Economic impact of Climate Change on major South African field crops: A Ricardian Approach

by

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In memory of my Uncle Michel Bedibeu

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ABSTRACT

The vulnerability of agriculture to climate change has become an important issue because of reduced crop productivity from adverse changes in climate, especially in Africa.

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 regions.*

Keys words: Agriculture, Climate change, sensitivity, net revenue and adaptations.

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ABBREVIATIONS

AEM	Agronomic-Economic Models
AEZ	Agro-Ecological Zones
AGE	Applied General Equilibrium
ARC	Agricultural Research Council
^0C	Degree Celsius
CH_4	Methane
CO_2	Carbon dioxide
FAO	Food and Agriculture Organisation
GCMs	Global Circulation Models
GDP	Gross Domestic Product
CGE	Computable General Equilibrium
GHG	Greenhouse gases
GIS	Geographical Information Systems
ha	Hectares
IPCC	Intergovernmental Panel on Climate Change
ISCW	The Institute for Soil, Climate & Water
LUT	Land Utilization Types
m3	Cubic meters
mm	Millimetres
N_2O	Nitrous oxide
NOAA	National Oceanic and Atmospheric Administration
NWBSA	National Weather Bureau of South Africa
O_3	Ozone
ppm	Parts per million
SAM	Social Accounting Matrix
SAAGIS	South Africa Agricultural Geo-referenced Information System
t	Ton
UNFCC	United Nations Framework Convention on Climate Change
USA	United States of America

CHAPTER 1 : INTRODUCTION

1.1 Background

Human activities during recent decades have contributed largely to the increased emissions of carbon and other greenhouse gases in the atmosphere. The atmospheric concentration of carbon dioxide (CO_2) has increased by 31% since 1750 and the rate of increase has been about 1.5 ppm[1] (0.4%) per year over the past two decades. Also, the atmospheric concentration of other gases such as methane (CH_4) and nitrous oxide (N_2O) have increased by 1060 ppb[1] (151%) and 46 ppb (17%), respectively since 1750 and continue to increase (IPPC, 2001a). Scientists agree that the increase of these emissions will change the world's climate. Forecasts of climate change from General Circulation Models (GCMs) indicate that a doubling of atmospheric CO_2 will increase the global average temperature from 1.5 to 4.5 degrees Celsius (^{0}C) by 2060[2], as well as alter precipitation amounts and frequency (Rosenzweig, 1989).

The global change of climate is a serious concern to the international community because it may affect prospects for sustainable development. Global warming poses a significant threat to future economic activities and the well being of a large number of human beings (Jepma and Munasinghe, 1998). Among all economic sectors, the agricultural sector appears to be the most sensitive and vulnerable. Plant production is influenced by climate factors such as temperature and rainfall. Each crop has its optimal conditions for growth. Therefore, any change in the climate can have serious impact on the crop production sector. World agriculture, whether in developing or developed countries, remains very dependent on climate resources and conditions.

Various studies have been done to assess the impact of climate change on agriculture. It has been shown that at a global level, the impacts will be small since production reduction in some areas is balanced by gains in others (Kane *et al.*, 1991). The

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[1] ppm (parts per million) and ppb (parts per billion) measure the ratio of the number of greenhouse gas molecules to the total number of molecules of dry air in million and billion units, respectively.

[2] This was the most accepted scenario before the new estimates of IPCC (2001), which reported a range between 1.4 to 5.8 ^{0}C over the period 1990 to 2100.

Intergovernmental Panel on Climate Change (IPCC) studies on climate sensitivity of agriculture across the globe, concluded that the tropical areas seem to be more likely to suffer negative consequences, while temperate climate and polar zones will gain in productivity. Developing countries agricultural systems are vulnerable to climate change because they tend to be less capital and technology intensive and because they tend to be in climate zones, which are already too hot and will likely get hotter (Mendelsohn, 2000). Many countries in tropical regions are expected to be more vulnerable to warming because additional warming will affect their marginal water balance.

Thus, the changes in climate will affect agriculture either negatively or positively depending on the location. There is a wide concern that the agricultural sector in Africa will be especially sensitive to future climate change and variability (Mendelsohn *et al*., 2000). In the Southern African region, the effects of climate change could be further exacerbated due to its high risk cropping environment and the marked intra-seasonal and inter-annual variability of rainfall (du Toit *et al*., 2002).

South Africa, as part of Southern Africa is predicted to be vulnerable to climate change due to the combined effects of the following factors:

- South Africa is energy and carbon intensive economy and among the top twenty greenhouse gas emitters in the world (Scholes *et al*., 1999).
- South Africa is a semi-arid country where the bulk of farming is practised on marginal land
- Frequent occurrence of droughts
- Scarcity of water, which is exacerbated by a high temporal and spatial variability of rainfall.

IPCC (2001a) forecasted the following key impacts in South Africa:

(i) A complete loss or displacement of succulent Karoo biome projected under climate change and many species losses in other biomes

(ii) Intensity of extreme events will significantly increase in South Africa; biome shifts will favour horticulture over plantation forestry and malaria risk areas projected to expand southward.

(iii) The dependence of production and crop yield on intraseasonal and interannual variation of rainfall.

1.2 Problem Statement and Motivation

The population of South Africa has been increasing over the years. South Africa's total population as per the 1996 census was 40,583 million and in 2001 the estimation of the population is about 43,586 million (SSA, 2002a). The growth in population increased the demand for food and the use of resources needed to feed this growing population. South Africa is also a major source of food for the rest of the region. Generally, South Africa has been meeting its food requirements with domestic production for most items. However projections show that although South Africa is currently meeting its consumption requirements, the growing population, rise in income levels and change in preferences may lead to increased demand for food (NDA, 2000). The ability of the agricultural sector to feed this increasing population will not be an easy task as South Africa is largely semi-arid with secluded sub-humid areas and with a large variation in soil types and physiography. With the threat of climate change, food insecurity in the country and in the region is expected to be worsening in the future without any proper policies actions.

In addition to being an important source of food supply, South African agriculture contributes almost 9% of the formal employment and 3.2% the Gross Domestic Product (GDP). Agriculture is also an important earner of foreign exchange for the country. Moreover, the agriculture sector has strong backward and forward linkages into the rest of the economy, such that the 'agro-industrial sector' is estimated to comprise 15% of the GDP (Van Zyl *et al.*, 1988; McDonald *et al.*, 1997; Townsend, 1997; GOVZA, 2001; Hassan, 1998). Consequently, any factor affecting the agricultural sector, like climate change, may have serious consequences for the rest of the economy. Van Zyl *et al.* (1988) showed that the overall impact of changes in agricultural production resulting from drought is almost twice on the general economy than its direct impact on the agricultural sector. Furthermore, given an estimate of 3 million farmers who produce food primarily to meet their family's needs, rural poverty in South Africa could be worsening with climate change. Indeed, due to their low income and lower technological and capital stocks, subsistence farmers are predicted to have limited options to adapt to climate changes (Mendelsohn, 2000; IPCC, 2001b and 2001c).

Although there are well-established concerns that climate change has the potential to affect crop production seriously, there is little quantitative information concerning how serious these effects will be in terms of economic losses and social welfare impacts in the case of South Africa. There have been limited agronomic studies conducted in field stations scattered across the country, which mostly examined how individual crops behave in controlled experiments, focusing on grain crops and mainly maize. These studies covered only a small part of the country (Schulze *et al.* 1993; du Toit *et al.*, 2001; du Toit *et al.*, 2002; Kiker, 2002 and Kiker *et al.*, 2002) and fail to account for farmers' adaptation strategies. Thus, as Wit (2000) states in his survey of climate change research in South Africa, there is specific need to determine the economic impacts of global climate change in South Africa. A study by Poonyth *et al.* (2002), using a Ricardian model to explore the agriculture sector performance with respect to climate change concluded that, rising temperatures will be detrimental to agricultural production without proper adaptation by farmers. With only 2^0C increase in temperature, the net revenue per hectare is expected to reduce by 25%. Poonyth *et al.* (2002) study used time series agricultural data and yearly climate variables. By doing so, the results of the study may have reflected weather variations rather than long-term climate change impacts. Moreover, by using aggregate provincial level data the study have neglected the climatic and geographical diversity within the province. Furthermore, given the semi-arid nature of the country where water resources are very sensitive to climate variability and change, Poonyth *et al.* (2002) study suffers from the same criticism levelled against earlier Ricardian studies of agriculture for the non-inclusion of water supplies and availability in the analysis. The present study re-examines Poonyth *et al.* (2002) study results by using cross-sectional agricultural data gathered at district level and with the inclusion of irrigation to re-assess the economic impact of climate change on agriculture in the Republic of South Africa. The effects of climate change on agriculture in South Africa may therefore not be as worse as envisaged by Poonyth *et al.* (2002) study if the role of irrigation in adapting to unfavourable conditions were also considered and much more spatial variability is allowed in the analysis.

1.3 Research objectives

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. Indeed, field crops occupy, on average, 80% of the total cultivated land and contributed about 40% of the gross revenue of the total agricultural sector (AAS, 2002).

The study pursues the following interrelated specific objectives:

i. To develop and estimate an empirical model to assess the potential impacts of climate change on South African field crops.

ii. Use the estimated model to predict the range of impacts on agriculture under various climate change scenarios

iii. Evaluate alternative courses of actions in terms of available policies and strategies for mitigation of likely climate change impacts.

1.4 Approach and methods of the study

This study will use an adapted version of the Ricardian approach following the modifications applied by Sanghi *et al.* (1998) in India. This modified model is adopted to evaluate the economic impact of climate change on South African field crops. Based on cross-sectional data, the present study will identify the contribution of environmental variables such as climate variables on farm income.

The Ricardian Method examines how climate in different places affects the net rent or value of farmland. This approach evaluates how profit–maximising farmers respond to various climatic 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. Due to imperfect land markets and weak documentation of agricultural farm values in South Africa, in the current study, net revenue per hectare rather than land value was used as the response variable. This formulation assumes that land prices reflect expected future net revenues.

The analysis was based on district level agricultural, climate, and edaphic data for 300 districts in South Africa, to examine farmer-adapted responses to climate variations across the country. Seven field crops (maize, wheat, sorghum, sugarcane, groundnut, sunflower and soybean), which comprise 80% of the field crops land and contribute about 80% of field crops gross revenues, have been studied.

1.5 Outline of the study

The study is presented in six chapters. Chapter one introduces the research problem, objectives and methods. Chapter two presents the structure of agriculture and climate patterns in South Africa. Chapter three presents a review of relevant literature on climate change and agriculture and empirical approaches to measuring the impact of climate change. The approach and methods applied in this study are presented in chapter four. Chapter five presents and discusses the empirical results and outcomes of the simulations of various scenarios of climate change. Chapter six derives the conclusions and implications of the study.

CHAPTER 2 :
AGRICULTURE AND THE CLIMATE IN SOUTH AFRICA

2.1 Introduction

The vulnerability of a country to climate change includes the extent to which current temperatures or precipitation patterns are close to or exceed tolerance limits for important crops, per capita income, the percentage of economic activity based on agricultural production, and the pre-existing condition of the agricultural land base (IPCC, 1997).

This chapter describes current South African agriculture across the landscape, the climate and land use and natural resource patterns of the country. Furthermore, the importance of the agricultural to South Africa's economy is discussed. Finally, the chapter emphasizes the influence of climate on the patterns of agricultural crops produced across the country and provides an overview of the crops included in the study.

2.2 Land use, Climate and the Natural resources of South Africa

The Republic of South Africa covers an area of 122.3 million ha divided into nine provinces. The total population of South Africa is estimated at 43,586,097 million people. Approximately 20 million hectares are used for non-agricultural purposes and 2 million hectares for nature conservation. The outstanding 100.7 million hectares, the largest part of the land is used for agriculture and forestry. However only 15.8 million hectares of the agricultural land are potentially arable.

South Africa is located in a predominantly semi-arid part of the world. The climate varies from desert and semi-desert in the west to sub-humid along the eastern coastal area, with an average rainfall for the country of about 450 mm per year. Evaporation is comparatively high. Rainfall is distributed unevenly across the country with an increase in rainfall from the western to the eastern parts. The 500 mm rainfall line actually divides the country into two sections. The country has three main rainfall regions:

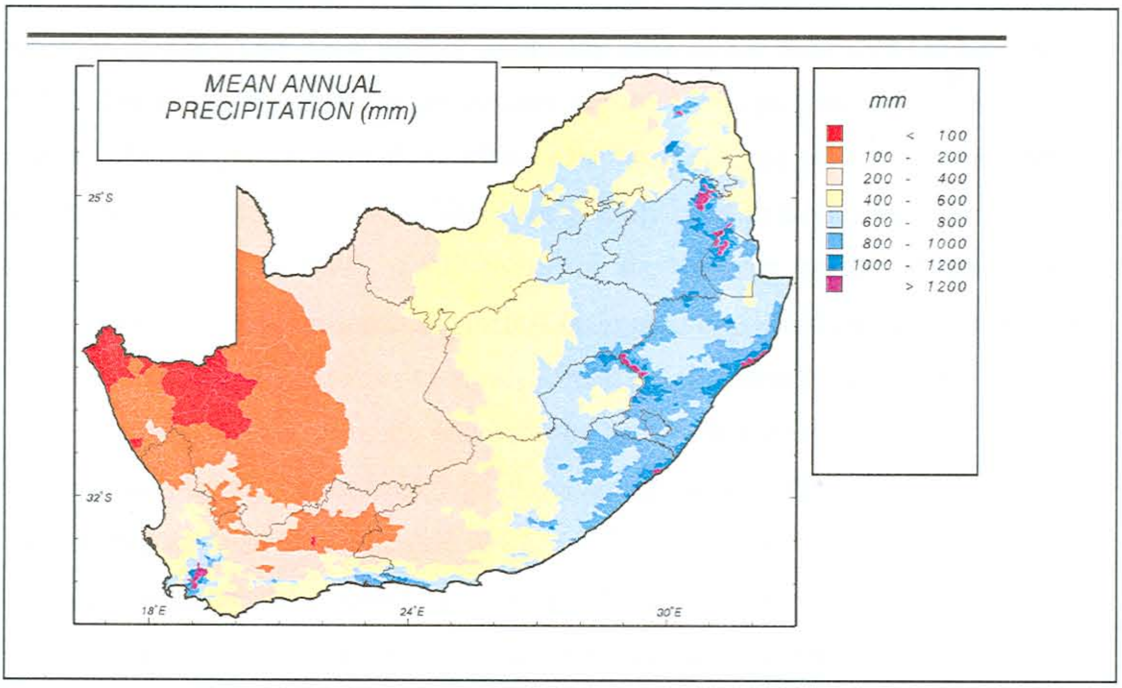
(1) The winter rainfall region in the southwestern cape with less than 500 mm per year;

(2) The area with rainfall throughout the year along the southern coastal region of more than 700 mm per year and;

(3) The summer rainfall area in the rest of the country with rainfall between 500 and 700 mm per year. Only 10% of the total area receives an annual precipitation of more than 750mm (Figure 2-1).

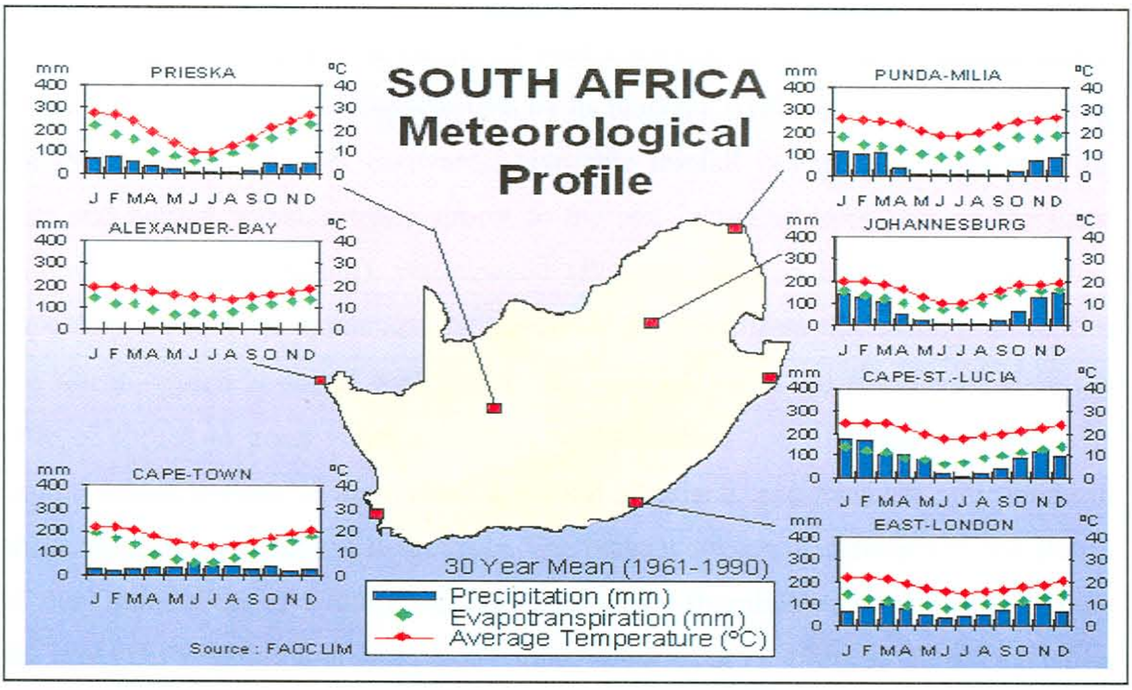
South African weather can be divided into two main periods: (1) summer seasons from October/November to March/April and (2) winter seasons from April/May to August/September. Summer temperatures on average vary across the country between mid thirties to twenties degree Celsius and the winter's between twenty and ten degree Celsius. Indeed, summers are generally warm while winters are not extremely cold except in certain regions where the night-time minimum temperatures can drop to a freezing point for at least 30 days a year over the entire high-lying inferior (about 50% of the country). Figure 2-2 gives an overview of the meteorological profile of South Africa.

Figure 2-1: South African Mean Annual Precipitation (1960-1990)



Source: Schulze (2003)

Figure 2-2: South Africa Meteorological Profile

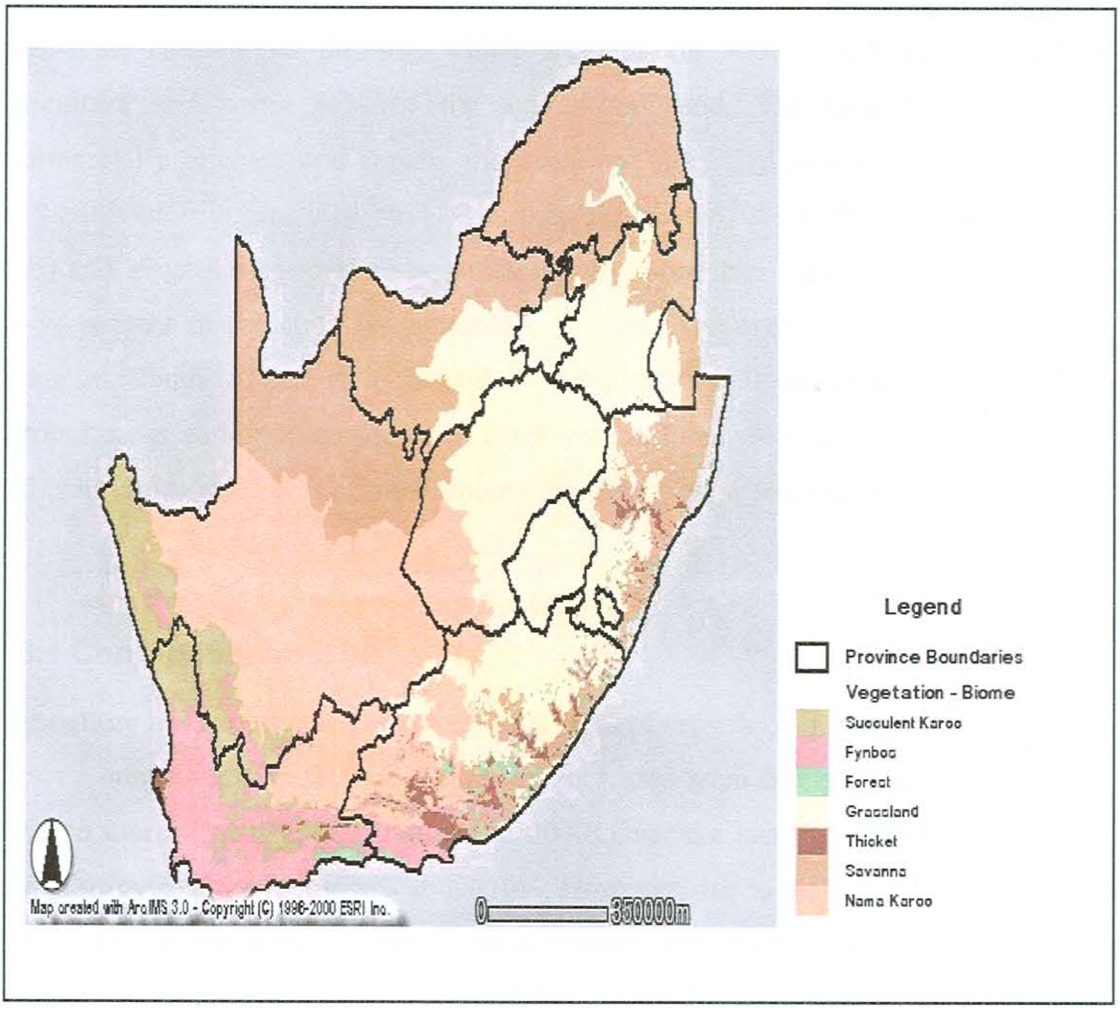


Source: FAO/GIEWS (2001)

South Africa's water resources are, in global terms scarce and extremely limited. The natural availability of water across the country is very unevenly distributed, with more than 60% of the rivers' flow arising from only 20% of the land area (Basson *et al.*, 1997). The four main rivers in the country are the Limpopo, Inkomati, Pongola and Orange, which together drain about 60% of the land area and contribute over 30% of the country's total surface runoff. There are no truly large or navigable rivers in South Africa and the total flow of all rivers in the country combined amounts to approximately 49 200 million cubic meters (m3) per year, less than half of that of the Zambezi River, the closest river to South Africa. South Africa is also poorly endowed with groundwater, as it is mainly underlain by hard rock formations, which, although rich in minerals, do not contain any major groundwater aquifers, which could be utilized on a national scale (Basson *et al.*, 1997). Indeed, water is the resource most limiting to national development particularly for agriculture. Almost 50% of South Africa's water resources are already used for agricultural purposes. There is evidence that climate change could cause increased variability of rainfall over the eastern parts of South Africa, and a decrease in rainfall from the west and over the Western Cape region (DWAF, 2002). Thus, plant and therefore irrigation water requirements will also increase should warmer climatic conditions manifest.

South Africa is covered by a variety of vegetation due to its diverse climatic zones. The winter rainfall area is characterized by its macchia (fynbos) vegetation, including the Protea family. Further eastwards, favorable rainfall is expected throughout the year and natural forest extends almost to the sea, including trees such as the Cape stinkwood (*Ocotea bullata*), yellowwood (*Podocarpus*) and black ironwood (*Olea capensis*). Behind the mountains, which divide the coast from the inland plateau, lies the Karoo, which is dotted with dwarf trees, shrubs, grass and succulents. Here the ratio of shrubs to grass varies according to the rainfall and livestock numbers. The central inland plateau or highveld is a natural grassland, and trees are only found in sheltered kloofs or along watercourses. The plateau stretches eastwards to the slopes of the Drakensberg and into KwaZulu-Natal where thornbushes predominate. Along the coast the vegetation is typical of humid, subtropical conditions. Other vegetation zones include the sparse desert flora along the west coast, which gradually changes eastwards to a savannah type with many *Acacia* spp. and other thorn-tree species (Figure 2-3).

