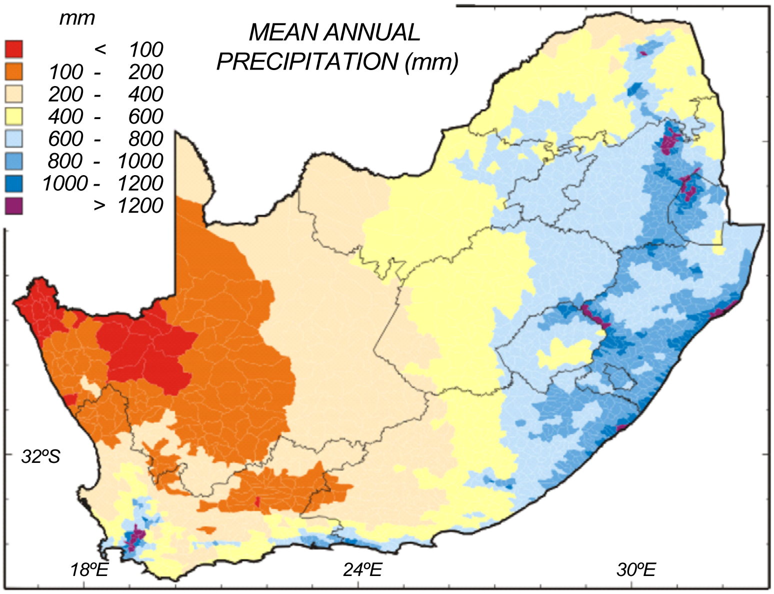
The issue of interest to this analyses is measuring the impact of exogenous changes in environmental variables (E) on land value as captured by changes in land values across differing environmental conditions. By regressing farm values on climate, soil and other control variables, the method enables measuring the marginal contribution of each variable to land value. Cross-sectional observations, showing spatial variation in normal climate and edaphic factors, can hence be utilized to estimate climate impacts on production and land value.

Due to imperfect land markets and weak documentation of agricultural farm values in South Africa, this study could not use land value as the dependent variable. Following the approach of Sanghi et al. (1998) and Kumar and Parikh (1998) for India, net revenue per hectare (NRHA) rather than land value was used as the response variable in this study. This formulation assumes that land prices reflect expected future net revenues.

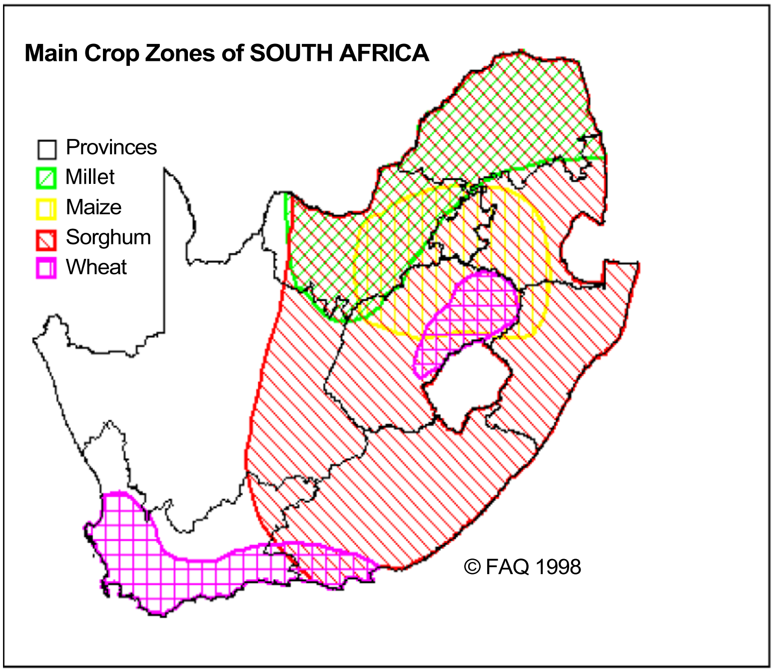
The empirical model for South African field crops assumed a quadratic relationship between district net revenue hectare and climate factors but a linear relationship with others variables. The quadratic terms were included to reflect the non-linearities between crop output and climate variables that are apparent from various field studies and also other Ricardian studies applied elsewhere (Mendelsohn et al., 1994, 1996; Dinar et al., 1998; Poonyth et al., 2002; Deressa, 2003; Mendelsohn and Dinar, 2003). Thus, the South African field crops' climate response model is specified using NRHA as a function of the following regressors: (1) climate variables: temperature and precipitation; (2) soil types, and (3) socio-economic variables, e.g. population, labour, irrigated land and geographical coordinates.