Figure 2-3: South Africa vegetation- biome



Source: SAAGIS (2000)

2.3 The importance of agriculture to the South African economy

Agriculture in South Africa is widely regarded as a highly sophisticated and successful sector. The dominant form of agricultural production in South Africa is the large-scale commercial farming, which accounts for 90% of the value added in agriculture and owns 86% of the agricultural land. The large-farm sector is commercially oriented and capital-intensive, and generally produces surpluses. Dry land cultivation is practiced on 11.2 million ha (about 10% of the total agricultural land) and irrigation agriculture occupies slightly more than 1.2 million ha producing 25-30 percent of the country's agricultural output. The average size of commercial farms in South Africa is estimated to be about 1200 hectares (SSA, 2002b). Agriculture is an important source of employment, foreign exchange and food supply and contributes to the rest of the economy through strong economic multipliers.

2.3.1 Contribution to GDP

Agriculture has experienced relatively high rates of growth over the past century. The sector's contribution to GDP at factor cost increased from 687 millions Rand (R)[3] in 1965 to more than R 25000 millions in 2000. Over the last two decades the annual rate of growth of the sector was about 10%. However, due to the transformation of the South African economy from a primary based economy to a more diversified economy, the share of the sector to GDP has declined (Figure 2-4). Indeed, the share of agriculture in total GDP has been decreasing over the years from 20% in 1911 to 10% in 1965 and to less than 5% in the late decade (AAS, 2002).

Agriculture contributed about 3.5% to the total value added of the country in 2002. Kwazulu Natal province made the largest contribution (28.3% of the total) followed by Western Cape (22.6%). Three categories of products contributed to the agricultural GDP namely: (1) Field Crops; (2) Horticultural products; and (3) Livestock. Over the past two decades the average contribution to the gross value of the agricultural sector was about 37%, 20% and 43%, respectively, from field crops, horticulture and livestock (AAS, 2002).

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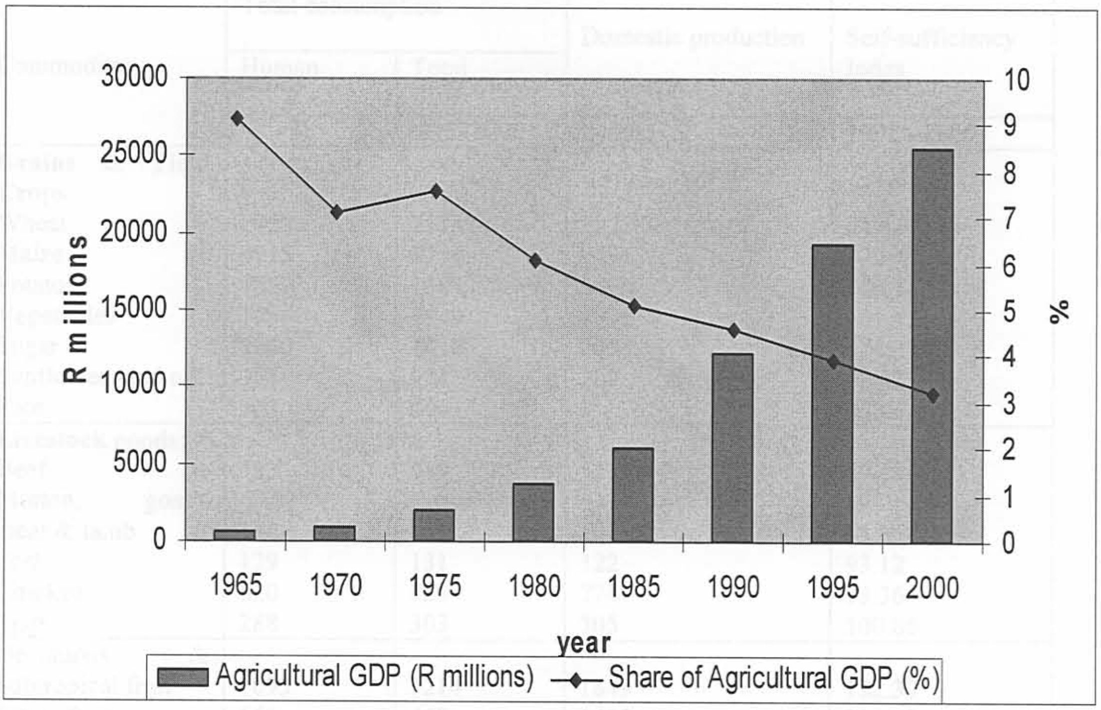
[3] Rand (R) is the local currency of the Republic of South Africa and 1 US $ was equal to approximately R 7 in 2000.

Figure 2-4: Contribution of the South African Agriculture to Gross Domestic Product (1965-2000)



Source: AAS (2002)

2.3.2 Food supply and food security

The National Department of Agriculture (NDA) reports that at the national level, South Africa is food secure. It produces most of its main staple foods exporting surpluses (NDA, 2002). Except for rice, for which the country has no domestic resource base and is imported, the country has met the needs for its main staple food by over 160%, 100%, 95%, and 80%, for sugar, maize, livestock needs and wheat, respectively (Table 2-1). However, future trends projections indicate that should current production trends continue, domestic production would be outstripped by domestic consumption for most major agricultural commodities by over 20% in 2010 and 30% in 2020 (Table 2-2). Therefore, with the likely adverse impacts of climate change, the predicted figures may be worse.

Table 2-1: Average production and consumption and Self-Sufficiency Indices (SSI) of selected agricultural commodities in South Africa (1995- 2000)

Commodity	Total consumption		Domestic production	Self-sufficiency Index
	Human	Total		
	1995- 2000 (1000 tons)			1995 - 2000
Grains & Field Crops:				
Wheat	2458	2513	2222	88.41
Maize	4213	7754	9496	122.47
Potatoes	1350	1584	1598	100.88
Vegetables	1754	1949	1976	101.42
Sugar	1260	1410	2453	174.01
Sunflower seed oil	301	331	207	62.42
Rice	501	506	0	0.00
Livestock goods:				
Beef	523	589	525	89.19
Mutton, goat's meat & lamb	164	165	105	63.36
Pork	129	131	122	93.12
Chicken	820	829	774	93.36
Eggs	288	303	305	100.86
Deciduous & Subtropical fruit	1093	1214	1849	152.30
Citrus fruits	661	668	1432	214.43
Diary products:				
Condensed milk & powder milk	313	313	302	96.74
Fresh milk	1565	2724	2724	100.00
Cheese	39	39	37	96.37
Butter	14	14	11	77.94

Note: Self-Sufficiency Index= (domestic production/total consumption) x 100

Source: NDA (2002)

Table 2-2: Expected requirements of basic agricultural products in South Africa by the years 2010 and 2020

Product	Per capita consumption (kg)	Expected demand growth by years (%)		Expected requirement by years ('000 ton)		Current production ('000 ton)	Estimated difference between projected consumption and current production ('000)			
		2010	2020	2010	2020		2010		2220	
							ton	%	ton	%
Maize	174.6	1.64	1.46	8371	10363	7299	1072	14.7	3064	42.0
Wheat	55.9	1.26	1.12	2670	3307	1763	907	51.4	1544	87.6
Potatoes	31.4	3.53	3.14	1533	1895	1218	315	25.9	677	55.6
Fresh milk	28	1.85	1.65	1345	1665	1082	263	24.3	583	53.9
Beef	18.3	3.07	2.73	889	1099	685	204	29.8	414	60.4
Mutton	5.0	1.85	1.65	240	297	177	63	35.6	120	67.8
Pork	3.2	3.07	2.73	156	192	121	35	28.9	71	58.7
Poultry	19.3	4.71	4.19	953	1176	747	206	27.6	429	57.4
Eggs	5.4	1.72	1.53	258	321	264	-	-	57	21.6

Source: NDA (2002)

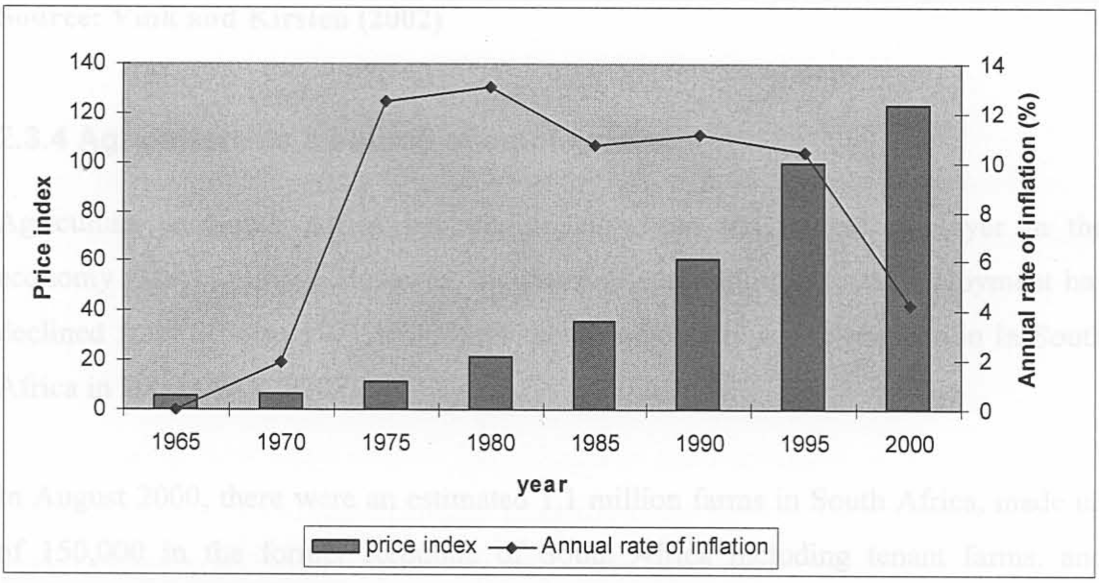
Another important role of the Agricultural sector is to provide food to consumers at reasonable prices. South Africa appears to be much less expensive in terms of food prices than the rest of the Southern Africa region. Indeed, the basket of basic food is around 50% more expensive in Mozambique and Zambia compared to South Africa, and twice as expensive in Malawi (Vink and Kirsten, 2002). Food prices in South Africa, however, have been increasing significantly over the years. The annual rate of growth of food prices over the period 1965 to 2000 show three main periods (Figure 2-5) reflecting different changes in agricultural policy in South Africa:

(1) 1965- 1980: This period witnessed sharp increases in producer prices as a result of the high protection in agriculture with marketing boards controlling trade in all agricultural commodities.

(2) 1980- 1995: Producer prices slightly declined during this period when the country has undergone changes in the broader political economy (financial sector, labour market) that induced important shifts in agricultural policy (e.g. reduction of budget allocation to farmers, scrapping of the Land Act, etc.).

(3) 1995 – 2000: This period is characterised by a sharp decline in producer prices due to the process of deregulation and liberalization in the agriculture sector that took place after the promulgation of the Marketing of Agricultural Products' Act in1996.

Figure 2-5: Trend of Producer prices of agricultural products at 1995 prices (1965- 2000)



Source: AAS (2002)

2.3.3 Agriculture as a source of foreign exchange

South Africa's agriculture has a positive trade balance. Agricultural exports have grown rapidly, especially from 1990. In 2000 the sector exported about R16 billion worth of products, or nearly 6 % of South Africa's total exports. Sugar, accounted for the largest agricultural export value and the top three countries to which it was exported are Iran, Korea and Saudi-Arabia. South Africa also exports wine, citrus fruit, grapes, preserved fruits and nuts. However, agricultural imports have grown even faster. Therefore, the agricultural terms of trade have decreased from 5.56 in 1980 to 1.6 in 2000. The trade performance of South Africa's agriculture over the past two decades is depicted in Table 2-3.

Table 2-3: Trends in South Africa's agricultural exports (1980-2000)

	1980	1990	2000
Exports			
Total SA exports (R millions)	19 915.4	60 770.0	253 809.0
Total agricultural exports (R millions)	2 052. 5	5 289.8	15 819.0
Agricultural exports as % of total exports	10.3	8.7	6.2
Imports			
Total SA imports (R millions)	14 381.3	44 141.5	227 918.0
Agricultural imports (R millions)	369.2	2 203.3	9 643.7
Agricultural imports as % of total imports	2.6	5.0	4.2
Exports + Imports/ Total production (%)	**34.5**	**34.5**	**57.5**
Agricultural terms of trade (Ag exports/Ag imports)	**5.56**	**2.4**	**1.6**

Source: Vink and Kirsten (2002)

2.3.4 Agriculture as a source of employment

Agriculture in South Africa has traditionally been the largest employer in the economy (Meyer, 1998). However, the share of agriculture in total employment has declined from 30% in 1971 to 13% of the economically active population in South Africa in 2000 (AAS, 2002).

In August 2000, there were an estimated 1.1 million farms in South Africa, made up of 150,000 in the former Republic of South Africa including tenant farms, and 943,000 in the former homelands (SSA, 2002b). Commercial farms provide livelihoods and housing to about six million family members of 1 million employees and provide for their educational needs. There are also 240,000 small farmers who provide a livelihood to more than one million of their family members and occasional employment to another 500,000 people. Furthermore, there are an estimated three million farmers, mostly in the communal areas of the former homelands, who produce food primarily to meet their own family needs (NDA, 2000).

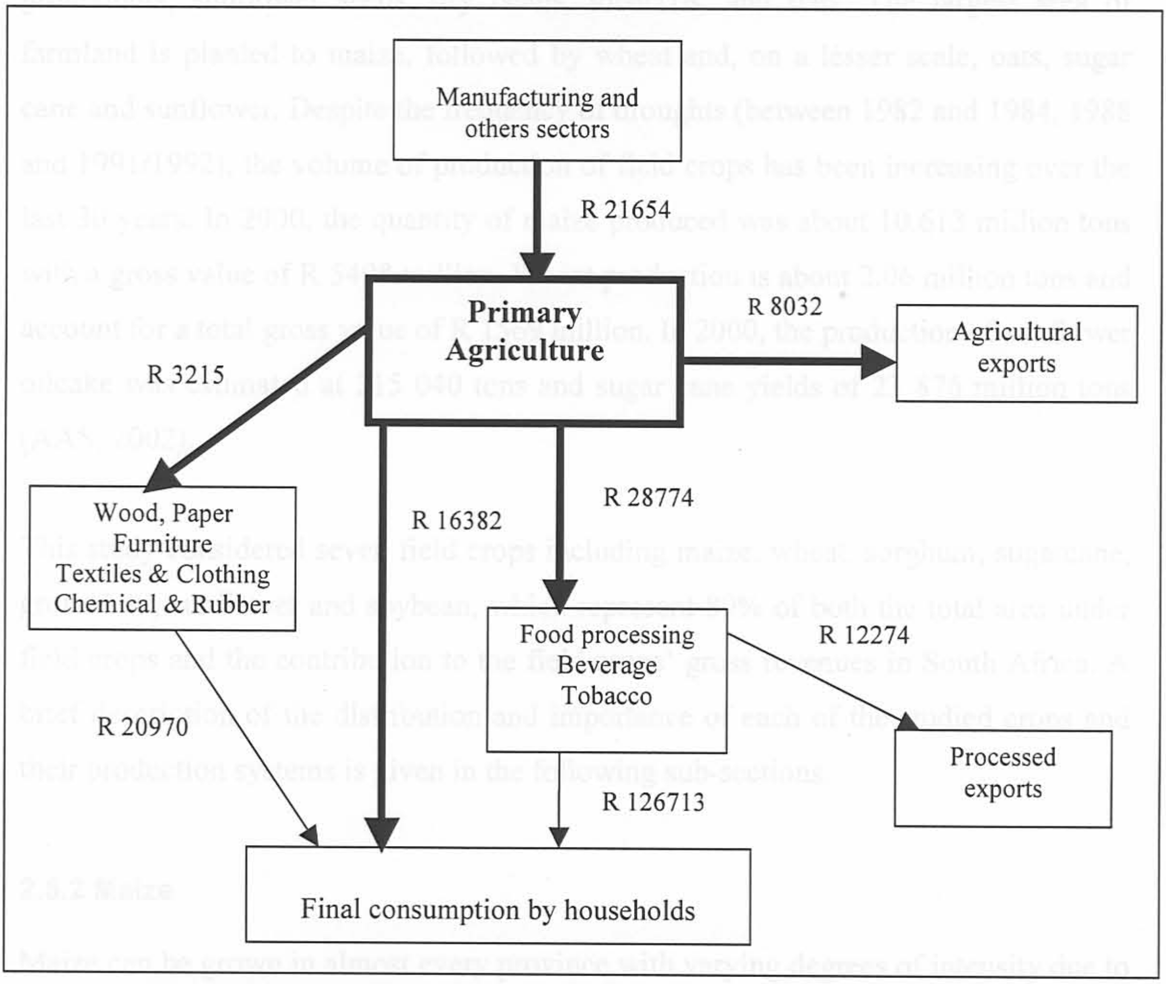
2.3.5 Economic multipliers of South African Agriculture

Many development economists (Lewis, 1954; Mellor, 1979; and Rostow, 1960) support the argument that agriculture has a very important role in the economic development process of a nation, stressing that improving agricultural productivity is the basis for a successful development strategy. Indeed through the interrelationships and the multiplier effects between food supply, rural purchasing power, labour and capital markets agriculture could stimulate overall economic growth.

In South Africa, agriculture is an important sector despite its relatively small share of total GDP. The sector has strong backward and forward linkages to the rest of the economy through the input supply and financial sectors as well as the agro-processing firms. Together, the agro-food complex contributes between 14% and 20% of the GDP (NDA, 2002). The input-output tables for 1993 (SSA, 1999) indicate that 60% of agricultural output is in the form of intermediates goods, suggesting that the downstream or forward linkages from the sector are relatively high. Using a quasi-input –output analysis, Hassan (2003) shows that for the sugar cane industry only, total employment benefits (direct and indirect) amount to about 1.02 full-time jobs per ha and total economic multipliers range from 1.82 to 8.71. Furthermore estimates of multipliers from studies using the Social Accounting Matrix (SAM) ranging from 4.39 to 5.54, showed that, in general, multipliers of agriculture in South Africa are relatively higher than international ones (Hassan *et al.*, 2002).

The following flow chart (Figure 2-6) illustrates the importance of the agricultural sector to the South African economy from the input level to the consumer level in terms of the demand by agriculture for outputs from other sectors (backward linkages) and the demand by the agro-based processing industries for the agricultural outputs (forward linkages).

Figure 2-6: Value of transactions of the Agro-food complex in 2000 (R millions)



Source: Conningarth Economists (2000)

2.4 The field crops' sector

2.4.1 Overview of the South African field crops sector

South Africa is suitable for the cultivation of a large variety of field crops. The main field crops of South Africa are maize; wheat, sugarcane, sorghum and minor crops are groundnuts, sunflower seeds, dry beans, tobaccos, and oats. The largest area of farmland is planted to maize, followed by wheat and, on a lesser scale, oats, sugar cane and sunflower. Despite the frequency of droughts (between 1982 and 1984, 1988 and 1991/1992), the volume of production of field crops has been increasing over the last 30 years. In 2000, the quantity of maize produced was about 10.613 million tons with a gross value of R 5498 million. Wheat production is about 2.06 million tons and account for a total gross value of R 1569 million. In 2000, the production of sunflower oilcake was estimated at 215 040 tons and sugar cane yields of 23 876 million tons (AAS, 2002).

This study considered seven field crops including maize, wheat, sorghum, sugarcane, groundnut, sunflower and soybean, which represent 80% of both the total area under field crops and the contribution to the field crops' gross revenues in South Africa. A brief description of the distribution and importance of each of the studied crops and their production systems is given in the following sub-sections.

2.5.2 Maize

Maize can be grown in almost every province with varying degrees of intensity due to climatic conditions. The Free State is the major maize-producing region whereas, Limpopo, Gauteng, Mpumulanga and KwaZulu-Natal are the minor growing regions in South Africa. Maize is the only crop that has two planting and harvesting periods depending on the region. In the Western part of the country, planting starts in December and January whereas in the eastern region planting starts in October to December.

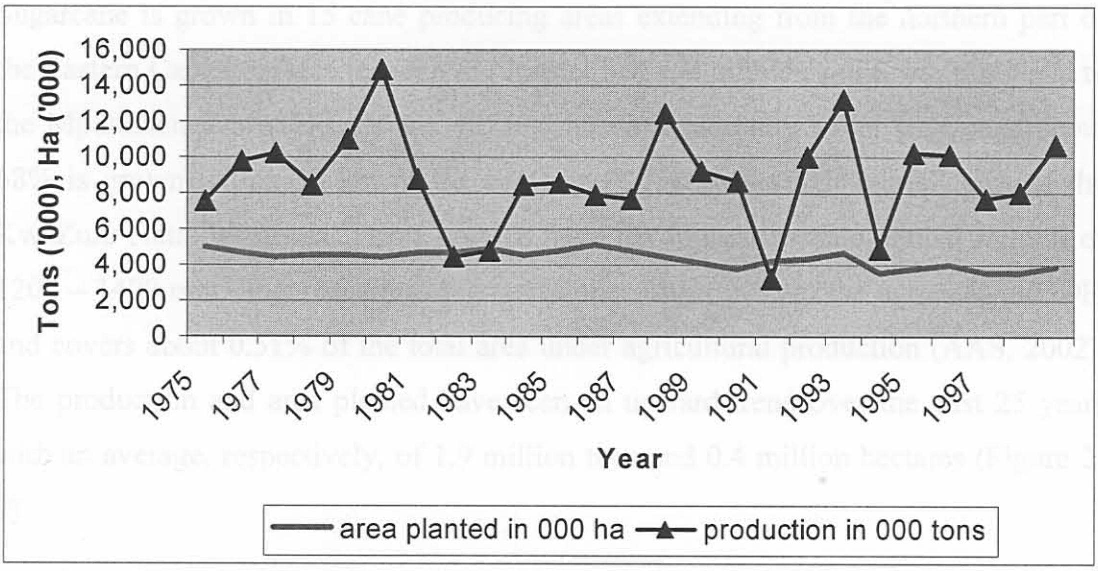
Maize is the most important crop in South Africa, being both the major feed grain and staple food for the majority of the South African population. Maize accounts for approximately 40% of the cultivated area and generates 15% of the gross value of all agricultural products (World Bank, 1994). The maize industry is also an important earner of foreign revenue for South Africa through the export of maize and maize products. South Africa mainly exports maize to Zimbabwe, Japan, Zambia, Malawi, Mauritius, Kenya and Mozambique.

The area planted to maize declined from 5 million hectares in the mid eighties, to approximately 3.5 million hectares in 1998/1999. Annual average maize production for the past decade has been approximately 8 million tons. Although the area planted declined over the past years, production has been erratic with slight upward trend (Figure 2-7). The decline in area planted was due to the changes in agricultural policies. The country produces two types of maize, white and yellow. The local consumption requirements are estimated at 7.5 millions tons. This can be split up into 4.4 million tons of white maize and 3.1 million tons of yellow maize.

2.5.3 Wheat

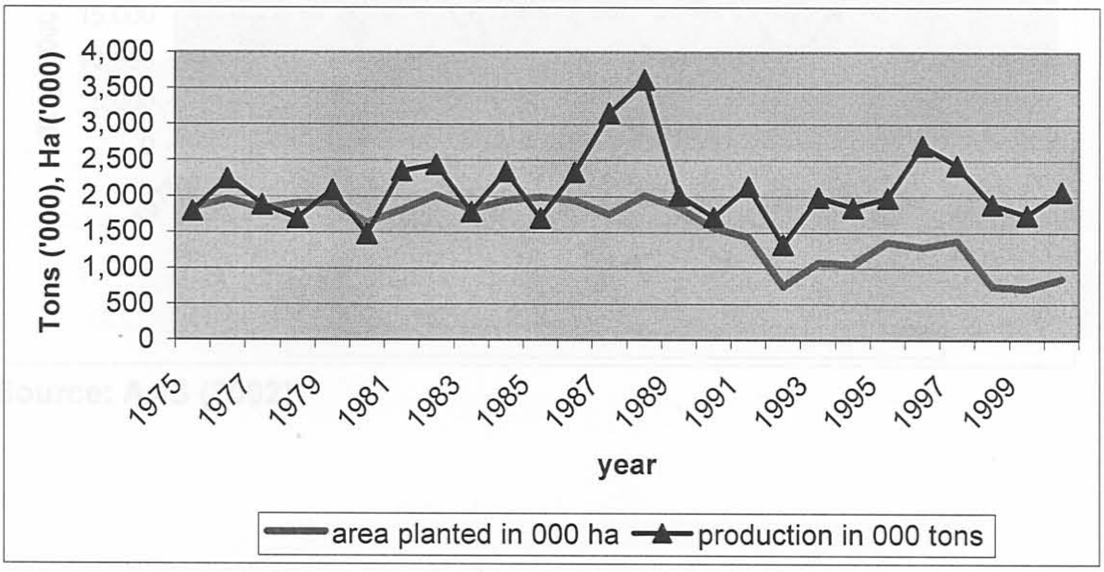
Wheat is the second most important grain crop in South Africa. Wheat, a winter crop is produced in the Western Cape, the Free State, the North West and the Northern Cape provinces. Wheat could be planted from mid-April to end-July. Domestic consumption is estimated at 2.4 million tons per annum. South Africa regularly imports wheat. During 2000/2001 season, 2.35 million tons of wheat were produced locally and approximately 300,000 tons of wheat were imported (12% of the domestic production). Over the two past decades, production quantities have been erratic with an average of about 2 million tons per year. Area planted under maize has declined over the years (Figure 2-8). The reduction in area planted in recent years was due mainly to droughts experienced by the country's central wheat regions and changes in government agricultural policies (Jooste and Van Zyl, 1999).

Figure 2-7: The trend in maize production and area planted (1975-2000)



Source: AAS (2002)

Figure 2-8: The trend in wheat productions and area planted (1975-2000)

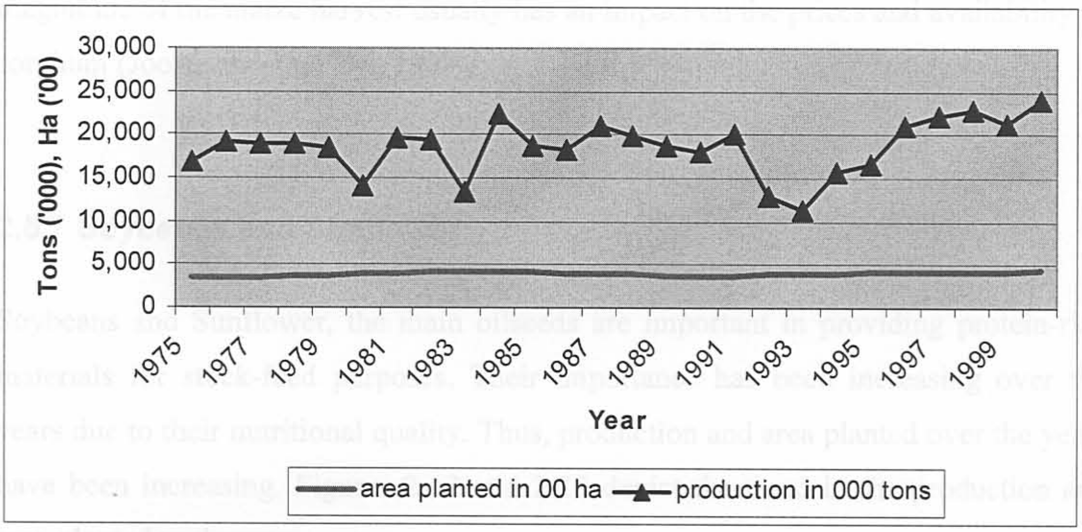


Source: AAS (2002)

2.5.4 Sugarcane

Sugarcane is grown in 15 cane producing areas extending from the northern part of the Eastern Cape Province through the coastal belt and midlands of KwaZulu-Natal to the Mpumalanga lowveld. Of the 427,000 hectares currently under sugarcane about 68% is grown within 30 km of the coast and 17% in the high rainfall area of the KwaZulu Natal midlands. These regions have the highest median annual rainfall of 1200 – 1400 mm. Sugarcane farming contributes about 20% of the agricultural GDP, and covers about 0.51% of the total area under agricultural production (AAS, 2002). The production and area planted have seen an upward trend over the past 25 years with an average, respectively, of 1.9 million tons and 0.4 million hectares (Figure 2-9).

Figure 2-9: The trend in sugarcane production and area planted (1975- 2000)



Source: AAS (2002)

2.5.5 Groundnuts

Groundnut, a summer crop is mainly grown in the summer rainfall areas of the North West Province and the Free State Province. Planting dates are mainly determined by the climatic conditions but normally fall between mid October and mid November when higher temperature and rainfall ensure good germination. Groundnuts are used principally for own –consumption in KwaZulu Natal and Mpumalanga provinces. Groundnuts production quantity and area planted have fluctuated over time with a downward trend and a slightly upward trend, respectively (Figure 2-10).

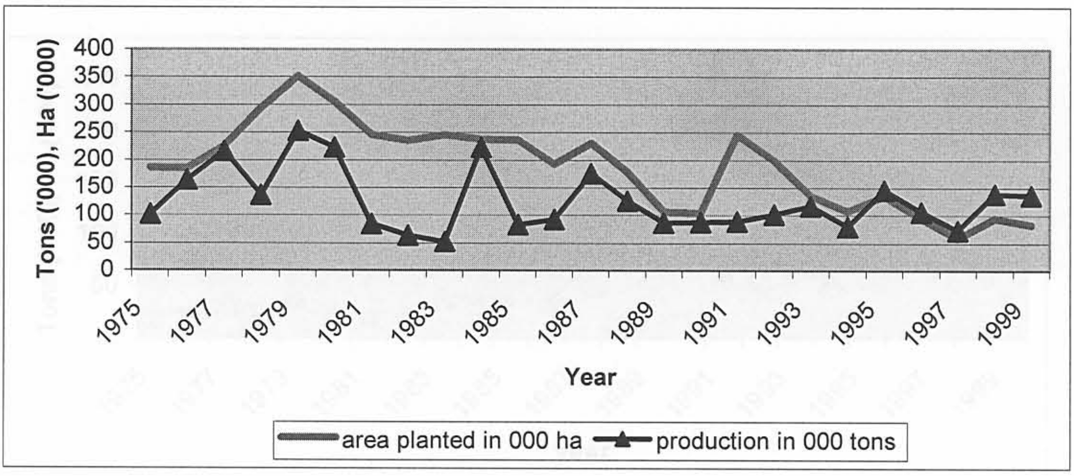
2.5.6 Sorghum

Sorghum due to climatic conditions is mainly produced in the Free State (64%), Mpumalanga (15%) and NorthWest (11%) (AAS, 2002). Production and area planted recently experienced a downward trend after a slight increase during the period 1975-1990. Figure 2-11 depicts production and area planted over the period 1975-2000. The magnitude of the maize harvest usually has an impact on the prices and availability of sorghum (Jooste and Van Zyl, 1999).

2.5.7 Soybeans and Sunflower

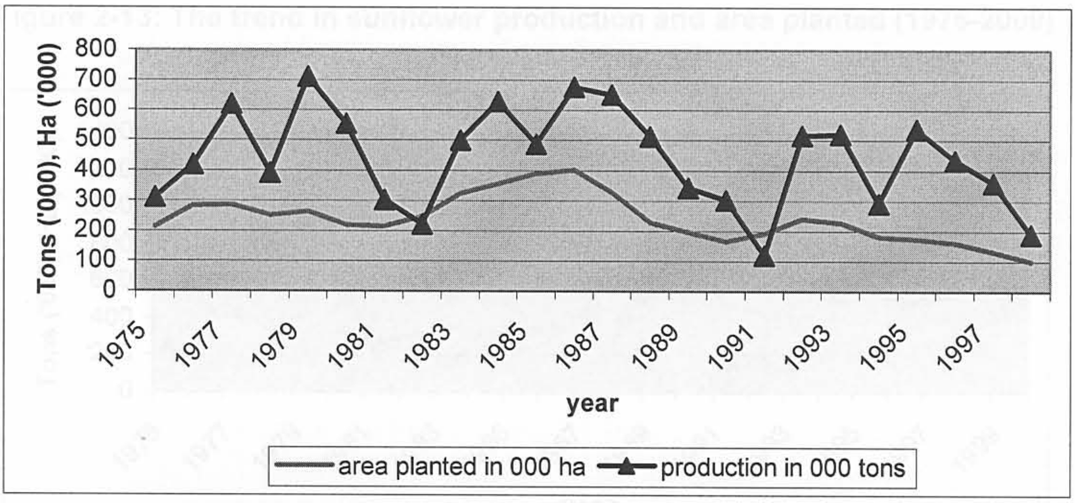
Soybeans and Sunflower, the main oilseeds are important in providing protein-rich materials for stock-feed purposes. Their importance has been increasing over the years due to their nutritional quality. Thus, production and area planted over the years have been increasing. Figures 2-12 and 2-13 depict the trend in the production and area planted to these two crops.

Figure 2-10: The trend in groundnut production and area planted (1975- 2000)



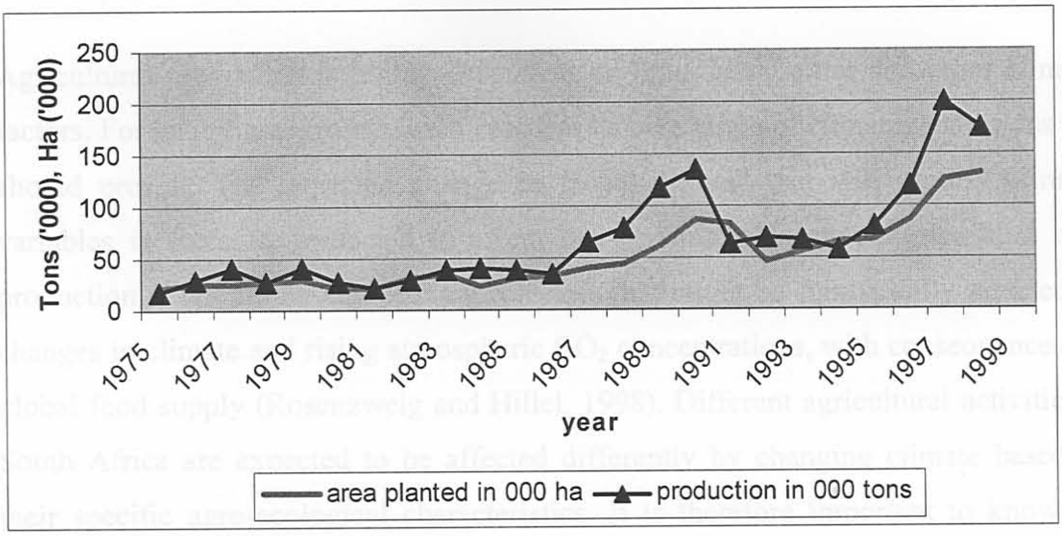
Source: AAS (2002)

Figure 2-11: The trend in sorghum production and area planted (1975-2000)



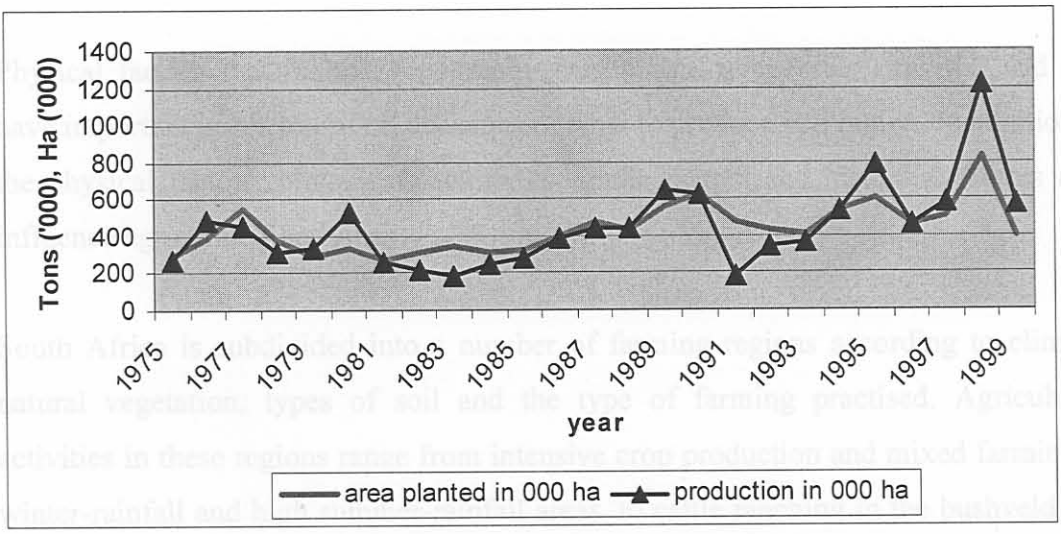
Source: AAS (2002)

Figure 2-12: The trend in soybean production and area planted (1975- 2000)



Source: AAS (2002)

Figure 2-13: The trend in sunflower production and area planted (1975-2000)



Source: AAS (2002)

2.5 Physiological vulnerability to climate change of field crops in South Africa

Agricultural production is highly dependent on light, heat, water and other climatic factors. For an optimal growth, each crop has its own range of climatic conditions that should prevail. The expected change in global climate that will modify climatic variables is therefore expected to affect the agricultural sector. Agricultural crop production is one of the key economic sectors that might be significantly affected by changes in climate and rising atmospheric CO_2 concentrations, with consequences for global food supply (Rosenzweig and Hillel, 1998). Different agricultural activities in South Africa are expected to be affected differently by changing climate based on their specific agro-ecological characteristics. It is therefore important to know the agro-ecological location and characteristics of the field crops studied and their sensitivity to climate variability.

2.5.1 The Agro-ecological features of South Africa

Physical factors that include topography, vegetation, temperature, rainfall and soil have important implications on decisions of what to produce in a region. In addition to the physical factors, biological factors, economic factors and historical factors also influence agricultural activities.

South Africa is subdivided into a number of farming regions according to climate, natural vegetation, types of soil and the type of farming practised. Agricultural activities in these regions range from intensive crop production and mixed farming in winter-rainfall and high summer-rainfall areas, to cattle ranching in the bushveld and sheep farming in the more arid regions. Jooste and Van Zyl (1999) identified six agro-economic zones in South Africa based on the differences in rainfall, vegetation, erodibility, biological productivity, water availability, resource quality and output and input price ratio of the regions. These are the Cape Fold region, the Nama Karoo Region, the Interior region, the Kalahari/Limpopo Plain region, the Eastern Plateau Slope or Lowveld region and the High Veld Region. The Joint Agriculture and Weather Facility of the National Oceanic and Atmospheric Administration (NOAA) of the United States determined four climatic zones for South Africa based on crop areas and climate profiles: steppe (arid), the desert, the sub-tropical wet and the sub-tropical winter rain zones (Figure 2-14).

Thus, due to the diversity in the country in terms of ecological and climate factors, each crop has its main production areas. Figure 2-15 below shows the geographical distribution of the main field crops' zones in South Africa. For example, Wheat is produced in the western cape and the Free State (the cooler provinces) while Sorghum is produced in the warmer eastern part of the country. However, climate change may alter the distribution of agroecological zones with highlands getting longer growing seasons (Hulme, 1996).

Figure 2-14: The Agro-climatic zones in South Africa

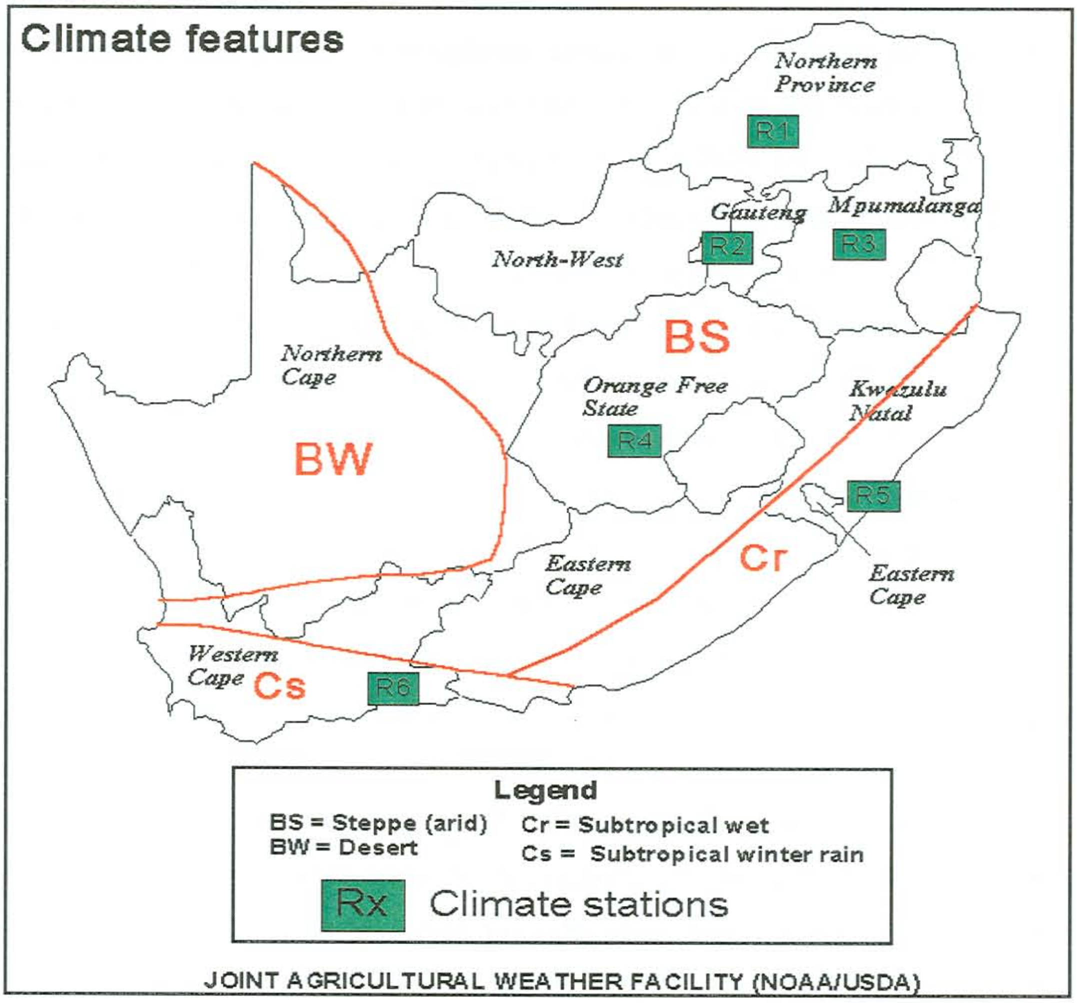
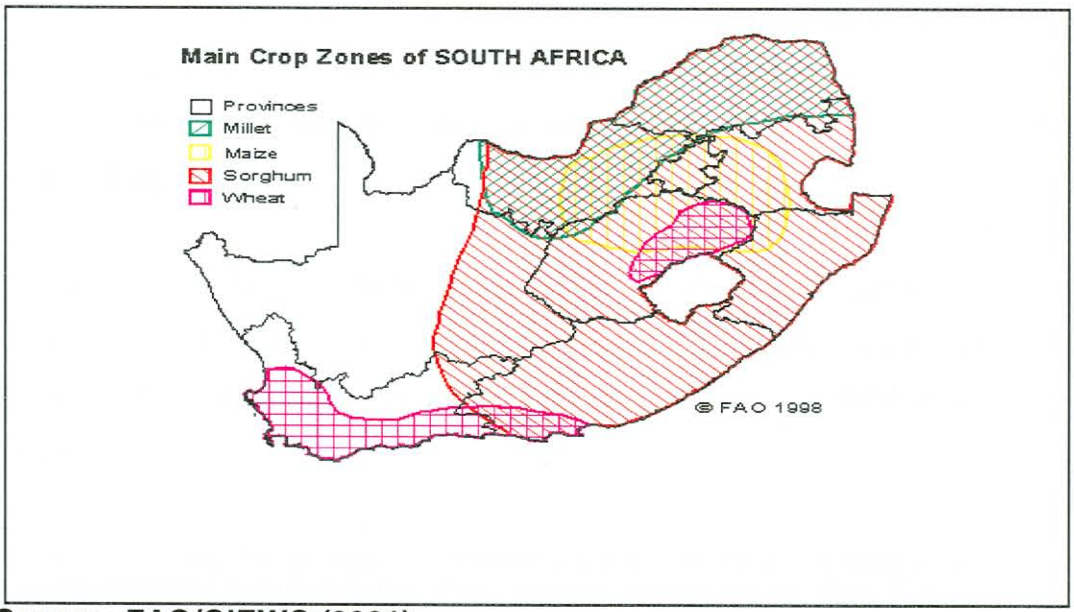


Figure 2-15: The main cropping zones of the field crops



Source: FAO/GIEWS (2001)

2.5.2 Vulnerability of field crops to climate change

Temperature, precipitation, atmospheric carbon dioxide content, the incidence of extreme events and sea level rise have been identified as the main climate change related drivers, which impact agricultural production (McCarl *et al*., 2001). A rise in carbon dioxide concentration for example, is expected to have a positive effect on crop yield due to the increase in water use efficiency and rate of photosynthesis. The impact of carbon dioxide on field crops will differ depending on whether the crop is C_3 or C_4 plants[4]. Rosenzweig and Hillel (1995) observed that C_3 plants like wheat and soybeans respond readily to increased carbon dioxide while C_4 plants like maize; sorghum, sugarcane and millet respond less to increased carbon dioxide. On the other hand, rising temperature has generally a negative impact on crop yield. Pimentel (1993) noticed that global warming is likely to alter production of wheat, maize and beans. Staple crops such as wheat and maize that are associated with subtropical latitudes may suffer a drop in yield as a result of increased temperature. The severity of the impacts of higher temperatures could be detrimental specifically for wheat in South Africa due to the fact that in many areas where the crop is grown, temperatures are already at the tolerance limit for its optimum growth. Indeed, high temperatures severely limit wheat yield by accelerating the plant development, affecting the floral organs and fruit formation and the functioning of the photosynthetic apparatus. Moreover, a rise in temperature is expected to increase evapotranspiration, coupled with the fact that precipitation is likely to decrease; water balances will be adversely affected. Hence, increased evaporation from the soil and accelerated transpiration in the plants cause moisture stress. The occurrence of moisture stress during flowering, pollination and grain filling is harmful to most crops particularly to maize, soybeans, wheat and sugarcane.