3. The data

South Africa is suitable for the cultivation of a large variety of crops. The main crops of South Africa are maize, wheat, sugarcane, sorghum and minor crops are groundnuts, sunflower seeds, dry beans, tobaccos, oats. The Ricardian approach would be successfully applied to the case of South Africa due to the fact that the geographical distribution of the crops under study seem to be highly correlated with variations in climate patterns across the country. Indeed physical factors that include topography, vegetation, temperature, rainfall and soil have important implications on decisions of what to produce in a region. For example, rainfall in South Africa is distributed unevenly across the country with sub-tropical conditions in the east and dry desert conditions in the west. There is an increase in rainfall from the western to the eastern part of the country. A 500-mm-rainfall line actually divides the country into two sections. Accordingly to the rainfall pattern, one can see that production of the main crops is concentrated in the eastern part of the country (Map 1).



Source: Schulze (2003)



Source: FAO/GIEWS (2001)

Map 1. Spatial correlation between rainfall and main cropping zone.

The study used district level data on crop revenues and other variables of the model. Data on seven crops from 300 districts across the nine provinces of the country for the year 1993 were obtained from various sources. The seven crops included are maize, wheat, sorghum, sugarcane, soybean, groundnut and sunflower. Data on area planted, production, input costs and output price for each of the seven field crops were provided by the Census of Agriculture 1993 carried by the National Department of Agriculture (SSA, 1998). However, sugarcane data were obtained from the Sugar Cane Growers' Association of South Africa (SCGA). The data on climate variables were compiled from the National Weather Bureau of South Africa (NWBSA). The appropriate climate variables for this study were the normal climate variables based on 30 years average of temperatures and precipitation observed over the period 1970–2000. Data on population for the year 1993 (year of the analysis) were deducted from the 1996 Population Census of Statistics South Africa (StatSA) by discounting the 1996 population numbers by the South African annual population growth rate of 1.5% (SSA, 2002). Data on number of farm workers per district and percentage of land under irrigation were extracted from the Census of Agriculture 1993 (SSA, 1998). The four groups of soil types have been derived from the Map of Generalized Soils patterns of South Africa produced by the Institute for Soil, Climate and Water (ISCW) of The Agricultural Research Council (ARC).

4. Results of the Ricardian analyses

The semi-log function gave the best statistical fit for the data in the regression analysis and the estimated model performed well according to its F and R^2 statistics explaining 63% of the variation in net revenue hectare. Also, the parameters have the expected signs except for the latitude variable (proxy for solar radiation). The results show that there is a quadratic relationship between climate variables and net revenue hectare. Furthermore, winter climate variables have a hill-shaped relationship with net revenue whereas summer climate variables have a U-shaped relationship (Table 1).

Table 1
Parameter estimates of the Ricardian field crops model

Response variable: log(NRHA) in R/ha

Variable	Coefficient
Intercept	10.60 (2.89)**
tempSummer	−1.28 (−3.71)**
tempSummer2	0.03 (4.06)**
tempWinter	0.72 (3.58)**
tempWinter2	−0.03 (−3.79)**
rainSummer	0.002 (1.43)
rainSummer2	0.0001 (3.36)**
rainWinter	0.015 (1.25)
rainWinter2	−0.0004 (−2.70)**
Temp×Rain Summer	−0.001 (−2.33)*
Temp×Rain Winter	0.003 (1.56)
Popd	5.77E−05 (2.47)*
Soildum1	−0.22 (−1.91)*
Soildum3	0.08 (1.84)*
Labour	0.0004 (2.18)*
Irrigation	0.338 (4.23)**
Latitude	0.12 (3.95)**
Altitude	−0.0004 (−2.21)*
R^2	0.66
F statistic	40.11
Adjusted R^2	0.63

Number of observations=300.
* Level of significance at 5%.
** Level of significance at 1%.