In general South Africa climatic conditions are suitable for the cultivation of field crops except with regard to rainfall where the required optimum levels are not reached (NDA, 2000). Table 2-4 gives a summary of conditions for field crops' growth suitability.

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[4] C_3 plants are plants that produce a three-carbon compound during photosynthesis, including most trees and agricultural crops such as rice, wheat, soybeans, potatoes and vegetables. C_4 plants are plants that produce a four-carbon compound during photosynthesis (mainly of tropical origin), including grasses and the agriculturally important crops maize, sugar cane, millet, and sorghum.

Table 2-4: Optimal climatic conditions for growth of field crops

Crop Type	**Growing days**	**Climate**	**Optimum Temperatures**	**Optimum Precipitation**	**Soils**	**Photoperiod Response**
Maize (***Zea mays*** subsp. ***Mays*),**	88 to 140	Tropical-wet and dry Steppe and semi-arid Subtropical-dry	Max: 33^{0}C Min: 18^{0}C	1200 mm	medium-textured organic soils, well drained with a pH of 5.5 to 7.5	short day and day neutral photoperiod response and need a bright light intensity
Sorghum (***Sorghum bicolor***)	90 to 300	steppe and semi-arid, temperate, tropical-wet and dry, subtropical	Max: 35^{0}C Min: 25^{0}C	900 mm	light-loams and heavy clays soils, well drained with a pH of 5.5 to 7.5	short day photoperiod response and need a bright light intensity
Wheat ***(Triticum aestivum*** subsp. ***Aestivum)***	90 to 120	tropical-rainy, dry climate, subtropical, temperate climate	Max: 23^{0}C Min: 15^{0}C	750 mm	silt and clays loams soils, well drained with a pH of 5.5 to 8	long day and day neutral photoperiod response and need a very bright light intensity
Groundnut ***(Arachis hypogaea)***	90 to 150	in Tropical-wet and dry, steppe and semi-arid, subtropical-humid climate	Max: 32^{0}C Min: 22^{0}C	1200 mm	light, sandy loam soils, well drained with a pH of 5.5 to 6.5	a long day, short day and day neutral photoperiod response and need a bright light intensity
Sunflower ***(Helianthus annus)***	70 to 200	steppe and semi-arid, tropical-wet and dry, subtropical, temperate climate	Max: 34^{0}C Min: 17^{0}C	1200 mm	medium light soils, well drained with a pH of 6 to 7.5	short day photoperiod response and need a bright light intensity.
Soybean ***(Glycine max)***	75 to 180	Subtropical-dry summer, steppe and semi-arid, tropical-wet and dry	Max: 33^{0}C Min: 20^{0}C	1200 mm	fertile loams soils, well drained with a pH of 5.5 to 7.3	short day photoperiod response and need a bright light intensity.
Sugar cane ***(Saccharum officinarum*** L.)	Perennial crop	Warm Temperate Dry to Moist through Tropical Very Dry to Wet Forest Life Zones	Max: 25^{0}C Min: 15^{0}C	1500 mm	loamy soils with good Proportions of sand, silt and clay with good water storage and drainage characteristics. A pH range of 6-8	Long day photoperiod and very bright light intensity.

Source: Illinois State Water Survey (2004)

CHAPTER 3 : LITERATURE REVIEW ON CLIMATE CHANGE AND AGRICULTURE

3.1 Introduction

Climate is a primary determinant of agricultural productivity. At the same time, agriculture has a significant impact on the process of climate change. Thus, food supply vulnerability to climate change is a major concern in the discussions and research on the impacts of climate change.

This chapter reviews the literature on climate change and agriculture. The chapter is subdivided into eight sections. First, brief definitions and key facts on the process of climate change are considered. Section 3 then highlights the physical impacts of climate change on agricultural productivity whereas section 4 deals with its economic impacts. Section 5 examines the literature on the potential distribution of the impacts of climate change across regions. Policy implications of climate change are discussed in section 6. The empirical approaches to measure the impact of climate change are reviewed and compared in section 7. Finally section 8 provides a brief review of empirical studies, which have predicted impacts of climate change on agriculture across the globe and particularly in South Africa.

3.2 The Process of climate change

The United Nations Framework Convention on Climate Change (UNFCC), in its Article 1, defines "climate change" as: "a change of climate, which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods." Solar radiation is emitted from the sun and travels towards the earth. In passage through the atmosphere, solar radiation diminishes in intensity through reflection, scattering, and absorption caused by water vapour, other gases, aerosols, and suspended particles. The earth's surface also emits infra-red radiation, which is trapped by atmospheric gases and reemit downward, warming the surface of the earth and the lower atmosphere. This is called the greenhouse effect. The gases, which allow the infra-red radiation to be retained, are the greenhouse gases (GHG). The main greenhouse gases are water vapour, carbon dioxide (CO_2), methane (CH4), nitrous oxide (N_2O), chlorofluorocarbons and ozone (O_3). If there were no natural greenhouse effects, the average surface temperature would be about 34°C (93°F) colder than it is today (Jepma and Munasinghe, 1998). Thus, most of the present life forms on the earth depend on the natural greenhouse effect for their existence.

Over the last 100 years, the atmospheric amounts of many greenhouse gases, particularly carbon dioxide, has increased significantly, primarily as a result of changes in land use (e.g., deforestation) and the increased use of coal, oil, and natural gas (e.g., in automobiles, industry, and electricity generation). The accumulation of greenhouse gases in the atmosphere is expected to alter the atmospheric balance and enhance the natural greenhouse effect, leading to a change in climate variables such as temperature, precipitation and solar radiation.

Atmospheric scientists have developed models, known as the Global Circulation Models (GCMs) to provide medium or long-term projections of climate under various concentrations of greenhouse gases in the atmosphere. The most common projection is of a doubling of the CO_2 concentration in the atmosphere. Under this assumption, the Intergovernmental Panel on Climate Change (IPCC) has recently projected that global average surface temperature will increase by 1.4 to 5.8^0C over the period 1990 to 2100. Higher world temperatures will increase the hydrological cycle activity leading to a general increase in precipitation and evapotranspiration. The global sea level is expected to rise by a further 15 to 95 cm (about 6 to 37 inches) by the year 2100, due mainly to the thermal expansion of the oceans and the melting of glaciers and ice sheets. Extreme events such as heavy rains and droughts are the most destructive forms of weather, and the frequency and duration of these events are likely to increase as the climate continues to change.

Droughts and floods occur naturally around the world, for example in association with El Niño[5] events, but these are likely to become more severe, causing water management to become an even more critical problem in the future (Jepma and Munasinghe, 1998; IPPC, 1996; and 2001a).

3.3 Climate change effects on agricultural productivity

Climate change will have potential effects on various sectors such as forestry, agriculture, animal production, fisheries, water resources and energy developments. The agricultural sector appears to be one of the most vulnerable sectors because agriculture is sensitive to the direct impact of climate through temperature, rainfall, CO_2, and indirect impact through water and forestry. According to McCarl *et al.* (2001), there are four main categories of agricultural productivity implications of climate change:

(1) Crops and forage productivity and production costs. Where temperature, precipitation, atmospheric carbon dioxide content and extreme events are likely to alter plant growth and harvestable or grazable yield through a mixture of climatic and CO_2 fertilization effects as well as impacts on plant water demand.

(2) Soil suitability for agricultural production, which is affected in terms of available soil moisture for plant growth, moisture storage capacity and fertility.

(3) Livestock productivity and production costs are affected both directly and indirectly. Direct effects involve consequences for the balance between heat dissipation and heat production. Indirectly effects work through the carrying capacity in a region by changing availability of feed and fodder.

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[5] El Niño, in its original sense, is a warm water current, which periodically flows along the coast of Ecuador and Peru, disrupting the local fishery. This oceanic event is associated with a fluctuation of the intertropical surface pressure pattern and circulation in the Indian and Pacific oceans, called the Southern Oscillation. This coupled atmosphere-ocean phenomenon is collectively known as El Niño-Southern Oscillation, or ENSO. During an El Niño event, the prevailing trade winds weaker and the equatorial contercurrent strengthens, causing warm surface waters in the Indonesian area to flow eastward to overlie the cold waters of the Peru current. This event has great impact on the wind, sea surface temperature and precipitation patterns in the tropical pacific. It has climatic effects throughout the Pacific region and in many other parts of the world. The opposite of an El Niño, event is called La Niña (IPCC, 2001a).

(4) Irrigation water supply is influenced by changes in the volume of water supplied by precipitation as well as by temperature alteration effects on evapotranspiration.

Antle (1995) highlighted that another significant effect of climate change on agriculture could be changes in the incidence of pest and diseases. Higher temperature and rainfall are favourable for the presence of pest and diseases. In warmer regions pests multiply faster impacting negatively crops.

3.4 Economic and social impacts of climate change on agriculture

In addition to its agronomic impacts, there will be socio-economic consequences of climate change impacts on the agricultural sector. The likely socio-economic effects can be grouped under changes in the following specific inter-related areas:

1. Price of agricultural products
2. Consumer welfare
3. Number of persons at risk of hunger or food security
4. Water and land market
5. Production pattern of countries
6. Comparative advantage and trade structure.

Deke *et al*. (2001) described the economic impacts of climate change as follows: First, climate change impacts will change the productivity of land and this direct effect will lead to a reallocation of resources within the agricultural sector and a change in the price of agricultural commodities. These adjustments on the input and output structure and the accompanying price changes will as a secondary effect change the sectoral allocation. Finally, in an open economy trade will balance the price effects in different world regions by changing the comparative advantage and thus the trade structure. By altering agricultural productivity and decreasing acreage available for agricultural purposes, climate change will decrease food supply leading to a price rise for agricultural commodities *ceteris paribus*. Increasing prices of agricultural goods will lead to changes in relative commodity prices, which in turn affect, the allocation of factors of production between sectors. Due to increasing relative prices for agricultural commodities, the demand for primary factors such as capital or labour and intermediate inputs in the agricultural sector increases.

Higher prices of agricultural products, on the other hand will reduce consumption levels and adversely affect consumer welfare. In general, total welfare tends to decline when supply is reduced. However, in the long run, higher prices stimulate producers to seek ways to increase supply, resulting in new equilibrium of prices and quantities. Climate change will shift the production possibilities of countries and regions. Hence climate change will alter the places in which specific crops are grown, both within countries and internationally, altering patterns of trade in agricultural commodities among regions and countries (McCarl *et al.*, 2001). Thus, shifting production possibilities combined with changing economic conditions and technological innovation will alter the nature of competition for land and water resources. Resulting land use patterns are likely to change domestic patterns of commodity production.

The change in climate is a threat to the sustainability of agriculture by impacting in two interrelated ways. First, climate change diminishes the long-term ability of agroecosystems to provide food and fiber for the world's population. Second, it induces shifts in agricultural regions that may encourage the expansion of agricultural activities into regions now occupied by natural ecosystems such as forests, particularly at mid-and high latitudes. Forced encroachments of this sort may thwart the processes of natural selection of climatically-adapted native crops and others species (Rosenzweig and Hillel, 1995).

Another important effect of climate change is its impacts on food security. Increasing prices is likely to affect a number of people with insufficient resources to purchase adequate amounts of food. Rosenzweig *et al*. (1993) found that the incidence of food poverty increases even in the least negative climate change scenario tested with prices of agricultural products related to the magnitude of the climate change impact. Rosenzweig and Hillel (1995) further argue that even if the overall global impacts of climate change on agricultural production may be small, regional vulnerabilities to food deficits may increase due to problems associated with distributing and marketing food to specific regions and groups of people. For subsistence farmers and more so for people who now face a shortage of food, lower yields may result not only in measurable economic losses, but also in malnutrition and even famine. Rosenzweig *et al*. (1995) estimated the number of people at risk of hunger due to climate change. They concluded that given a continuation of current trends in economic growth rates, partial trade liberalisation and medium population growth, the net effect of climate is to potentially reduce global cereal production by up top 5 percent, and increase the disparities in cereal production between developed and developing countries. Consequently, the number of people at risk from hunger would increase by about 40 to 300 million (6 to 50 percent). Since regional changes in crop yields and productivity are expected to occur in response to climate change, there is likely to be an increased risk of famine, particularly in subtropical and tropical semi-arid and arid locations (Rosenzweig *et al*., 1993).

3.5 The distribution of climate change impacts

The expected effects of climate change on the agricultural sector will not be uniform across continents, within continents and even within countries. The magnitude of the impact of climate change in different regions depends on the initial temperature of the region, the size of the warming, resources endowments, structure and performance of the economy. Projected climate change will have beneficial and adverse effects on both environmental and socio-economic systems, but the larger the changes and the rate of change in climate; the more the adverse effects predominate. The adverse impacts of climate change are expected to fall disproportionately upon developing countries and the poor persons within countries (IPCC, 2001b). In fact, developing countries may be more vulnerable to climate change than developed countries because of the low-capital intensive nature of production, the incomplete markets, the predominance of agriculture and other climate sensitive sectors, and their relatively warm baseline climates.

Mendelsohn and Williams (2002) in comparing forecasts of global impacts of climate change found that estimated impacts in 2100 vary considerably depending on climate scenarios and climate sensitivity. All the models do concur that tropical nations will be hurt, temperate nations will be barely affected, and polar nations will benefit. Regions such as the tropics that are already warm are generally damaged from further warming. Regions, such as North America and Western Europe that have temperate climates, benefit from small warming but get harmed by large warming. Polar regions such as the former Soviet Union, in contrast, benefit from all warming scenarios. Thus, the study suggests large damages in tropical regions, whereas large gains are expected in polar and temperate regions. Mendelsohn and Dinar (1999) also noted that tropical regions in the developing world are particularly vulnerable to potential damage from environmental changes because large areas of these regions are covered by poor soils, which have already made much of the land unusable for agriculture. Small-scale farmers who have little capital will not be able to pursue the new strategies that will be required to adapt to the change in climate.

Among the developing countries of Asia, Latin America and Africa, climate change will also have differential impacts. Winters *et al.* (1996) show in their study that all these countries will lose and that their agricultural outputs will fall, but that Africa will by far the most severely affected. The reasons why Africa will be the most negatively affected are because it has the largest share of its GDP in agriculture, the lowest substitution possibilities between imported and domestically produced cereals, it is the only continent subject to a negative shock in the price of its export crops and it has the lowest elasticities of supply response. Africa is also particularly vulnerable to the impacts of climate change because of factors such as widespread poverty, recurrent droughts, inequitable land distribution and over dependence on rain-fed agriculture. Although adaptation options, including traditional coping strategies, theoretically are available, in practice the human, infrastructural and economic response capacity to effect timely response actions may well be beyond the economics means of some countries (IPCC, 1997).

3.6 Policy implications of climate change: Mitigation and Adaptation

In order to address the expected pressures on agriculture as well as other economic sectors, policy makers have thus far largely focussed on addressing climate change through mitigation options aimed at reducing human induced emissions of greenhouse gases (GHG) and sequestration of carbon (Kurukulasuriya and Rosenthal, 2003). Agriculture is likely to be directly or indirectly involved in climate change mitigation efforts. Hence agriculture is mentioned as both an emitter and a sink of GHG in the Kyoto protocol[6]. Agriculture accounts for about 4.5% warming potential since farmers' activities also contribute to the amount of GHG. IPCC (1996) estimated that global agriculture emits about 50% of total methane, 70% of nitrous oxide and 20% of carbon dioxide. Carbon dioxide emissions from the agricultural sector arise from fossil fuel usage, soil tillage, deforestation, biomass burning and land degradation.

Therefore, agriculture has the potential to diminish GHG through improved agricultural practices aimed at enhancing carbon sequestration such as conservation tillage, crop rotations, management of fallow lands, soil conservation and rehabilitation of degraded lands (Tiwari, 2000). Also, agriculture could be a way of offsetting net GHG emissions by providing substitute products, which replace fuel intensive products. For example biomass can directly be used in fuelling electrical power plants or maybe processed into liquid fuels or cotton and other fibers could be used as substitutes for petroleum based synthetics (Mc Carl *et al.*, 2001).

Moulton and Richards (1990) suggested that agriculture's contribution to meeting future obligations to reduce GHG$_s$ emissions could be much larger than its share of current emissions. They mentioned the benefit of shifting from cropland and pasture to forest by individual farmers. The shift from cropland and pasture to forest could benefit producers but harm consumers since it will result in higher food and fibre prices for consumers (Parks and Hardie, 1996). Recent studies have shown that improved agricultural practices can significantly help in reducing the emission of the carbon dioxide by increasing carbon sequestration (Lal *et al.*, 1998). However, actions to mitigate GHG in the agriculture sector have economic costs. The cost of carbon sequestration in the agricultural sector is estimated to be between $ 10-25 per ton (Tiwari, 2000). Also, food supply capacity may be altered by efforts to reduce GHG as society tries to mitigate future implications of climate change. Thus, economic impacts of climate change on agriculture may well not be related to shifts in

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[6] The Kyoto Protocol of the United Nations Framework Convention on Climate Change (UNFCCC) was adopted at the Third Session of the Conference of the Parties to the UNFCCC in 1997 in Kyoto, Japan. It contains legally binding commitments in addition to those included in the UNFCCC. Countries included in Annex b of the protocol (most OECD countries and countries with economies in transition) agreed to reduce their anthropogenic greenhouse gas emissions by at least 5% below 1990 levels in the commitment period 2008 to 2012. As at 13 November 2002, 84 Parties have signed and 97 Parties have ratified or acceded to the Kyoto Protocol.

temperature and precipitation patterns but also to more immediate effect efforts to mitigate greenhouse gas emissions (McCarl *et al*., 2001).

Mitigation policies for the reductions of GHG even stabilization of their concentrations in the atmosphere at a low level, neither will altogether prevent climate change or sea-level rise nor prevent their impacts (IPCC, 2001c). Therefore, adaptation becomes a necessary strategy at all scales to complement climate change mitigation efforts. The consequences of climate change-induced agricultural productivity impacts will be, to a great extent, determined by human adaptations (Mc Carl *et al*., 2001). Adaptation is defined here as actions undertaken by individuals, firms and governments that either ameliorates the harmful effects of climate change or capitalise on the beneficial opportunities arising from climate change. Different regions and types of farming are likely to respond differently to climate change. The adaptive capacity of each region or each country will be determined by the following factors: range of available technological options, resources and their distribution, the structure of critical institutions, the stock of human capital, property rights, the system's access to risk spreading processes, the ability of decision-makers to manage information and make decisions, and the public's perception of attribution (Mendelsohn, 2001a). The region or country that would be able to adapt to future climate change will lessen the effects of climate change on agriculture.

Recent studies consistently predicted that in the United States of America (USA) agricultural systems will readily adapt to climate change, by introducing new technologies, new crop varieties, and cultivation practices, so leading to minimal changes in yields and net profits. That means, American agriculture will be resilient to climate change. In contrast, the low adaptive capacity of developing countries makes them the world potentially most vulnerable to climate change. Many agronomic studies predict large agricultural losses in developing countries. However, when studies considered that adaptation mechanisms exist, global warming was not likely to reduce dramatically aggregate productivity in developing countries (Mendelsohn and Dinar, 1999; Rosenzweig *et al*., 1995).

Adaptation can happen at the farm or government levels. At farm level, adaptation is made by changing planting and harvesting dates, crop rotation, crop mix, crop varieties, switching to a different crop and changing to non-agricultural activities. Governments could contribute to mitigating climate change effects by monitoring and publishing climate data, developing climate forecasts and investing in strategic research on how to adapt to climate change. The government could thereby set the stage for private actions and be an active agent by reallocating water supplies, modifying water and transportation infrastructure and developing breeding programs for new crops and animals (Mendelshon, 2001a; Smith and Lenhart, 1996). Kurukulasuriya and Rosenthal (2003) categorise adaptations' options in agriculture into four types:

1. **Micro level options** that include farm production adjustments such as diversification and intensification of crop livestock production; changing land use and irrigation, and altering the timing of operations.
2. **Market responses** that include development of crop and flood insurance schemes, innovative investment opportunities in crop shares and futures, credit schemes, and income diversification opportunities.
3. **Institutional changes** mainly government responses that include pricing policy adjustments such as the removal of perverse subsidies, development of income stabilization options, agricultural policy including agriculture support and insurance programs; improvement in agricultural markets, and broader goals such as the promotion of inter-regional trade.
4. **Technological developments** consist of the development and promotion of new crop varieties and advances in water management techniques (e.g. irrigation, conservation tillage).

3.7. Measurement of climate change impacts on the agricultural sector

According to Mendelsohn (2000), three methods have been developed in the literature to measure the climate sensitivity of the agricultural sector: cross-sectional models, agronomic-economic models (AEM) and agro-ecological zone (AEZ) models. These methods are based on two basic approaches for evaluating crop and farmer response to changing climate: (1) structural modelling of the agronomic response of plants and the economic/management decisions of farmers based on theoretical specifications and controlled experimental evidence; and (2) reliance on the observed response of crops and farmers across landscape and climatic zones.

3.7.1 Structural modelling of the Agronomic Response

This approach is considered as a "production function approach" since it is based on climate-yield relationships, i.e. it explains the impact of climate change on agricultural production. This approach takes an underlying production function and estimates impacts by varying one or a few climate input variables, such as temperature, precipitation, and level of carbon dioxide. The measurement of the climate-yield relationship is based on survey or experimental data. However controlled experiments are the most commonly used source. Sufficient structure and detailed data are needed to represent specific crops and crop varieties, which respond to different climatic conditions. Detailed information on farm management such as, the timing of field operations, crop choices, and how these decisions affect costs and revenues of the farmer are also needed. This approach typically models a representative crop or farm by implicitly incorporating a crop response function. One of the criticisms of this approach is that while providing a useful baseline for estimating the impact of climate change on farming, the approach has an inherent bias and will tend to overestimate the damage. It is also indicated that the bias of the production function approach arises because it fails to allow for economic substitution as conditions change. (Mendelsohn *et al.*, 1994) The production function approach can be classified into two broad models: Agronomic-economic models and Agro-ecological models.

3.7.1.1 Agronomic-economic models (AEM)

The Agronomic-economic method is implemented in two steps: the agronomic modelling and the economic modelling. The agronomic or crop modelling assesses how a crop responds to changing conditions of its environment. In this first step, environmental variables are used in estimating crop yields and outputs functions. In the second step, crop yield functions are then fed into an economic model as inputs to measure the aggregate impact under different settings.

The determination of climate-yield relationships can be done at different levels of sophistication using descriptive methods, regressive methods and crop simulation approaches (Smith, 2002). Crop simulation models attempt to describe crops' behaviour (physiological development) as a function of environmental conditions. Typically, crop simulation models incorporate several components or sub-models and include the crop physiologic and phonological development processes. The model accounts for photosynthetic, assimilation, partitioning and respiration and root growth and the water balance processes that simulate the way water from rain or irrigation infiltrates the soil, is taken up by the roots for transpiration and percolates to deeper layers. Through repeated experiments, agronomists have developed and calibrated models, which forecast yield of specific crops for different weather patterns (Adams *et al*., 1989; Rosenzweig and Parry, 1994). Several crop simulation models have been developed worldwide: CERES (Hawaii), CROPSYST (Washington), WOFOST_SWAP (Wagenn), SARAH (Montpellier), SWB (Pretoria), APSIM (Australia), CROPWAT and CROP Yield Forecasting (Food and Agriculture Organisation (FAO)). These simulation models have been successfully used in a wide number of past studies (e.g. Easterling *et al*., 1993; Rosenzweig *et al*., 1995; Makadho, 1996; Du Toit *et al*., 2002; Tubiello *et al*., 2000; Iglesias *et al*., 2000).

Crop simulation models are preferred over the regressive or descriptive methods because they are more accurate and versatile. Also, the predictions and simulations of crop growth models in measuring biological responses are valid under a wide range of conditions and outside the calibration range. However, these models are complicated because they deal with the complex physiological relationships between crop and climate. Moreover, they are ecological and management sensitive. Because each crop requires extensive experiments, the model has been applied to only major crops, with the exception of the work of Adams *et al*. (1998), which included crops other than grains (Mendelsohn, 2000). Also, due to the cost implication of these experiments they can only be applied to few locations. For aggregate analyses, inferences must be made from relatively few sites and crops to large areas and diverse production systems.

To translate biological responses (yield impacts) into measures of economic and welfare impacts, crop simulation results are then integrated into economic impact assessment models. Two types of economic models are commonly used for this purpose: partial equilibrium models looking at specific sectors, sub-sectors or commodities and economy-wide models for assessing impacts on the overall economy. The economic models associated with the assessment of climate change impacts in the literature are:

A. **Partial equilibrium models**. The most common partial equilibrium models used in assessment of climate change impacts, particularly to assess the impact on the agricultural sector are the normative mathematical programming models (Erasmus *et al.*, 2000; Chang, 2002) and the spatial equilibrium models of the agricultural sector (Adams *et al.*, 1999; Chen, McCarl and Adams, 2001).

B. **Computable General equilibrium (CGE) Models**, which assess the economy-wide impacts of climate change. CGE models are based on a system of linear and non-linear equations that are solved on computer to stimulate equilibrium. The principal advantage of using CGE models in policy analysis is that they permit taking into account interactions between many economic activities throughout the economy in a consistent manner. Examples of this group of models assessing the impact of climate change on agriculture include: Winters *et al.* (1996); Yates and Strzepek (1996); Nordhaus *et al.* (1996); Deke *et al.* (2001).

C. **The Basic Linked System approach**, which is a tool for analysing agricultural policies and food system prospects in an international setting. It is an applied general equilibrium (AGE) model system. The model views national agricultural systems as embedded in national economies, which interact with each other through financial flows and trade at the international level. The national models linked in the Basic Linked System cover about 80% of the most important attributes related to the world food system, such as population, land, agricultural production, demand, and trade. Several applications of the Basic Linked System to climate –change impact analysis have been published (Rosenzweig and Parry, 1994; Fischer *et al.*, 1996; and Parry *et al.*, 1999).

According to Mendelsohn (2000), agronomic-economic models have dependable predictions of how climate affects yields because crop yields are determined through controlled experiments. Therefore, the results from such models are more accurate and can isolate climate change impacts from other impacts. However, one problem with this approach is that estimates do not control for adaptation and ignore adoption of new technologies. Thus, results from studies adopting the agronomic-economic model can exaggerate the impact of climate change on agriculture by not taking into account the possibilities of private adaptation to climate change. This bias of the model has been called the "dumb farmer scenario" (Mendelsohn *et al*., 1994).

3.7.1.2 Agro- Ecological Zones models

The agro-ecological zones (AEZ) methodology is promoted at national, sub-national and international levels to assess agricultural production potentials across various ecological zones. The main objective of this model is to determine crop suitability areas. The AEZ methodology for land productivity assessment follows an environmental approach; it provides a framework for establishing a spatial inventory and database of land resources and crop-production potentials. This land-resources inventory is used to assess, for specified management conditions and levels of inputs, the suitability of crops/Land Utilization Types (LUT) in relation to both rain-fed and irrigated conditions, and to quantify expected production of cropping activities relevant to the specific agro-ecological context (Fischer *et al*., 2002).

Like the Agronomic-economic approach, the AEZ model developed by FAO (1992) relies heavily on natural science relationships. However, instead of taking an agronomic approach, the AEZ model develops a detailed ecophysiological process model. The AEZ uses a simulation of crop yields, rather than measured crop yields (Mendelsohn, 2000). Yield potential for a specific production area is estimated using a yield biomass simulation model. The yield biomass model uses information such as radiation and temperature for a specific growing site, along with photosynthetic capacity of crops, and certain economic variables that influence yield to generate an estimate of the maximum attainable yield for the specific zone. The estimated maximum potential yield is adjusted to reflect the different levels of technology, agro-climatic factors such as growth, water stress, presence of crop pests and diseases. In its original form, the model was not aimed at assessing climate change impacts, however it can be used to look at the impact of various aspects of climate change on potential crop production over a wide geographic area. The AEZ model can simulate the impacts of changing precipitation and cloud cover on potential crop production, and to a lesser extent simulate impacts of temperature changes. Similar to the agronomic economic model, economic variables can be integrated in the model through an optimisation component to perform economic analysis.

According to Mendelsohn (2000), one of the strengths of this model is the coverage of developing countries, where little climate change research has been done and where data constraints may preclude the use of other methods. Adaptation to climate change specific impacts can also be captured in the AEZ model by generating static scenarios through the definition of Land Utilization Types (LUT). By using detailed ecophysiological relationships, the model has the advantage to model future technology and genetic strains if their impact on specific parameters were known. However, the disadvantage of this modelling process is that one cannot predict final output without explicitly modelling all relevant components.

3.7.2 Observed Response Models: Cross sectional methods

This approach relies on the observed responses of crops and farmers. The simplest method is to observe the current climatic boundaries of crops and to redraw these boundaries for predicted changes in climate. Researchers have applied statistical analysis of data across geographic areas to separate climate from other factors such as for example, different soil quality, and varying economic conditions, to explain production differences across regions, and used these data to estimate the potential impact of climate change on agriculture. Two models rely on this analogous regions concept: the "Ricardian" method and the "Future Agricultural Resources Model: "FARM".

3.7.2.1. The Ricardian Approach

The cross-sectional model is based on observed response of crops and farmers to varying climate, i.e. it uses actual observations of farm performance in various climatologic regions (Mendelsohn *et al.*, 1994, Mendelsohn and Dinar, 1999; Sanghi *et al.*, 1998; Kumar and Parikh, 1998; Ouedraogo, 1999; Mendelsohn, 2001b; Balti and Zekri, 2002). This is also called the Ricardian approach. Specifically, the method examines farm performance across different agro-climatic zones. It measures how long term farm profitability varies with local climate while controlling for other factors.

Mendelsohn *et al*. (1994) noted that climate variables have a quadratic relationship with farm value and that climate could be captured by seasonal measures from evenly spaced months. The study found that it was important to control for other variables that could explain spatial farm values. Some of these effects could be dealt with by including a battery of control variables capturing soil and economic effects. Moreover weighting was also required to capture heteroskedasticity and to remove the undue influence of cities on farm value. Two types of weights were explored by Mendelsohn *et al*. (1996). One approach focused on land use and used the percentage of land under crops as a weight. The other focused on production and used the magnitude of crop gross revenues as the weight.

Mendelsohn *et al*. (1996) relied on aggregate farm value per area of land in a county instead of using farm value per acre as the dependent variable. This change in the dependent variable allowed exploring the effect of climate not only on the value of existing farms but also on the probability that land would be farmed. Also, a modified version was applied to Indian and Brazilian agriculture (Sanghi and Mendelsohn, 1999). In the case of India annual net revenue was used instead of land prices, whereas in the case of Brazil farmland values were used.

The Ricardian method has received a number of criticisms. The approach assumes that the way that farmers respond to alternative climates over space is the same way that farmers will respond in the long run to those same climates over time. However, this assumption may not hold if important variables that are likely to be correlated with climate have been omitted. In fact, farms may differ greatly within the area of analysis. The differences may not be due to climate but other factors such as farm management due to different level of education etc. Thus the main issue of this method is how to control for unwanted variations. Darwin (1999) also pointed out that this method does not take into account water supply and availability. The Ricardian method estimates assume that the only limiting factor to agriculture is the climate. However, the problem of water cannot be handled properly without using a sophisticated hydrological-economic model (Mendelsohn, 2001b). 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. According to Sanghi *et al*. (1998) the Ricardian method is more reliable for estimating impacts of small changes in climate because of the assumption of unchanged relative crop prices. In fact it is reasonable to assume constant prices. Due to the predicted moderating effects of climate change on international market, aggregate world supply will not 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).

In spite of the criticisms, the Ricardian model has its own merits. The Ricardian approach has the flexibility to incorporate private adaptation, which will allow the farmer to modify the operational environment to increase profit, for example, change crop due to climatic conditions since each crop is suited for a different climatic condition. The Ricardian model can be adopted to evaluate country level as well as regional level impacts, and with modification it can be used to address many questions that arise such as ones concerning private adoption. Moreover, the model does not depend on controlled experiments. In this model it is possible to measure the direct impact of climate on farm income or revenue as well as the indirect substitution effects of different inputs and the potential adaptations to different climates.

3.7.2.2 The Future Agricultural Resources Model: FARM

Another method that accounts for farmer adaptation in response to global climatic change is named the Future Agricultural Resources Model (FARM) and has been promulgated by Darwin *et al.* (1994). FARM is based on the same concept of the Ricardian method, which suggests that similar climates mean similar production practices to implicitly capture changes in crop or livestock outputs, production inputs or management practices that farmers are likely to adopt under new climatic conditions. Darwin *et al.* (1994, 1995, 1996) used geographic information system (GIS) to empirically link climatically derived land classes with other inputs and agricultural outputs in a computable general equilibrium (CGE) economic model of the world. FARM provides estimates of economic impacts that fully account for all responses by economic agents under global climate change as well as estimates of land rents.

Similar to the Ricardian approach, FARM simulates immediate farm-level adaptations to climatic changes while by-passing crop growth models (Darwin *et al*., 1994, 1995 and 1996). Instead of direct econometric estimation, however, the FARM framework uses a GIS to link climatic variables with agricultural production and land rents. FARM divides the world into twelve geographic regions. While the FARM analysis may have gone one step beyond the Ricardian analysis by simulating additional interactions between farmers and downstream consumers (both domestic and foreign) of agricultural products that are likely to occur under climatic change, it suffers from some limitations. First, the FARM as it has so far been applied relies on aggregate data. In fact, climate is captured by six land classes (LCs) defined by length of growing season, which may affect the sensitivity of land rents to changes in climatic variables at grid levels. Furthermore, the downscaling of this method at country level may be problematic since some countries may be covered by only one or two grids. Another important limitation of FARM is that the model does not capture the seasonal effects of climate change.

3.8 Empirical studies of climate change impacts on agriculture

In this section a brief review of empirical studies, which have predicted impact of climate change on agriculture, is provided. The review is organised in three subsections. First, studies, which have predicted the impact of climate change on agriculture in developed countries, are discussed, followed by those which have evaluated the impact in developing countries and studies of climate change impacts on agriculture in South Africa are reviewed in the last section.

3.8.1 Climate change impacts literature in developed countries

Extensive literature exists on the impacts of climate change on agriculture in developed countries. Generally, the early studies on vulnerability of the agricultural sector to climate change (Newman, 1980; Rosenzweig, 1985; Parry *et al*., 1988; Adams *et al*., 1989) used the experimental approach, the so-called the "production function approach". They predicted quantitative estimates of temperatures and rainfall changes on crop yields through crop simulation models. Most studies have used a limited set of climate scenarios in which global temperature increases ranged from about 2.5^0 C to 5.2^0 C. The Ricardian method has been employed and many studies have incorporated "adaptation" scenarios in the experimental approach in recognition of adaptation as a vital component of studying the impact of climate change (Adams *et al.*, 1990 and 1995; Kaiser *et al.*, 1993; Easterling *et al.*, 1993; Mendelshon *et al.*, 1994; Mendelshon and Dinar, 1999; Skinner *et al.*, 2001). Most studies predicted that the impacts of climate change on developed countries' agriculture would vary from a modest negative to a net positive. The predicted impacts of climate in the developed countries range from -2% to +5% of agricultural value.

An example of agronomic studies is Adams *et al.* (1990), which analysed the effects of climatic conditions on farmer input and output choices in the United States (U.S.). With CO_2 fertilization and trade effects they found net gains of $9-10.8 billion. Another study by Adams *et al.* (1995) using recent GCM forecasts, improved plant science and water supply data and refined economic modelling capabilities reassessed the economic consequences of long-term climatic change on U.S. agriculture. The yield enhancing effects of atmospheric CO_2 are an important determinant of potential economic consequences. Inclusion of changes in world food production and associated export changes generally has a positive effect on U.S. agriculture. As with previous studies, the magnitude of economic effects estimated here is a small percentage of U.S. agricultural value. Similar micro level studies based on other countries have also been completed. Alexandrov and Hoogenboom (2000) conducted a study on the impact of climate change on maize production in Bulgaria using a crop simulation model. With regard to changes in climatic conditions they concluded that precipitation was sensitive to climatic behaviour whereas air temperature was not significantly affected. The results indicate decreased precipitation, which limits the growth, development and yield of maize.

Results from studies using the Ricardian model concluded that American Agriculture would not suffer large damages from climate warming over the twenty-first century. With mild climate scenarios, warming will most likely lead to large benefits in the agricultural sector. These benefits will not be evenly spread across the United States but rather will be concentrated in the Midwest and Northern Plains. Some regions especially the Northwest and the Southwest are likely to suffer damages from warming. In their analysis, the economic effects of farm level adaptation were included without having to enumerate specific adjustments. The observations for the analysis were at county level and several grain crops were considered (Mendelshon *et al*., 1994 and 1996; Mendelshon, 2001).

3.8.2 Studies on climate change impacts on Agriculture in developing countries

Summarizing the results from IPCC studies on climate sensitivity of agriculture across the globe, the conclusion is that there will be a negative impact on agriculture. Out of 43 studies surveyed for Africa, South Asia, China and Latin America, 25 have concluded negative impacts and 6 positive impacts. Downing (1992) assessed the impact of climate change on four countries: Zimbabwe, Kenya, Senegal and Chile employing a variety of methods and giving attention to the definition of vulnerability. Data on numerous non-climatic factors such as the socio-economic setting, trade issues, institutional structures and geography were used to examine current vulnerability, risk of recent and future climatic variations and responses to reduced present vulnerability and improved resilience to future risks. Downing (1992) found that climate change would have mixed impacts between and even within developing countries. Some high potential areas, such as the highlands of Kenya, could benefit from warming, whereas with a 2^0 C increase in temperature, the core agricultural zone decreases by a third in Zimbabwe. Farmers in the studied zones are already vulnerable in terms of self-sufficiency and food security and are expected to be further marginalized due to increased risk of crop failure.

In South Asia, specifically in India, using crop modelling approach, Rosenzweig and Parry (1994) found that extensive warming could cause significant reductions in yields in the absence of adaptation and carbon fertilization. Grain yields would fall in India by 25-40 percent if temperatures rise by 4^0 C. Similarly in a crop-simulation study, Rao and Sinha (1994) estimated that wheat yields could decrease by 28% to 68%.

Sanghi and Mendelsohn (1999) have also applied the Ricardian approach to India, regressing annual net revenues on climate, soil and other control variables such as tractors per hectare, percentage of farm area under HYV, soil topology, as well as literacy. Temperature proved to be more harmful than rainfall and had higher impact with a decrease of approximately 4% in net revenue due to 2°C increase in temperature. On the other hand, Kumar and Parikh (1998) using the same Ricardian approach for India, predicted changes of -7% to +19% in net farm income with 2°C increase in temperature.

In Africa, most of the agronomic studies focused on Southern Africa (Kurukulasuriya and Rosenthal, 2003). Muchena (1994) explored the impact of climate change on maize production in Zimbabwe, and found that a 2^0 C rise in ambient temperature led to very low yields. A similar result was observed even when the positive physiological effects of higher atmospheric carbon dioxide were taken into account. Using CGM and the dynamic crop growth model CERES- maize to assess the potential effects of climate change on corn in Zimbabwe, Makadho (1996) found that under both irrigated and non-irrigated conditions, in some regions, maize production is expected to decrease significantly by approximately 11-17 percent. Increments in temperature that shorten the crop growth period, especially in the grain filling period, are underlined as the primary cause of crop reductions. Munalula *et al.* (1999) addressed regional impacts of climate change in Zambia and found that a decrease in net revenue per hectare in various regions in Zambia would be between 60% and 100% depending on the region and climate scenario. The study done in Kenya by Fisher and Van Velthuizen (1996) found that Kenya's national level of food productivity potential would increase with higher levels of atmospheric carbon dioxide, but the impacts may intensify regional disparities. Based on the Basic Link System of a National Agricultural Model (IBSNAT) Yates and Strzepek (1998) explored how climate induced changes in water resource availability, crop yields, crop water use, land resources and global agricultural markets affect Egyptian agriculture. They found that with adaptation GDP would grow by 0.7% whereas without adaptation climate change would cause a decrease in GDP by 6.2%.

Few studies in Africa have used the Ricardian Approach to assess the vulnerability of agriculture to climate change. In a study of the south-western region of Cameroon, Molua (2002) explored the impact of climate variability on agricultural production analysing farm household level data. The results suggest that precipitation during growing and adaptations including change in tillage and rotation practices and change in planting and harvesting dates positively correlate with higher farm returns. In addition, Molua (2002) found that irrigation in the growth period, especially during dry spells, was very important for productivity. Balti and Zekri (2002) examined the economic impact of climate change on agriculture in Tunisia using cross-sectional regional data over 8-years period. Assuming CO_2 doubling, as well as increase in temperature of 1.5^0 C and 7% increase in rainfall, their results pointed out that Tunisia is likely to suffer losses in agricultural production of 7% to 22%. The authors submit that primary crop production areas in the non-coastal regions are likely to experience a reduction in revenues.

3.8.3 Studies on climate change impacts on Agriculture in South Africa

Limited numbers of studies have assessed the impact of climate change on agriculture in South Africa. Both the "production function" and the "cross-sectional" approaches have been used. In general, climate change was predicted to have negative impacts on South African agriculture.

Using a CERES-maize model, Schulze *et al*. (1993) assessed the potential production of maize under different climatic conditions taking into account the effects of increasing carbon dioxide concentrations and consequent expected increases in temperature. Changes in precipitation are not considered given the uncertainty of predicted changes. The results pointed an overall increase in potential maize production with the varied intensity across geographic sites. In areas yielding at least 8 tons/ha, elevated temperatures and carbon dioxide concentrations fail to increase yields significantly. Under lower yield conditions (4-8 t/ha), there is an expansion into areas previously yielding below 4t/ha. Soil water availability is a key variable and accounts for a fair amount of this geographic variability.

In contrast, using the same Ceres-Maize crop simulation model, Du Toit *et al*. (2002) found that South African maize yield is vulnerable to fluctuations in seasonal precipitation. Four potential climate scenarios were tested for nineteen individual sites representing most of the current maize production area. The results showed that maize yields will either remain at current levels or decrease ten to twenty percent according to the climate scenario used. Some of the marginal western areas may become unsuitable for maize production under current management strategies while some of the eastern production areas may remain unchanged or increase production levels.

The two cited studies gave reliable results in terms of the relationship between yield and climatic variables because they were based on crop modelling. However, a question that arises is whether the experiment (choice of only few sites) is really representative of the entire agricultural sector. Also, as stated early the crop system is constant, thus farmer behaviour is largely ignored, that is, private adaptation is not addressed. The agronomic model ignores new production technologies. Moreover, these studies focus only on maize crop and fail to incorporate economic indicators.

Erasmus *et al.* (2000) used a sectoral mathematical programming model by incorporating predicted climate change, specifically rainfall, on the GCM to determine the effects on key variables of the regional farm economy of the Western Cape in South Africa. They found that climate change would lead to lower precipitation, which implies that less water will be available to agriculture in the Western Cape. This will have a negative overall effect on the Western Cape farm economy. According to the study, climate change will lead to a relative shift away from intensive production sectors in agriculture towards more extensive systems. Both producer welfare and consumer welfare will decrease. Total employment in the farm sector will also decrease as producers switch to a more extensive production pattern. Total decline in welfare, therefore falls, disproportionately on the poor in the province. Although this study is a first attempt of economic analysis of climate change impact on various crops in South Africa, the study covered only one province and did not also control for farmers' adaptation.

Two recent studies used the Ricardian approach to account for farmers' adaptations in analyzing the impacts of climate change on agriculture. Poonyth *et al.* (2002) explored the agriculture sector performance with respect to climate change by including several crops and covered the whole country. They found that an increase of 2^0C in average temperature decreases agricultural net revenue hectare by 25%. On the other hand, Deressa (2003) studied the impact of climate change on South African sugarcane production. His results indicated that climate change reduces sugarcane production net revenue per hectare and that sugarcane production in South Africa is more sensitive to future increases in temperature than precipitation. While these studies accounted for spatial variability in responding to climate in different productions regions, by using time series data, especially yearly climate data, their results may reflect more weather variations impacts on agriculture revenues than long-term climate change impacts. Moreover, Poonyth *et al.* (2002) study suffered from the same criticism levelled against earlier Ricardian studies of agriculture for the non-inclusion of water supplies and availability in the analysis. While Deressa (2003) incorporated irrigation as other source of water in his study, the study may have put significant weight on climate influence on agriculture because of the fact that the study area covered only one agro-ecological zone, the subtropical wet region.

Conclusion

The above literature review 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. Consequently this will induce a reallocation of resources within the agricultural sector and a change in the price of agricultural commodities, altering the structure of the economy of numerous countries and the international trade pattern.

Secondly, there are numerous empirical studies on climate change impacts on agriculture across the world. Most of them have been conducted in the developed world. The quantitative estimates of these studies have been based in two main approaches: the experimental and the cross-sectional. The results suggest that the effects of climate change will not be uniform across the globe. Developed countries will be less affected by climate change. However, in developing countries where the effects of climate change are predicted to be greater, only few studies have been done. Thus, the literature on climate impact assessment in developing countries has not provided a clear picture of what will be the consequences of climate change for the agricultural sector.

Specifically in South Africa, climate impact' studies on agriculture are limited, focused mainly on maize and applied mainly the experimental approach. Although the experimental approach has the advantage of reliable results in terms of 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. Indeed adaptations to climate change are a crucial element in climate change issues and could not be ignored. The Ricardian approach, on the other hand, can be easily adopted to evaluate country level as well regional level impact, and with modifications it can be used to address farmers' adaptations strategies. Thus, the present study will accordingly apply the Ricardian model to measure the economic impact of climate change on filed crops in South Africa.

So far only two studies have applied the cross-sectional (Ricardian) approach (Poonyth *et al.*, 2002 and Deressa, 2003) in assessing the economic impact of climate change in South Africa. The present study intends to extend the Poonyth *et al.* (2002) and Deressa (2003). More precisely, this study intends to re-examine the results of Poonyth *et al.* (2002) study by incorporate in the analysis:

(1) Cross-sectional district level data instead of aggregate provincial time series data to capture within province variability

(2) Long-term climate variables instead of yearly climate variables

(3) Irrigation as another source of water and adaptation options.

CHAPTER 4 : THE RICARDIAN APPROACH AND EMPIRICAL MODEL OF CLIMATE CHANGE IMPACTS ON FIELD CROPS IN SOUTH AFRICA

4.1 Introduction

For the assessment of the economic impact of climate change on South Africa's major field crops, the present study adopts the Ricardian approach. The rest of the chapter is organised as follows. Section two will introduce the analytical framework of the Ricardian model. Section three presents the empirical model specification for South Africa. Sources of the used data and collection procedures are discussed in section four.