For further insights of the interaction between field crops net revenue hectare and climate variables, firstly, estimated model parameters were used for sensitivity analysis to derive elasticities as well as implied optimal climate points' identification. The calculated elasticity evaluated at mean values indicated that at current levels of rainfall, increasing temperatures in both summer and winter seasons reduce net revenue. On the other hand, at current levels of temperature, increasing precipitation in winter is beneficial whereas increasing summer rainfall would negatively affect net revenue (Table 2).

The implied optimal temperature points (i.e. at which net revenue hectare is maximised) are 14.78 and 22 °C for winter and summer, respectively. With a hill-shaped relationship between net revenue and winter temperature, increasing winter temperature was found to increase net revenue hectare up to 14.78 °C after which net revenue declines with higher winter temperatures. On the other hand, the U-shaped relationship between summer temperature and net revenue hectare indicates that net revenue decreases

Table 2
Estimates of elasticity to climate factors

	Temperature	Rainfall
Winter season	−0.08	0.89
Summer season	−0.115	−0.406

with warmer summer climates up to 22 °C, after which net revenue improves. The 22 °C may be considered the minimum optimal temperature for plant growth in summer. The implied optimal precipitation points are 390 and 570 mm for winter and summer seasons, respectively. An increase in winter rainfall beneficial until the critical point of 390 mm is reached. Further rise in winter rainfall above 390 mm decreases yield. On the other hand, there is a positive response to summer rainfall above the critical point of 570 mm. Current average temperature levels are 15 °C in winter and 23 °C in summer, which are very close to implied critical temperature levels. On the other hand, current average rainfall levels are 130 and 462 mm in winter and summer, respectively, which are far from estimated critical points. This implies that field crops in South Africa will be very sensitive to marginal changes in temperature as the remaining range of tolerance to increased temperature is narrow compared to changes in precipitation.

5. Climate change impacts simulations

By analysing the climate sensitivity of the field crops using elasticity and implied optimal climate points only, the cumulative impact of increasing/decreasing temperature/rainfall marginally across all seasons could not be captured. Furthermore, changes in climate that will occur in the next 50 years are not marginal changes; therefore elasticity measures could not give a full picture of the climate change impacts. Accordingly, sensitivity analysis was carried to assess the likely impacts of climate change on the South African field crop sector, by projecting net revenue per hectare using a range of climate outcomes that are predicted to occur over a period of 30–100 years under a conventional CO_2 doubling scenario (IPPC, 2001). The scenarios used in this study forecasted rise in temperature and reduction in rainfall from the current levels. The impacts of climate change (changes in the dependent variable net revenue per hectare) were simulated using the estimated model for each of the 300 districts for the 1993 year. Additionally, in the study we explored if moving from rain-fed to irrigated agriculture could be an effective adaptation option to reduce the harmful effects of climate change for the field crops.

Simulation results revealed large seasonal variations in the response of net revenue to climate change. The results showed that warmer summer temperatures have positive effects on net revenue hectare, whereas decrease in rainfall reduces net revenue. For winter, both rise in temperature and reduction in rainfall damage field crops. The results also confirmed that irrigation provided an effective adaptation option to reduce the harmful effects of climate change. It was found that when changes in climate variables create negative impacts, with irrigation as an adaptation option, the situation could be reversed, i.e. net gains in revenue (Table 3).