4.2 The Ricardian approach

4.2.1 Theoretical background

The Ricardian method is an empirical cross-sectional model to studying agricultural production. The method was named after Ricardo[7] because of his original observation that land rents would reflect the net productivity of farmland at a site under perfect competition (Ricardo, 1817 and 1822). Farm value consequently reflects the present value of future net productivity. This method has been developed by Mendelshon *et al*. (1994) to measure the economic impact of climate on land prices in the USA. By regressing farm values on climate, soil and other control variables, the method enables measuring the marginal contribution of each variable to land value. 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. However, in the Ricardian analysis, adaptation cost is 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 and carbon dioxide fertilization.

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[7] David Ricardo was a British economist, who articulated and rigorously formulated the "classical system" of political economy.

The Ricardian approach is based on the following hypotheses (Mendelshon *et al.*, 1994):

1) Climate shifts the production function for crops
2) Farmers at particular sites take environmental variables like climate as given and adjust their inputs and outputs accordingly
3) Farmers operate under perfect competition in both product and input markets
4) The economy has completely adapted to a given climate so that the current land rents have attained the long-run equilibrium that is associated with each site's climate
5) The way that farmers respond to alternative climates over space is the same way that farmers will respond in the long run to those same climates over time

4.2.2 The analytical model

The analytical Ricardian framework assumes a set of well-behaved production functions of the form (Dinar *et al.*, 1998):

$$Q_i = \left(K_i, E\right), \tag{4.1}$$

Where, Q_i is the quantity produced of good i, $K_i = \left[K_{i1},\ldots K_{ij},\ldots K_{iJ}\right]$ is a vector of all purchased inputs in the production of good i; K_{ij} is input j $\left(j = 1,\ldots J\right)$ used in the production of good i, and $E = \left[E_1,\ldots E_m,\ldots E_M\right]$ is a vector of exogenous environmental inputs such as temperature, precipitation, and soils which are common to a production site.

Given a set of factor prices w_j for K_j, E, and Q, cost minimization leads to the cost function:

$$C_i = C_i\left(Q_i, w, E\right) \tag{4.2}$$

Where C_i is the cost function for the production of good i and $w = \left[w_1,\ldots w_j,\ldots w_J\right]$ is the vector of factor prices.

Given market prices P_i for good i, producer' profit maximization equation on a given site can be specified as:

$$Max\pi = \sum_i [P_iQ_i - C_i(Q_i, w, E) - P_L L_i] \tag{4.3}$$

Where 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 above cost function for all purchased inputs other than land; therefore the full cost function of production of good i is defined as $C_i + P_L L_i$.

Perfect competition in the land market will drive profits to zero:

$$P_iQ_i^* - C_i^*(Q_i^*, w, E) - P_iL_i = 0 \tag{4.4}$$

If the production of good i is the best use of the land given E, the observed market on the land will be equal to the annual net profits from the production of good i. Solving for P_L from the above equation (4.4) gives land rent per hectare to be equal to the net revenue per hectare:

$$P_L = [P_iQ_i^* - C_i^*(Q_i^*, w, E)] / L_i \tag{4.5}$$

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

$$V_L = \int_0^\infty P_{Lt} e^{-rt} dt = \int_0^\infty [(P_{it}Q_{it} - C_{it}(Q_{it}, w, E)) / L_{it}] e^{-rt} \; dt \tag{4.6}$$

The issue of interest to this analysis is measuring the impact of exogenous changes in environmental variables (E) on net economic welfare (ΔW). Consider an environmental change from the environmental state A to B, which induces environmental inputs to change from E_A to E_B. The change in annual welfare from this environmental change is given by:

$$\Delta W = W(E_A) - W(E_B) = \int_0^{Q_B} [(P_{it}Q_{it} - C_{it}(Q_{it}, w, E_B)) / L_{it}] e^{-rt} \; dQ - \int_0^{Q_A} [(P_{it}Q_{it} - C_{it}(Q_{it}, w, E_A)) / L_{it}] e^{-rt} \; dQ \tag{4.7}$$

If market prices are unchanged as a result of the change in E, then the above equation reduces to:

$$\Delta W = W(E_B) - W(E_A) = \left[PQ_B - \sum_{i=1}^{n} C_i(Q_i, w, E_B) \right] - \left[PQ_A - \sum_{i=1}^{n} C_i(Q_i, w, E_A) \right] \tag{4.8}$$

Substituting $P_L L_i = \left[P_i Q_i^* - C_i^*(Q_i^*, w, E) \right]$ from (4.5) into the above equation (4.8):

$$\Delta W = W(E_B) - W(E_A) = \sum_{i=1}^{n} (P_{LB} L_{Bi} - P_{LA} L_{Ai}) \tag{4.9}$$

Where P_{LA} and L_A are, respectively, price and land units at E_A, and P_{LB} and L_B are at E_B.

The present value of this welfare change is thus:

$$\int_0^{\infty} \Delta W_t e^{-rt} dt = \sum_i (V_{LB} L_B - V_{LA} L_A) \tag{4.10}$$

The Ricardian model takes the form of either (4.5) or (4.10) depending on whether the dependent variable is annual net revenues or capitalized net revenues (farm values). The value of change in the environmental variable is captured exactly by the changes in land values across differing environmental conditions. Cross sectional observations, showing spatial variation in normal climate and edaphic factors can hence be utilized to estimate climate impacts on production and land rents.

4.4 Specification of the empirical model

4.4.1 The field crops' climate response model

The standard Ricardian model relies in an implicit form of land value as a function of its determinants (Mendelshon *et al.*, 1994):

$$V = V(F, Z, G) \tag{4.11}$$

Where V is the land value; F is a vector of climate variables; Z set of soil variables and G is a vector of socio-economic variables.

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. Indeed land prices are presumably based on expected future net revenues, therefore the current net revenue is considered as a proxy for expected future net revenue.

4.4.2 Regressors of the model

Net revenue per hectare (NRHA) the dependent variable will be regressed on the following set of regressors: (1) Climate variables: temperature and precipitation; (2) Soil types and (3) Socio-economic variables, e.g. Population, labour, irrigated land and geographical coordinates.

Climate variables will be included in the model in both linear and quadratic terms for monthly temperature (T) and precipitation (R). In the regression the year is subdivided into two main periods, summer and winter. Summer in South Africa corresponds to the period between October to March. Winter extends over April to September. Interaction terms between precipitation and temperature are introduced for each season.

Soil types vary significantly over the various districts of South Africa and hence need to be controlled for in order to isolate climate from other effects. Four soil dummies have been defined and were included in the model.

Population density is also included to control for urban influences on agricultural rent. The number of persons employed on a given farm may influence the productivity of that farm as one element of adaptation. Therefore labour per hectare is included in the equation.

The study also extends the Ricardian model to thoroughly capture the impact of water availability on farm value. It is true that water comes to farms in the form of precipitation and that is already reflected in the Ricardian model. However, farmers have two other sources of water: surface water and groundwater. Because the sources of this additional water can be remote from the farm, the climate at the farm may give little indication of the amount of surface and groundwater accessible to the farm (Mendelsohn and Dinar, 2003). Thus the percentage of cropland that is irrigated is included in the model to compare the climate sensitivity of irrigated land to rain-fed land (Mendelsohn and Dinar, 2003). Geographical coordinates such as District latitude and mean altitude are included in the model as proxies for solar flux and day length respectively. Table 4.1 defines the variables included in the empirical model for the South African field crops.

Table 4-1: Definition of the variables included in the empirical analysis

Variables	Definition
NRHA	Net revenue for district i measured in R/ha
tempSummer	Average temperature in Summer over 30 years (1960- 2000) in degree Celsius
tempSummer^2	Square of average Summer temperature in degree Celsius
tempWinter	Average temperature in Winter over 30 years (1960- 2000) in degree Celsius
tempWinter^2	Square of average winter temperature in degree Celsius
rainSummer	Average rainfall in Summer over 30 years (1960- 2000) in millimetres
rainSummer^2	Square of average Summer rainfall in millimetres
rainWinter	Average rainfall in Winter over 30 years (1960- 2000) in millimetres
rainWinter^2	Square of average winter rainfall in millimetres
Temp*Rain Summer	The interaction term between temperature and rainfall for summer
Temp*Rain Winter	The interaction terms between temperature and rainfall for winter
Popd	Population density measured in inhabitants per km^2
Popd^2	Square population density
Soildum1	Soil type 1, takes the value of one if the soil is the red-yellow latosols well drained soils and zero other wise.
Soildum2	Soil type 2, takes the value of one if the soil is plinthic catena and zero other wise
Soildum3	Soil type 3, takes the value of one if the soil is with a strong texture contrast or with high clay content and zero otherwise.
Irrigation	Intensity of irrigation in district i, represents the share of total cultivated land, which is irrigated in a given district.
labour	Number of farm workers employed in a given district
latitude	Measured in degree centigrade
altitude	Measured in meters

4.4.3 Sources of the data

The study used district level data on crops' revenues and other variables of the model. Data on seven crops from 300 districts 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 yields, input costs and output price for each of the seven field crops were provided by the Census of Agriculture 1993 from the National Department of Agriculture (SSA, 1998). However, for sugarcane, data were from the Sugar Cane Growers' Association of South Africa. The data used in this study were secondary data and focus mainly on the commercial agricultural sector.[8]

For each district, net revenue was calculated as the value of production of the seven crops minus total farm expenditure on inputs and labour used:

$$NRHA^d = \sum_{i=1}^{7} \left[\left(P_i Q_i \right) - C_i \right] / TA^d \tag{4.13}$$

Where d refers to districts (1, …, 300) and i refers to crops (1, ..., 7), $NRHA^d$ is the net revenue per hectare for district d. P_i and Q_i are output prices and output quantities for crop i. C_i^d is the total expenditure on inputs and labour for crop i in district d. C_i^d was estimated by using the commercial enterprise budgets for each crop per district, published annually by the provincial departments of agriculture (COMBUD, 1993).

District total area under the seven crops (TA^d) was calculated as:

$TA^d = \sum_{i=1}^{7} A_i$ Where A_i is the area planted to crop i.

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[9] climate variables based on 30 years averages of temperatures and

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[8] Although, it is well known that the subsistence-farming sub-sector is the most vulnerable to climate change since it does not have much in terms of crop substitutability and also limited ability to adapt, this study could not include this sub-sector due to lack of data. The subsistence-farming sector however, contributes about 10% of the total value added in South African agriculture (NDA, 2000).

[9] The normal climate is defined in climatology as 30-year average climate.

precipitation observed over the period 1970-2000. Indeed, normal climate variables are used instead of yearly climate variables because the analysis focus on the long-run impacts of precipitation and temperature on agriculture, not year to year variations of weather (Mendelshon *et al.*, 1994).

The information on climate variables provided by NWBSA was gathered at 74 weather stations across South Africa. Since the units of analysis in the study are districts, Geographical Information Systems (GIS) methods have been used to identify weather stations that can describe the climate for each district. The climate variables of weather stations within a given district have been averaged over to describe the district temperature and rainfall.

Data on population for the year 1993 (year of the analysis) were deducted from the 1996 Population census of the Department of Statistics South Africa by discounting the 1996 population numbers by the South African population annual growth rate of 1.5% (SSA, 2002b). 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 & Water (ISCW) and The Agricultural Research Council (ARC).

Soil type 1: is the category of the red-yellow latosols, well drained soils lacking a strong texture contrast. These soils are deep with no clear horizon boundaries. The physical properties of these soils are good. They have rapid infiltration and low water holding capacities. They are very low in plant nutrients as very weatherable materials are found.

Soil type 2: is the category of soils within a plinthic catena with red yellow and greyish soils. This category is composed of low medium base status or high base status. The water holding capacity is low with rapid infiltration. These soils are poor in organic carbon and phosphor content.

Soil type 3: is the category of black to very dark grey brown with high clay content. These soils are very productive. Drainage is poor and soil reaction is neutral.

Soil type 4: is the category of greyish, sandy well-drained soils with high base status. The texture is fine sand to coarse sand. Infiltration is rapid. These soils enable the growth of deep-rooted crops. Soils are very low in soil organic matter and plant nutrients. Generally, crops can be grown with high management.

As noted earlier, the Ricardian model could be applied at country level if there is sufficient spatial variation in net revenue and climate variables across the country. In South Africa, the level of net revenue per hectare seems to be highly correlated with variations in climate patterns across the country. Figure 4-1 presents the distribution of the field crops' net revenue hectare across South Africa for the 300 districts. Kwazulu Natal and Mpumalanga appears to be the most valuable agricultural regions whereas Limpopo and the North West the least valuable regions. It is apparent from Figure 4-2 to Figure 4-5 that the most valuable regions are the hottest and wettest regions. Thus, high temperature and abundance of rainfall may be beneficial to field crops' net revenues.

Figure 4-1: Net revenue Hectare in South Africa by district (1993)

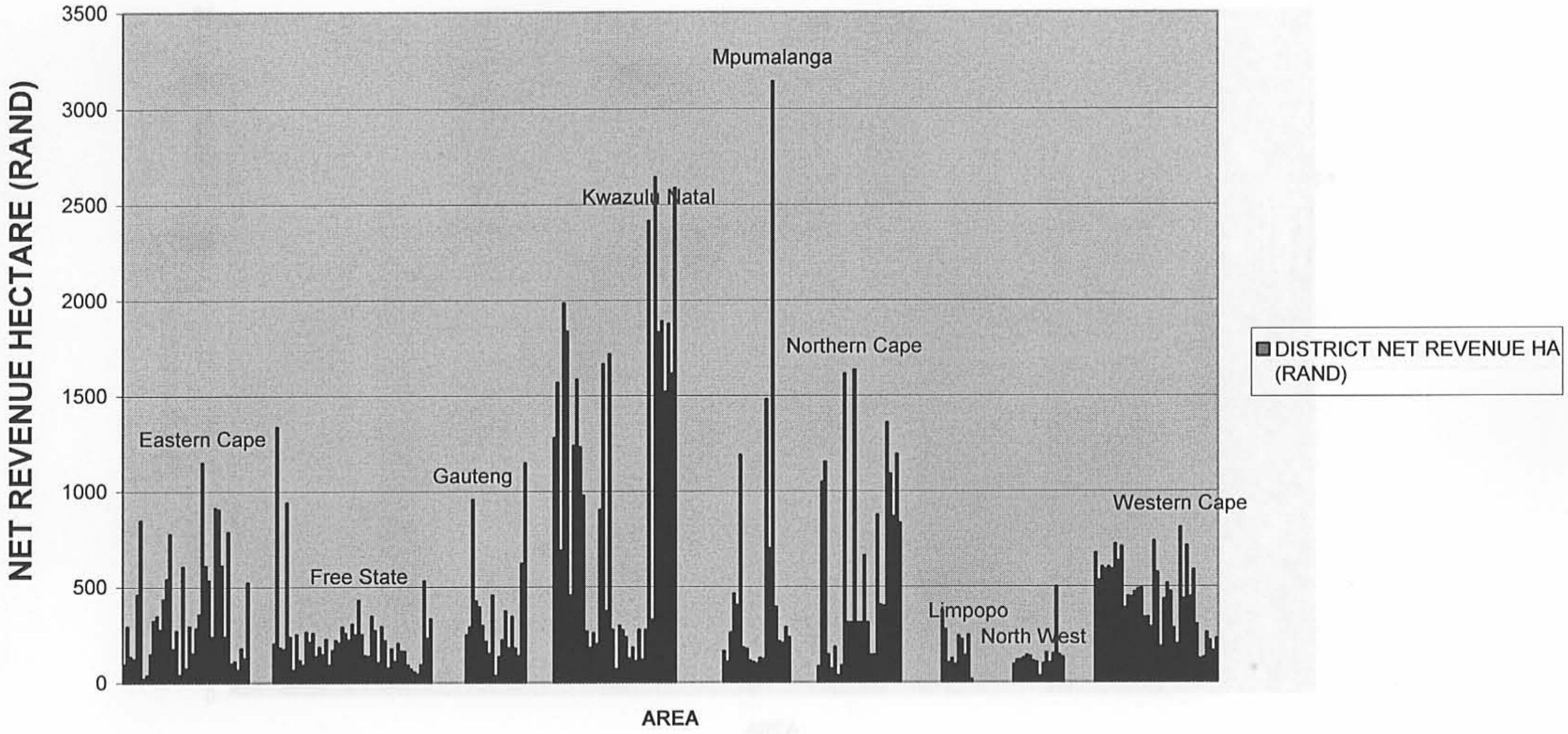


Figure 4-2: Average Summer Temperature in South Africa by district (1970- 2000)

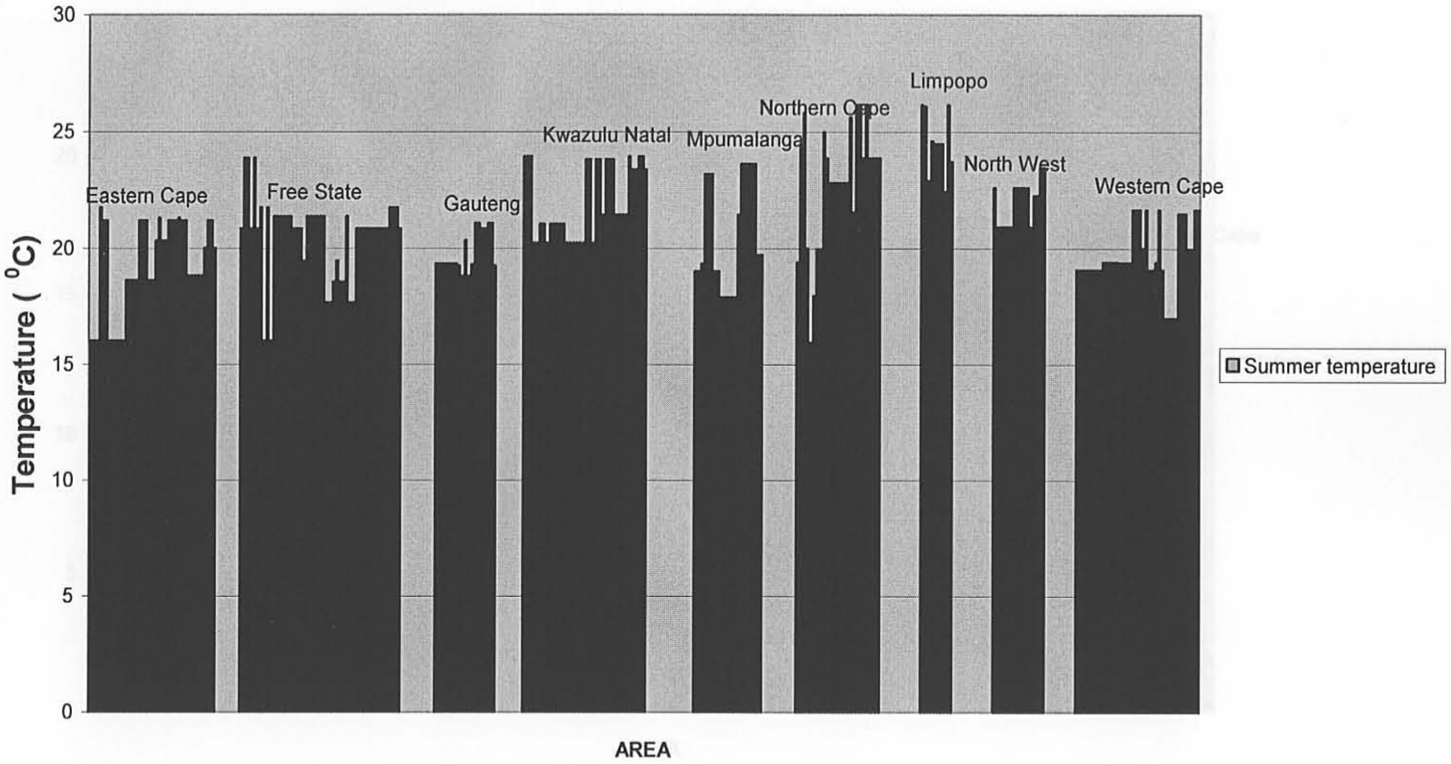


Figure 4-3: Average Winter Temperature in South Africa by district (1970 – 2000)

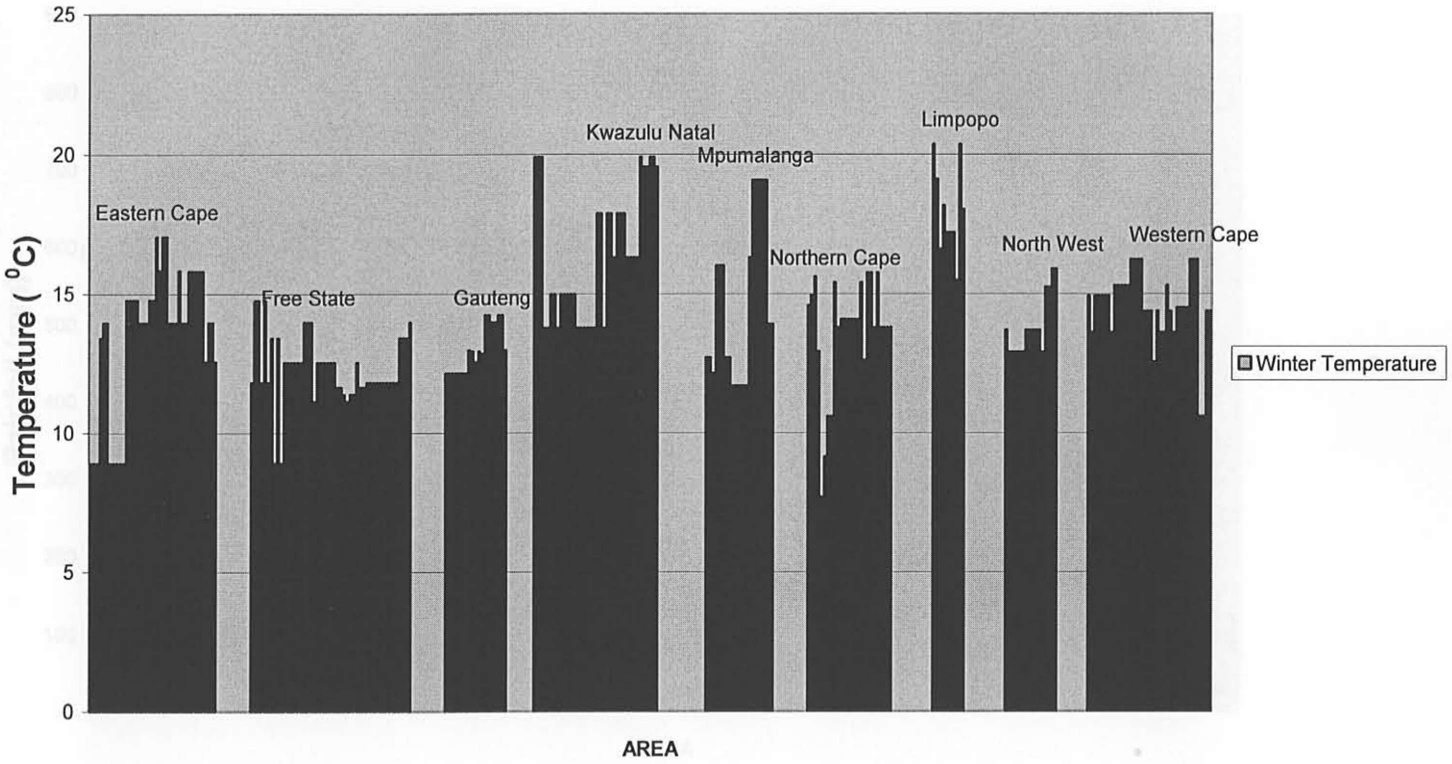


Figure 4-4: Summer Rainfall in South Africa by district (1970 –2000)

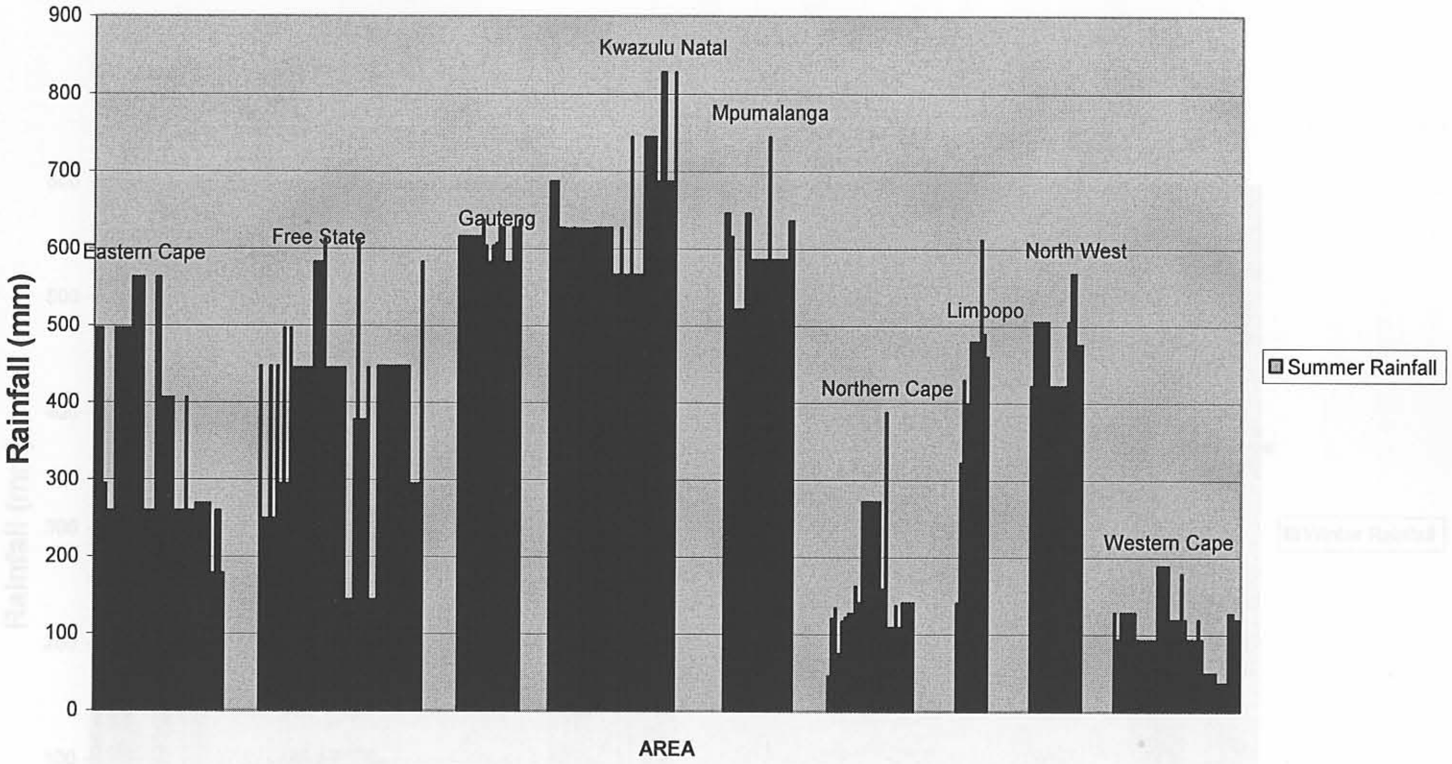
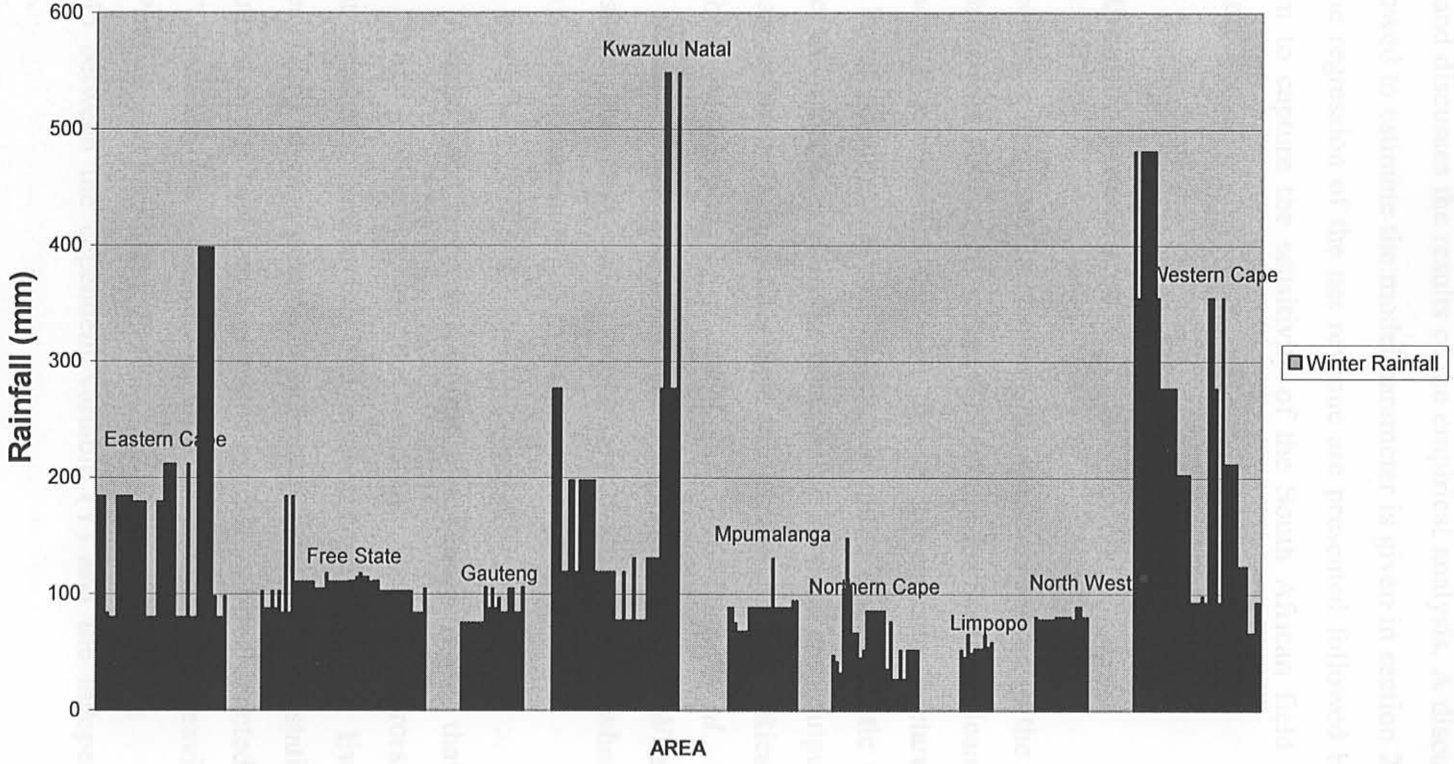


Figure 4-5: Winter Rainfall in South Africa by district (1970 – 2000)



CHAPTER 5 : RESULTS OF THE EMPIRICAL ANALYSIS

5.1 Introduction

This chapter presents and discusses the results of the empirical analysis. A discussion of the procedures followed to estimate the model parameter is given in section 2. The estimated results of the regression of the net revenue are presented followed by the simulations undertaken to capture the sensitivity of the South African field crops sector to global warming.

5.2 Parameters' estimation procedures

Using the Ricardian technique discussed in chapter four, the study estimated the value of climate in the South African field crops sector. The 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 nonlinearities in the relationship between crop output and climate variables that are apparent from various field studies and also other Ricardian studies applied elsewhere (Mendelshon *et al.*, 1994 and 1996; Dinar *et al.*, 1998; Poonyth *et al.*, 2002; Deressa, 2003; and Mendelshon and Dinar, 2003). When the quadratic term is positive, the farm value function is U-shaped, and when the quadratic term is negative, the function is hill-shaped.

The model for South African field crops is a multiple regression model that was estimated using the White Heteroskedasticity-Consistent Standard Errors and Covariance consistent estimator employing the econometric software Eviews. Ordinary Least Squares (OLS) method parameter estimators have desirable statistical properties. They are known as the best linear unbiased estimators often denoted with the acronym "BLUE." However, the optimality of OLS estimators relies heavily on six key assumptions (Pindyck and Rubinfeld, 1998):

1. The relationship between the dependent variable (Y) and the independent variables (X's).
2. The X's are nonstochastic.

3. No exact linear relationship exists between two or more of the independent variables.
4. The error term has 0 expected value and constant variance for all observations (homoscedasticity).
5. Errors corresponding to different observations are independent and therefore uncorrelated (no serial correlation).
6. The error variable is normally distributed.

When examining, cross-sectional data, there may be reason to believe that the assumptions of homoscedasticity and no serial correlation of the error term are violated. With data from different sub-populations, when an independent estimate of the error variance is available, OLS estimators will place more weight on observations with large error variance, therefore the estimators will be unbiased and consistent, but not efficient (the variances of estimated parameters are not the minimum variances). Furthermore, the estimated variances of the estimated parameters will be biased estimates of the true variances. White (1980) has derived a heteroskedasticity consistent covariance matrix estimator, which provides correct estimates of the coefficient covariances in the presence of heteroskedasticity of unknown form. The White covariance matrix assumes that the residuals of the estimated equation are serially uncorrelated. Newey and West (1987) have proposed a more general covariance matrix estimator that is consistent in the presence of both heteroskedasticity and autocorrelation of unknown form. EViews provides the option to use the White Heteroskedasticity-Consistent Standard Errors and Covariance consistent estimator in place of the standard OLS formula to avoid heteroscedasticity and serial correlation.

This study used the above method to estimate the empirical Ricardian model specified for South African field crops.

Several runs have been tried in order to find the model estimates that describe best the relationship between net revenue hectare and climate, soil and other socio-economic variables. In the preliminary runs, to describe the climate, three seasons were included in the model namely Spring, Summer and Winter. However, because of the high correlation between spring temperature and both summer and winter temperature and spring rainfall and summer rainfall, the data have been rearranged into two seasons (summer and winter). To control for extraneous factors influencing net revenue, a set of variables have been included in the regression. Firstly, three soil dummies to represent the three main soil types in the country were considered but soil dummy 2 was found statically insignificant and therefore was dropped out. However, since none of the districts in the dataset has only one soil type, the removal of soil dummy 2 in the regression did not affect the results. None of the observations have been lost. On the other hand, the other variables (soil, irrigation, population density, labour and geographical coordinates) were found significant. Labour is expected to show diminishing marginal productivity. Accordingly a quadratic term for labour was included but was found not significant and therefore dropped out.

Moreover, the model was first estimated using absolute values of variables, which produced residuals of the estimated linear equation that were not normally distributed. Thus the empirical model was then estimated in a semi-log functional form with the logarithm district net revenue per hectare as the dependent variable:

$$\log(NRHA) = \beta_0 + \beta_1 T + \beta_2 T^2 + \beta_3 R + \beta_4 R^2 + \beta_5 T * R + \beta_6 Z + \beta_7 G + u \quad (5.1)$$

where: T is the vector of temperature variables (summer and winter), R is the vector of rainfall variables , Z is the set of soil variables (soil dummy 1 and soil dummy 3), G is the set of others variables (population density, irrigation, labour and geographical coordinates: altitude and latitude) and u the error term.

5.3 Results of the regression analysis

The results of the regression showed that climate variables (temperature and rainfall), soil indicators, labour, irrigation, population and geographic variables (altitude and latitude) have significant influences on the behaviour of net revenue hectare of the South African major field crops. Statistically, the coefficients, except that of rainfall, were all significant at a 5% level of significance. The model, according to the F statistic gave a good fit at a 5% level of significance. According to adjusted R², the model explained 63% of the variation in net revenue hectare (Table 5-1).

Table 5-1: Parameter estimation of the Ricardian field crops model

Dependent variable: log (NRHA) in R/ha

Variable	**Coefficient**	**Variable**	**Coefficient**
Intercept	10.25 (2.79)**	Temp*Rain Summer	-0.0009 (-1.96)*
tempSummer	-1.25 (-3.71)**	Temp*Rain Winter	0.0025 (1.64)
tempSummer2	0.03 (4.06)**	Popd	5.09E-05 (2.23)*
tempWinter	0.72 (3.58)**	Soildum1	-0.22 (-1.89)*
tempWinter2	-0.027 (-3.79)**	Soildum3	0.067 (1.84)*
rainSummer	-0.0007 (-1.43)	Labour	2.20E-05 (2.16)*
rainSummer2	0.0001 (3.18)**	Irrigation	0.96 (4.23)**
rainWinter	0.01 (1.22)	Latitude	0.13 (4.09)**
rainWinter2	-0.0004 (-2.57)**	Altitude	-0.0004 (-2.29)*
R-squared	0.66	Adjusted R-squared	0.63
F-Statistic	40.11		

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

The results showed that the quadratic terms of climate variables are significant, which denotes a quadratic relationship between climate and net revenue as hypothesised earlier. Winter climate variables have a hill shaped relationship with net revenue whereas summer climate variables have a U shaped relationship. Net revenue seems to benefit from warmer and wetter winter with diminishing marginal benefits up to a turning point after which Net revenue starts declining. Also, above a minimal point, net revenue seems to benefit from higher rainfall and higher temperature.

The estimated parameters that control for farm production technology (irrigation and labour) are positively correlated to net revenue as expected. Irrigation has strong positive effects and increases net revenue per hectare substantially. Thus, irrigation may allow crops to grow well in warmer temperatures and dryer regions. These results suggest that irrigation could be an effective mitigation measure to climate change adverse impacts. Furthermore, the positive correlation between population density (proxy for urbanisation) and net revenue indicated that net revenue increases in a more denser and wealthier regions. Indeed because of the higher local demand for food and the potential for conversion of land to non-farm uses, farm values are higher in more urbanised areas.

Soil type 1 which is the category of the red-yellow latosols is negatively related to net revenue. In contrary soil type 3, the category of black to very dark grey brown with high clay content, influence net revenue positively as expected. Soil type 1 has rapid infiltration and low water holding capacities and is very low in plant nutrients, whereas soil type 3 is a very productive soil.

The altitude (proxy for day length) has a negative effect on net revenue as expected. Indeed, the longer the day, the higher is the photoperiod of the plant. At higher altitudes, days are shorter and hence reduce the photosynthesis activity of the plant. Additionally, because the presence of light during the daytime enhances absorption of mineral nutrients and water from the soil, latitude has been included in the regression as a proxy for solar radiation. We expected a negative relationship between latitude and net revenue since regions at low latitude receive more solar radiation than those at higher latitude. However this is not the case in our results.

In general, all the parameters are significant and have the expected signs except for the latitude variable (proxy for solar radiation), which gives high confidence in the model to use for further analysis.

5.4 Climate sensitivity of the South African field crops

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 (Deressa, 2003). Thus, the climate sensitivity of the South African field crops sector is analysed in this section through calculation of seasonal elasticity and identification of climate critical damage points.

5.4.1 Elasticity measures

Elasticity measures the percentage change in the response variable induced by a percentage change in the independent variables. The economic interpretation of the coefficients of a semi-log model is not that straightforward, further complicated by climates interaction terms. The estimated coefficients of the semi-log model are neither marginal values nor elasticity, but can be easily converted to the right measures (Studenmund, 1992).

Elasticity (ε) is defined as:

$$\varepsilon = \frac{(\Delta NRHA)}{(\Delta F_i)}\left(\frac{\overline{F}_i}{\overline{NRHA}}\right) \qquad (5.2)$$

Where *NRHA* is the net revenue hectare, F_i is the level of climate variable *i* (temperature and rainfall).

The calculated elasticity estimates[10] evaluated at mean values indicated that at current levels of rainfall, increasing temperatures in both seasons reduce net revenue. On the other hand, at current levels of temperature, increasing precipitation in winter is beneficial whereas increase summer rainfall affected negatively net revenue (Table 5-2).

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[10] $\ln nrha = \beta_1 T + \beta_2 T^2 + \beta_3 R + \beta_4 R^2 + \beta_5 R * T$ Note that β_i cannot be directly interpreted as elasticities unless you use a double-log term. With the inclusion of interaction term in the equation, the elasticity for Temperature (T) for example will therefore be:

$$\varepsilon = \frac{\partial \ln NRHA}{\partial T} * \overline{T} = \left(\beta_1 + 2\beta_2 \overline{T} + \beta_5 \overline{R}\right) * \overline{T}$$

Table 5-2: Estimates of elasticity to climate factors

	Temperature	Rainfall
Winter season	-0.08	0.89
Summer Season	-0.115	-0.406

For a typical specification of agricultural technology, there exits an optimal configuration of seasonal temperatures and rainfall. Climate change will be costly (or beneficial) if, on average climatic conditions in the area modelled move further away from (or closer to) the climatic optimum. Thus as Quiggin and Horowitz (1999) observe, for further insights into the relationship between net revenue and climate, one needs to determine whether current levels of climate variables are below or above the climatic optimum levels (turning points). In the next section, the climatic optimum points will therefore be calculated and compared to current climate normal.

5.4.2 Climatic optimum points

The climatic optimum points for the two seasons were calculated from the first order conditions of optimisation:

$\frac{\partial LNNRHA}{\partial X_j} = 0$, Where NRHA is the net revenue hectare and X_j is the level of climate variable j (temperature or rainfall).

At first, the net revenue hectare estimated graphs (Figure 5-1 to 5-4) were obtained by changing only a specific season's temperature or rainfall in the estimated above net revenue function, keeping other factors constant at mean values. However, since in the estimated model of field crops net revenue, interaction terms between rainfall and temperature were included, we also investigate how the optimum points of a specific climate variable will change with changes in the other (Figure 5-5 to 5-8).

5.4.2.1 Identification of climatic optimum points

A. Temperature level analysis

Assuming rainfall constant at current levels, the optimum temperature points for South African field crops' sector were calculated at 14.78^{0}C and 22^{0}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 for temperature levels below 14.78^{0}C and to reduce net revenue beyond 14.78^{0}C (Figure 5-1). At very low temperatures, most plants may not grow well and therefore incremental increase in temperature will be beneficial until a certain point. Indeed the decline in net revenue for winter temperature higher than 14.78^{0}C could be attributed to the moisture stress occurring in the plant due to higher temperature that induces higher evaporation coupled with very low rainfall in winter. Additionally, occurrence of temperatures higher than 14.78^{0}C in winter season may be favourable for pests and diseases. The current average winter temperature in South Africa is 14.5^{0}C that is very close to the critical damage point. The critical damage point of 14.78^{0}C falls in the range of agronomic optimal temperature for the growth of wheat, the main winter crop in South Africa (Table 5-3). Therefore additional rises in winter temperature will induce yield reduction at national level. Indeed a 1% increase in winter temperature will reduce national net revenue by 0.08% (table 5-2). However, this may differ across regions. Indeed cooler regions below the optimal winter temperatures may benefit. Examples include the Eastern Cape (13.5^{0}C), the Free State (12.3^{0}C), the Gauteng (13.35^{0}C) and the Northern Cape (13.62^{0}C). Whereas, climate change would be costly to regions currently above the winter optimum temperatures such as the Kwazulu Natal (16.5^{0}C), Mpumalanga (14.80^{0}C) and Limpopo (18^{0}C).

On the other hand, with a U shaped relationship between summer temperature and net revenue hectare, the minimum optimum temperature for plant growth is 22^{0}C. Thus, temperature higher than 22^{0}C will increase net revenue (Figure 5-2). There is a positive response of net revenue per hectare to increased summer temperature because the optimal temperatures for summer crops (maize, sugar cane, sorghum, groundnut, sunflower and soybean) are around 25^0 to 35^0 C (Table 5-3).

Figure 5-1: The sensitivity of net revenue to winter temperature

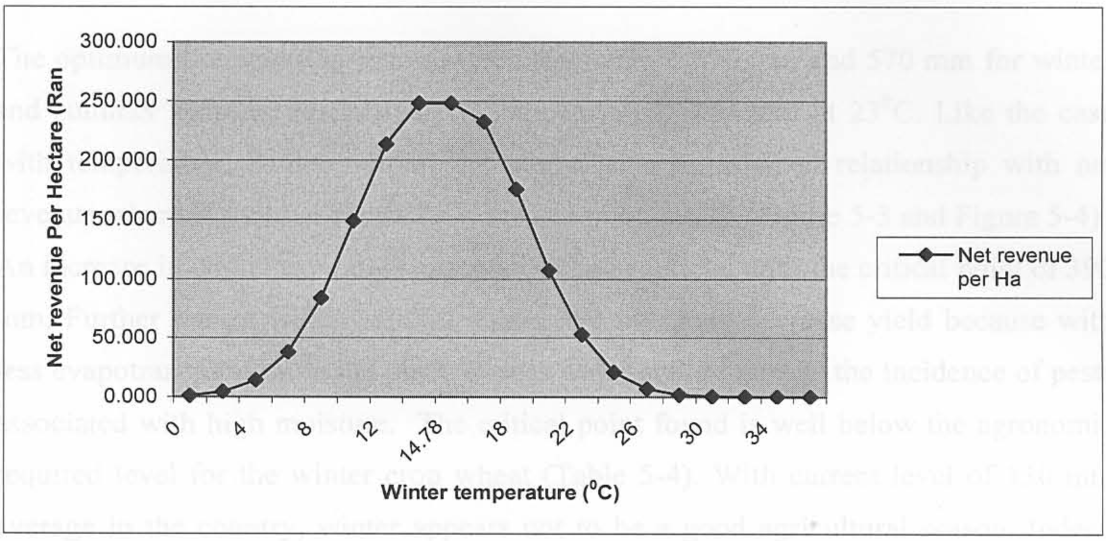


Figure 5-2: The sensitivity of net revenue to summer temperature

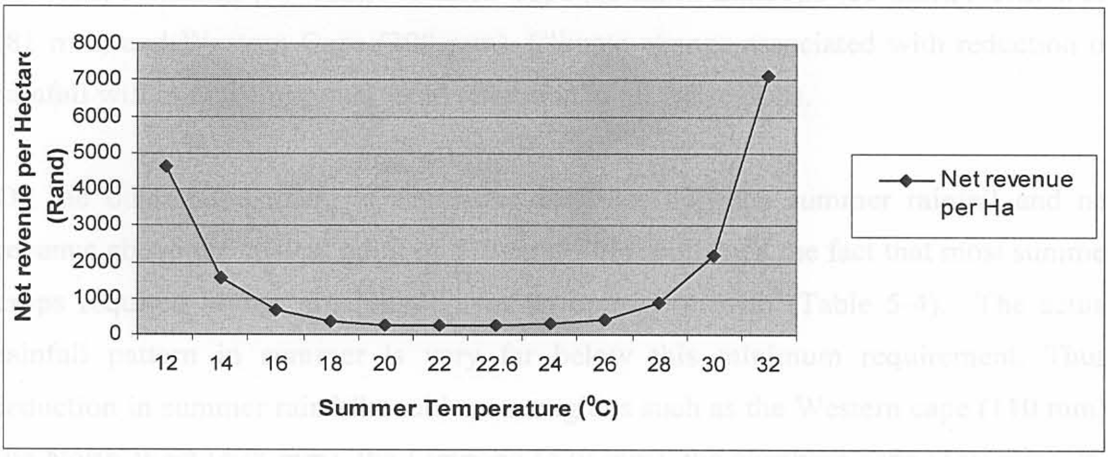


Table 5-3: Current level, critical point and agronomic optimal temperatures

Seasons	Crops produced	Current temperature levels (^{0}C)	Critical damage points (^{0}C)	Agronomic optimal range of average temperature[1] (^{0}C)
Winter	Wheat	14.5	14.78	10-20
Summer	Maize	23	22	18- 30
	Sugar cane			22-35
	Sorghum			25-35
	Groundnut			22-32
	Sunflower			17-34
	Soybean			20-33

1) Source: Illinois State Water Survey (2004) and Deressa (2003)

B. Precipitation level analysis

The optimum precipitation points were calculated at 390 mm and 570 mm for winter and summer seasons, respectively if temperature is constant at 23^0C. Like the case with temperature, winter rainfall depicted also a hill shaped relationship with net revenue whereas summer rainfall a U shaped relationship (Figure 5-3 and Figure 5-4). An increase in winter rainfall is expected to be beneficial until the critical point of 390 mm. Further rise in winter rainfall above 390 mm may decrease yield because with less evapotranspiration in the plant, excess water could increase the incidence of pests associated with high moisture. The critical point found is well below the agronomic required level for the winter crop wheat (Table 5-4). With current level of 130 mm average in the country, winter appears not to be a good agricultural season. Indeed actual winter rainfall level across the country is well below the optimal level: the Eastern Cape (176 mm), Free State (110 mm), Gauteng (97 mm), Kwazulu Natal (186 mm), Mpumalanga (87 mm), Northern Cape (65 mm), Limpopo (55 mm), North West (81 mm) and Western Cape (300 mm). Climate change associated with reduction of rainfall will induce important yield reduction in all the regions.