Furthermore, the study examined the total effect of simultaneously changing both temperature and precipitation in all seasons on the net revenue. Since climate scenarios are uncertain, we firstly analyse how sensitive is production of field crops to diverse climate scenarios from a mild scenario of 2 °C increase in temperature and 5% decrease in rainfall to a severe scenario of 3 °C temperature

Table 3
Impacts of changing only temperature or rainfall on field crops' net revenue in percentage (%)

Climate variable	Climate scenarios	Winter season		Summer season		Both seasons	
		No adaptation	With adaptation	No adaptation	With adaptation	No adaptation	With adaptation
Temperature	+2 °C	−11	26	26	63	12	47
Rainfall	−5%	−4	26	−1	34	−2	27

Table 4
Sensitivity of the impacts of climate change on net revenue to climate scenarios in percentage (%)

Climate change scenarios	Impacts on net revenue hectare (%)
+2 °C and 5% reduction in rainfall	9
+2 °C and 20% reduction in rainfall	−4.4
+3 °C and 5% reduction in rainfall	17.3
+3 °C and 20% reduction in rainfall	−11.3

and 20% decrease in rainfall. The results show that differences among climate scenarios are important and can generate wide ranges of impacts. With minimal reduction in rainfall, benefits effects from rising temperature exceed the negative impacts from lowering rainfall. With further reduction in rainfall, the benefits effects from rising in temperatures are more than offset by the negative effects of rainfall reduction giving negative net effects (Table 4).

The expected effects of climate change on the agricultural sector will not be uniform across continents, within continents and even within countries (Mendelshon and Williams, 2002). To assess how different provinces will fare as climate change in South Africa, the study applied a mild scenario of an increase of 2 °C in temperature and 5% decrease in rainfall. Individual districts changes in the net revenue per hectare were averaged over to yield an average impact at provincial level. The spatial distribution of climate change effects in South Africa are displayed in Fig. 1.

Although the temperature rise and the rainfall reduction are uniform across the different districts, the spatial distribution of impacts is not. Some provinces experienced gains while others experienced severe damages. The winners were the Free State, Northern Cape, North West, Western Cape and Limpopo Provinces. The losers were Eastern Cape, Gauteng, Kwazulu Natal and Mpumalanga. With the exception of Limpopo, the winners were all from the western part of the country (cooler and dryer regions) and the losers from the eastern part (warmer and wetter zones) of the country (Appendix A).

The benefits that occur due to rise in temperature and lower rainfall are somehow controversial. One would have expected that the Northern Cape Province characterized by the desert agro-ecological zone with lower rainfall region to experience damages instead of benefits. However, these results may be due to the fact that farmers in a arid situations have already adapted to harsher climatic conditions and have developed other alternatives such as irrigation to manage their unfriendly environment, and hence they are less sensitive to climate adversities. Indeed, irrigation schemes in the country are been developed in these regions and 50% of the land under annual crops in Northern Cape Province is irrigated.

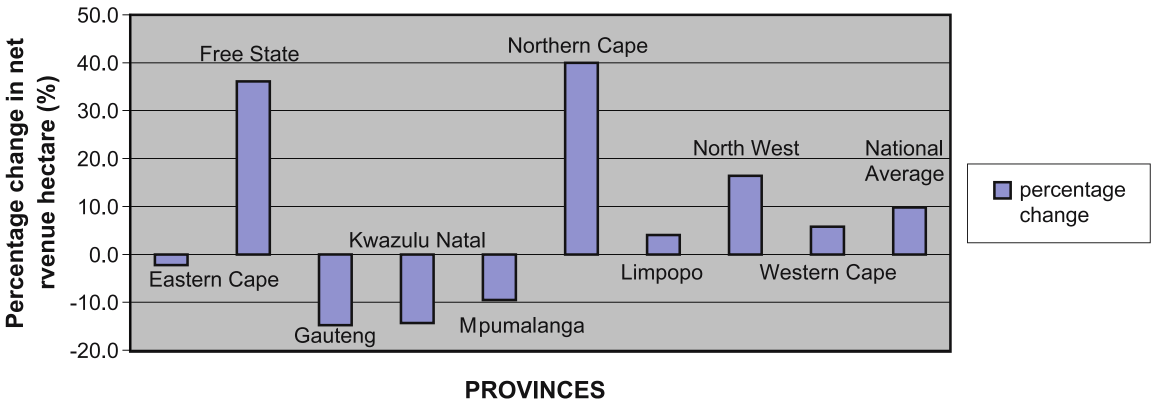


Fig. 1. Distributional effects of 2 °C increase in temperature and 5% reduction in rainfall across South African provinces.

The subtropical winter region (Western Cape Province) has also experienced around 5% increase in net revenue hectare. The region was expected to experience reduction in wheat yield or not be able to produce wheat anymore as winter becomes warmer. However, the Western Cape may have become suitable for crops like soybean or sunflower making farmers shift to those crops offsetting losses from wheat production through gains from the production of soybean and sunflower. Also, the benefits occurring in the interior regions of steppe arid zone (Free State, Limpopo and North West) may be due to the fact that the damages due to lowering of rainfall may be overcome by the benefits from warmer winter. Indeed with warmer winter, these areas may be able to produce summer cereals (maize, sorghum) during the winter season.

The magnitude of the losses in net revenue for a 2 °C increase in temperature and 5% decrease in rainfall, vary from 2% to 16% for Eastern Cape, Gauteng, Mpumalanga and Kwazulu Natal. Indeed, the relatively warmer regions of Kwazulu Natal and Mpumalanga are the most affected by the temperature rise and reduction in rainfall. These regions are the principal production areas of sugar cane in the country. For an optimal growth, sugar cane requires a long warm summer growing season with adequate rainfall. Therefore, it is likely that lower rainfall and further increases in temperature in regions already hot can cause heat injury and water deficit for sugar cane production. As a result, Kwazulu natal and Mpumalanga sugar cane productivity may be significantly lowered to the extent that farmers may be forced to switch to other crops of lower value like sorghum that are heat tolerant.

Overall, the results of the simulation imply that field crops sector would experience different changes in cropping patterns. Cropping zones of major crops may shift from one region to another. At lesser extent, farmers in a given region may be obliged to shift their cropping calendar. For example, the sugar cane region may disappear. Western Cape may become suitable for crops like soybean or sunflower. The sowing period of most crops (maize, soybean, sunflower) could shift from October (summer season) to early March or April (winter season).

6. Conclusions and implications

The empirical results presented in this study provide sufficient evidence that climate change would affect the South African field crops' sector in many subtle ways. The current patterns of climate, and when, where and how climate change will unfold will determine the nature and extent of its impacts on net revenue. This study found that production of field crops in South Africa will be very sensitive to marginal changes in temperature as the remaining range of tolerance to increased temperature is narrow compared to changes in precipitation. This result has important implications for appropriate adaptation measures and strategies. For instance, these results suggest that research on breeding for heat tolerance rather than draught tolerance should shape future agricultural research in the country. On the other hand, irrigation has proved to be an effective adaptation measure to limit the harmful effects of climate change. However, the country is water-stressed, which indicates the need for research in production technologies and methods that are more water-efficient.

Given the sensitivity of the South African field crops to climate change, there is a need to identify effective risk-pooling mechanisms. Adaptation can be addressed in a variety of ways. First and foremost is the greatest challenge of educating farmers about the happenings of climate change and its impacts. Hence more effective extension programs are needed to increase farmers' awareness of climate change. Certainly, prevention of losses can occur through more effective farm planning. Crop insurance, diversified economic bases of regions dependent on farming, and improved monitoring/forecasts of weather will also increase resilience to cope with future changes. These strategies, however, must take note of the fact that the study showed large seasonal variability in the response of field crops to climate change. Rising temperature is found beneficial in summer whereas it negatively affects net revenue in winter. Moreover, the study highlights the importance of location in dealing with climate change issues because climate impacts will differ within and between agro-ecological regions of the same country. The study also indicates that knowledge about the economic impact of climate change on agriculture in South Africa is limited and requires much wider research and deeper analyses.

Appendix A. Geographical representation of South Africa and Current climate patterns

Map of South Africa provinces delimitation

Source: FAO/GIEWS (2001)

Table of Current level of provincial rainfall and temperature

Agro-ecological zones	Provinces*	Rainfall pattern (mm)		Average temperature (ºC)	
		Summer	Winter	Summer	Winter
Desert	**Northern Cape**	200	100	23	14
Steppe (arid)	**Free State**	400	150	20	12
	North West	500	100	22	14
	Limpopo**	600	150	25	18
	Gauteng	600	150	20	13
	Eastern Cape	400	200	19	13
	Mpumalanga	600	150	21	15
Sub-tropical wet	Kwazulu Natal	800	200	23	16
Sub-tropical winter	**Western Cape**	150	400	19	14

* Provinces in bold are winners/ ** Previously Northern Province

Source : South African Weather Bureau

References

AAS (Abstract of Agricultural Statistics), 2002. Directorate Agricultural Information. National Department of Agriculture, Pretoria.

Cline, W., 1996. The impact of global warming on agriculture a Ricardian analysis: comment. Am. Econ. Rev. 86, 1308–1311.

Darwin, R., 1999. The impact of global warming on agriculture a Ricardian analysis: comment. Am. Econ. Rev. 89, 1042–1049.

Deke, O., Hoos, G.K., Kasten, C., Klepper, G., Springer, K., 2001. Economic Impact of Climate Change: Simulations with a Regionalized Climate-Economy Model. Kiel Institute of World Economics, Kiel Working Paper No. 1065.

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

Dinar, A., Mendelsohn, R., Evenson, R., Parikh, 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, Washington, DC.

IPPC, 2001. Climate change 2001: the scientific basis. Report edited by Houghton, J.T. et al., Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK.

Kumar, K., Parikh, S., 1998. Climate change impacts on Indian Agriculture: the Ricardian approach. In: Dinar, A., Mendelsohn, R., Evenson, R., Parikh, J., Sanghi, A., Kumar, K., McKinsey, J., Lonergan, S. (Eds.), Measuring the Impact of Climate Change on Indian Agriculture, World Bank Technical Paper No. 402. World Bank, Washington, DC.

Mendelsohn, R., 2001. Agriculture: a Ricardian analysis. In: Mendelsohn, R. (Ed.), Global Warming and the American Economy: A Regional Assessment of Climate Impacts. Edward Elgar, pp. 32–53.

Mendelsohn, R., Dinar, A., 2003. Climate, water and agriculture. Land Econ. 79 (3), 328–341.

Mendelshon, R., Williams, L., 2002. Comparing forecasts of the global impacts of climate change. Paper presented at the International Conference on Climate Change and Environmental Policy. University of Illinois, USA.

Mendelsohn, R., Nordhaus, W., Shaw, D., 1994. The impact of global warming on agriculture: a Ricardian analysis. Am. Econ. Rev. 84, 753–771.

Mendelsohn, R., Nordhaus, W., Shaw, D., 1996. Climate impacts on aggregate farm values: accounting for adaptation. Agric. For. Meteorol. 80 (1), 55–67.

Poonyth, D., Hassan, R.M., Gbetibouo, G.A., Ramaila, J.M., Letsoalo, M.A., 2002. Measuring the impact of climate change on South African agriculture: a Ricardian approach. A paper presented at the 40th Annual Agricultural Economics Association of South Africa Conference, 18–20 September, Bloemfontein, South Africa.

Quiggn, J., Horowitz, J.K., 1999. The impact of global warming on agriculture: a Ricardian analysis: comment. Am. Econ. Rev. 89 (4), 1044–1046.

Ricardo, D., 1817. On the Principles of Political Economy and Taxation. John Murray, London.

Ricardo, D., 1822. On the Protection in Agriculture. John Murray, London.

Sanghi, A., Mendelsohn, R., Dinar, A., 1998. The climate sensitivity of Indian Agriculture. In: Dinar, A., Mendelsohn, R., Evenson, R., Parikh, J., Sanghi, A., Kumar, K., McKinsey, J., Lonergan, S. (Eds.), Measuring the Impact of Climate Change on Indian Agriculture, World Bank Technical Paper No. 402. World Bank, Washington, DC.

SSA (Statistics South Africa, formerly Central Statistical Service), 1998. Census of Agriculture 1993: Provincial Statistics. Central Statistical Service, Pretoria.

SSA, 2002. Statistics in Brief 2002. Statistics South Africa, Pretoria.