On the other hand, there is a positive response between summer rainfall and net revenue above the critical point of 570 mm. This confirmed the fact that most summer crops required higher precipitation for an optimal growth (Table 5-4). The actual rainfall pattern in summer is very far below this minimum requirement. Thus, reduction in summer rainfall could cause regions such as the Western cape (110 mm), the North West (478 mm), the Limpopo (429 mm), the Northern cape (180 mm), the Free State (408 mm) and the Eastern cape (420 mm) severe damages as opposed to the Mpumalanga (600 mm), Kwazulu Natal (670 mm), Gauteng (617 mm) regions that are currently above optimal summer rainfall.

As observed, current rainfall levels are far from estimated climatic optimum points in contrary to current temperature levels. This therefore implies that the field crops 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 finding is in line with Deressa (2003) study that was focussed only on sugar cane.

Figure 5-3: The sensitivity of net revenue to winter rainfall

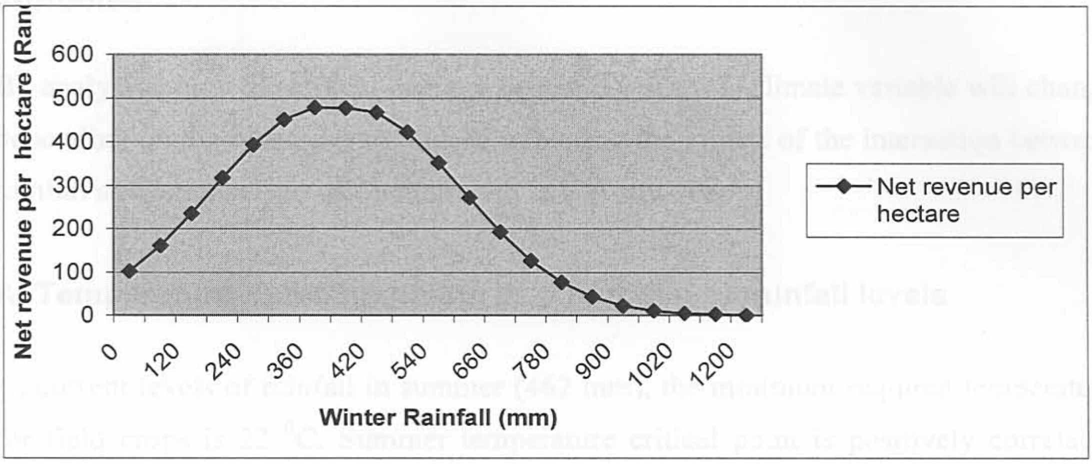


Figure 5-4: The sensitivity of net revenue to summer rainfall

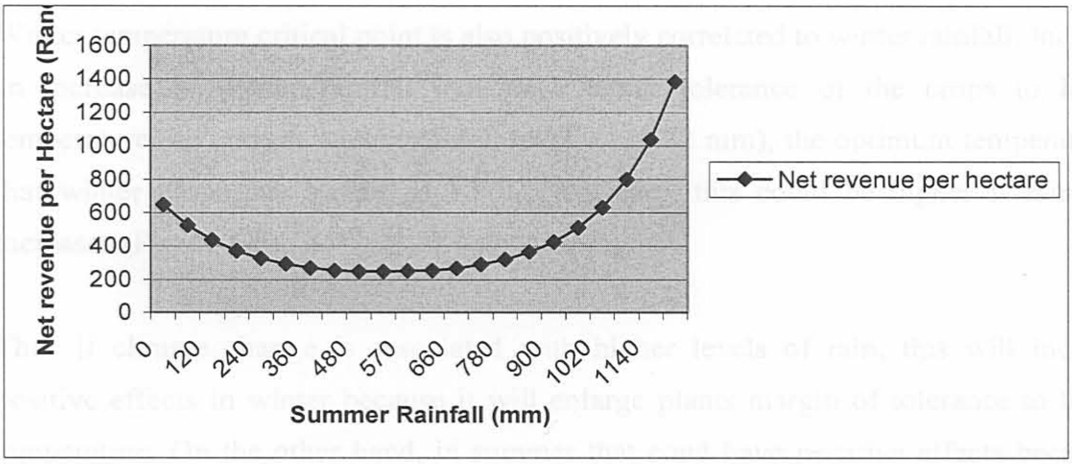


Table 5-4: Current level, critical damage point and agronomic optimal level of precipitation

Seasons	Crops produced	Current precipitation levels (mm)	Critical damage points (mm)	Agronomic optimal precipitation[1] levels (mm)
Winter	Wheat	130	390	750
Summer	Maize	462	570	1200
	Sugar cane			1200
	Sorghum			900
	Groundnut			1200
	Sunflower			1200
	Soybean			1200

1) Source: Illinois State Water Survey (2004) and Deressa (2003)

5.4.2.2 The sensitivity of climatic optimum points to other climate attributes

By analyzing how the critical damage points of a specific climate variable will change depending on the other, we are indeed exploring the effects of the interaction between rainfall and temperature on plant growth in a given season.

A. Temperature optimum points as a function of rainfall levels

At current levels of rainfall in summer (462 mm), the minimum required temperature for field crops is 22 ^{0}C. Summer temperature critical point is positively correlated with summer rainfall. Increasing rainfall will raise the required minimum temperature and a reduction in rainfall will reduce the required minimum temperature (Figure 5-5).

Winter temperature critical point is also positively correlated to winter rainfall. Indeed an increase in winter rainfall induces a better tolerance of the crops to high temperature. At current winter rainfall level (130.62 mm), the optimum temperature that winter crops can sustain is 15 ^{0}C. However, this could be higher if rainfall increases (Figure 5-6).

Thus if climate change is associated with higher levels of rain, this will induce positive effects in winter because it will enlarge plants margin of tolerance to high temperature. On the other hand, in summer that coud have negative effects because higher rain, increased the minimum required level of temperature. A reverse situation could happen if climate change is associated with low rainfall in South Africa (negative effects in winter and positive effects in summer).

Figure 5-5: Variation of temperature critical points to rainfall in summer

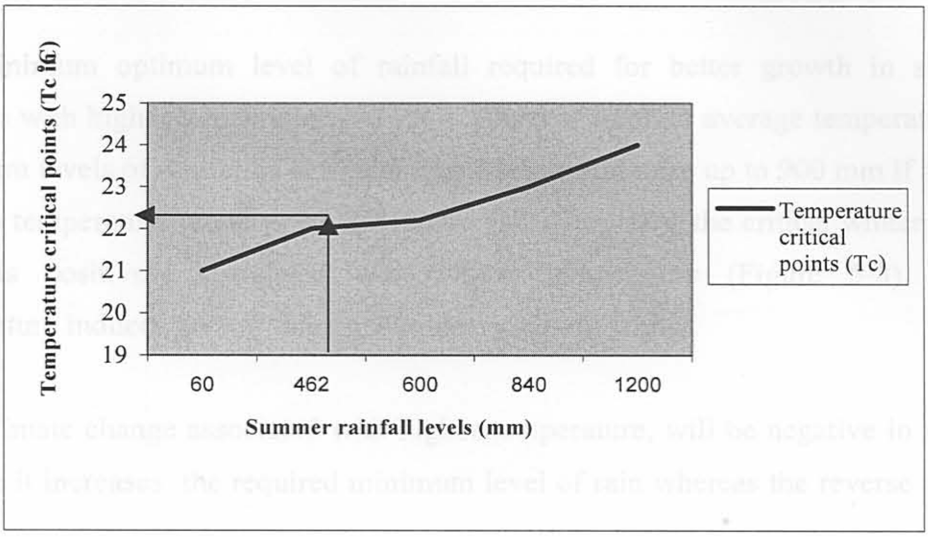
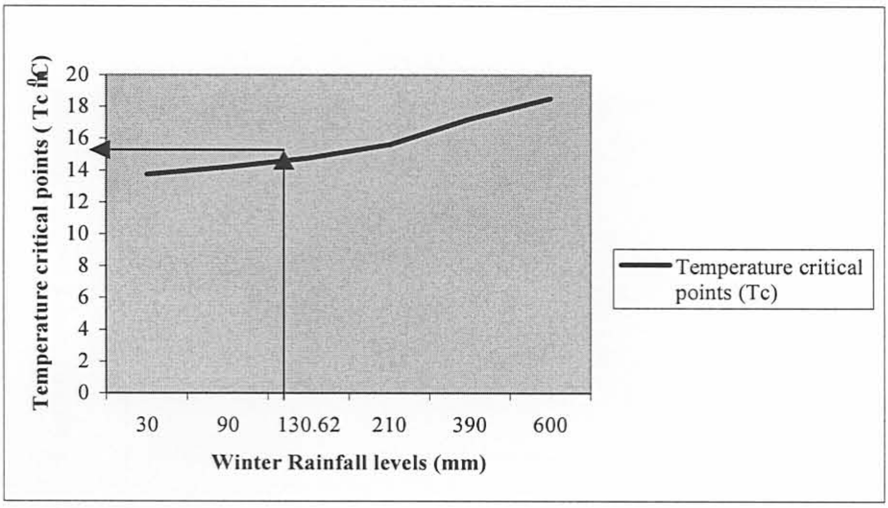


Figure 5-6: Variation of temperature critical points to rainfall in winter



N.B.: The narrows indicate actual climate levels and their respective critical points in Figure 5-5 and 5-6.

B. Rainfall optimum points as a function of temperature levels

The minimum optimum level of rainfall required for better growth in summer, increase with higher temperature. At 23 ^{0}C, current summer average temperature, the minimum levels of rainfall is at 570 mm, and this could raise up to 900 mm if summer average temperature go up to 30 ^{0}C (Figure 5-7). Similarly, the critical winter rainfall point is positively correlated with winter temperature (Figure 5-8). Higher temperature induces greater tolerance to heavy rain in winter.

Thus climate change associated with higher temperature, will be negative in summer because it increases the required minimum level of rain whereas the reverse holds in winter.

In general we observe that high temperature is benefecial with high rain in both seasons.

Figure 5-7: Variation of Rainfall critical points to temperature levels in summer

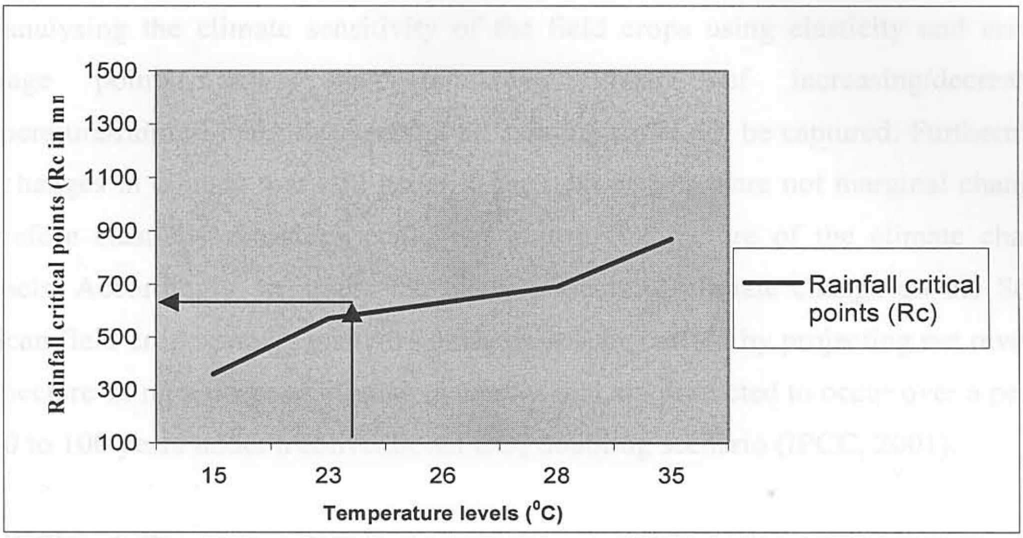
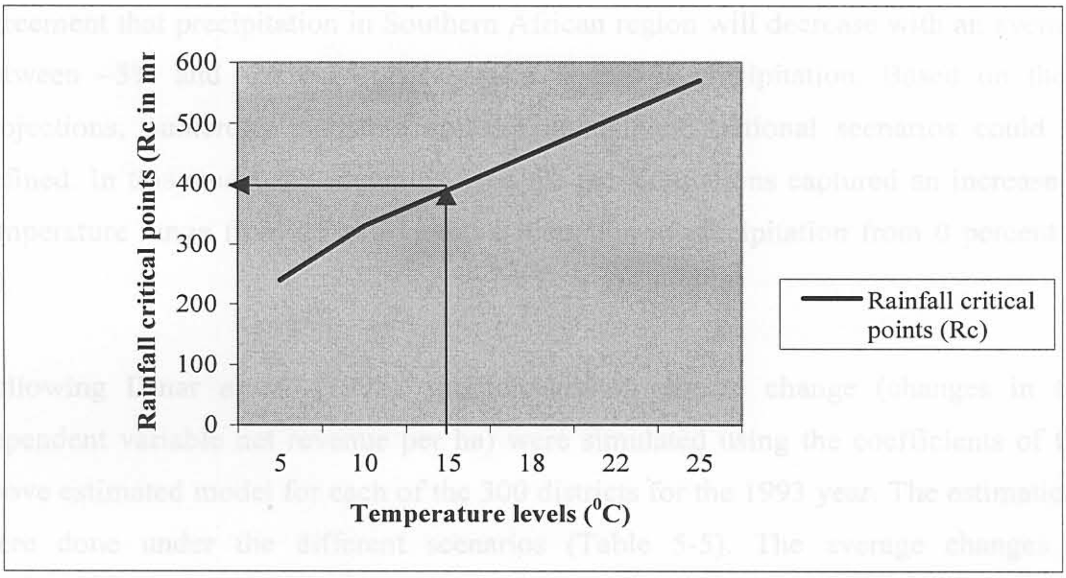


Figure 5-8: Variation of Rainfall critical points to temperature levels in winter



N.B.: The narrows indicate actual climate levels and their respective critical points in Figure 5-7 and 5-8.

5.5 Likely impacts of climate change on the South African Field Crops

By analysing the climate sensitivity of the field crops using elasticity and critical damage points only, the cumulative impact of increasing/decreasing temperature/rainfall marginally across all seasons could not be captured. Furthermore the 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, to assess the likely impacts of climate change on the South African field crop sector, sensitivity analysis will be carried by projecting net revenue per hectare using a range of climate outcomes that are predicted to occur over a period of 30 to 100 years under a conventional CO_2 doubling scenario (IPCC, 2001).

5.5.1 Simulation procedures

Following Mendelshon *et al.* (2001), instead of relying on the direct outputs of GCMs this study examined a set of uniform climate change scenarios. According to IPPC (2001a), the Southern African region is expected to warm greater than the average global warming of 1.5^0 to 4.5^0C (warming in excess of between 0-40%). There is an agreement that precipitation in Southern African region will decrease with an average between –5% and -20% of their current levels of precipitation. Based on these projections, numerous plausible uniform annual and national scenarios could be defined. In this study, the scenarios used for the simulations captured an increase in temperature range from 2^0 to 3^0C and a reduction in precipitation from 0 percent to 20.

Following Dinar *et al.* (1998), the impacts of climate change (changes in the dependent variable net revenue per ha) were simulated using the coefficients of the above estimated model for each of the 300 districts for the 1993 year. The estimations were done under the different scenarios (Table 5-5). The average changes in temperature were added to the baseline temperatures, while the baseline rainfall was multiplied by the percentage changes in precipitation.

Table 5-5: Simulations scenarios

Scenarios		**Temperature changes in ^{0}C**		**Changes in rainfall in %**	
		Summer	**Winter**	**Summer**	**Winter**
Baseline	**Scenario 0**	0	0	**0**	**0**
Partial Effects	Scenario I	+2	+2	0	0
	Scenario II	0	0	-5	-5
Seasonal Effects	Scenario III	+2	0	0	0
	Scenario IV	0	+2	0	0
	Scenario V	0	0	-5	0
	Scenario VI	0	0	0	-5
	Scenario VII	+2	0	-5	0
	Scenario VIII	0	+2	0	-5
Total Effects	Scenario IX	+2	+2	-5	-5
	Scenario X	+2	+2	-20	-20
	Scenario XI	+3	+3	-5	-5
	Scenario XII	+3	+3	-20	-20

Additionally, in this study we are interested in exploring 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. Thus, the irrigation variable in the model has been used to make simulations. Indeed the irrigation variable in the model describes the intensity of irrigation in district i. To investigate adaptations options, we assume that farmers will responded to climate change by increasing their intensity of irrigation. Two alternatives were considered:

Alternative 1: no adaptation, farmers do nothing; therefore no change is made on the irrigation variable in the model, (baseline scenario).

Alternative 2: Farmers undergo some adaptations to climate change by increasing intensity of irrigation. The modification to the irrigation variable is not uniform across the districts. We assumed that the development of irrigation infrastructures could be restraint by natural, physical and economic factors. Districts with high shares of their land under irrigation were assumed to have approached their maximum potential for irrigation, whereas those with low intensity have more opportunity for expanding area under irrigation. Therefore, when share of land under irrigation is higher than 50%, no change was made on the dataset, for shares between 20% and 50%, intensity was increased by 25%, and for observations with less than 20% intensity increased by 50%.

Using the Ricardian approach, a regression of national farmland values or net revenues that combines both dryland and irrigated farming regions, is likely to understate future capital costs in the farming areas that need additional surface water for irrigation due to the effects of climate change (Schlenker *et al.*, 2003). Indeed dams and irrigation systems are long lasting investment. The value of these facilities depends on a number of climatic factors including precipitation in the catchments areas, evapotranspiration rates and the suitability of the irrigated areas for growing different crops. All these will be affected by climate change and likely will lead to increased water shortage. One the other hand, higher temperatures significantly raise crop evapotranspiration, which is likely to lead to both an increase in the acreage under irrigation and also an increase in the amount of water applied per irrigated acre. On the other hand, hydrological studies suggest that climate change will lead to a reduction in the effective supply of water in some areas. This could be met in various ways by developing new water surface, water storage and conveyance facilities, through water rights reallocation and water marketing, through increased conservation, or through land retirement. Although these adjustments to climate change are likely to entail economic costs, they are not fully reflected in the Ricardian approach adopted for this study[11].

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[11] Most relevant effects of climate change are unpredictable on the basis of present knowledge. The only thing that can be predicted with certainty is that the optimal location of irrigation infrastructures will change and this change will be costly. In general, the full cost of supplying agricultural users is generally not completely capitalized in the current farmland values. The economic cost of climate change in irrigated areas could be substantial. A region-specific analysis accounting for the relevant hydrology and institutional framework of water deliveries will be required to evaluate these costs in more detail (Cline, 1996; Quiggin and Horowitz, 1999 and 2003 and Schlenker *et al.*, 2003).

5.5.2 Climate change impacts results

5.5.2.1 Partial effects analysis

The partial effect analysis evaluates the impact of changing only temperature or precipitation levels one at a time on net revenue while keeping all other variables constant. Every season is expected to experience the same climate change from their current condition. In this section, partial temperature and precipitation effects were analysed with and without adaptation options.

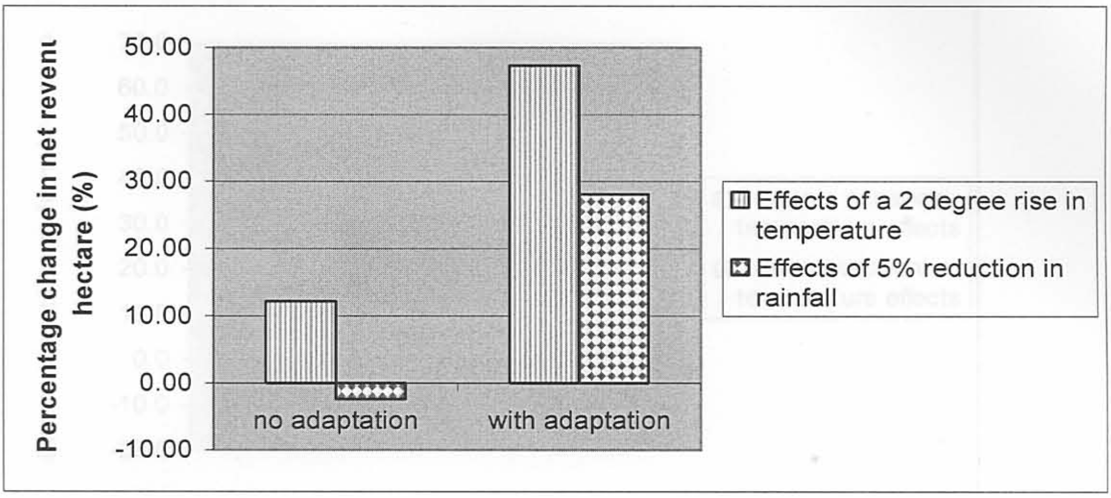
5.4.2.1.1 Partial temperature effects

The partial effect of 2^0C increase in temperature was evaluated in this section (scenario I). The results show that by increasing only temperature in all the seasons, the net revenue of the field crops sector will increase by 12%. The rise in net revenue could even be greater if farmers increased their irrigation intensity. This may be attributed to the fact that most field crops are summer crops and also in South Africa the current levels of summer temperature are above the minimum optimum point of 22^0C (Figure 5-9).

5.4.2.1.2. Partial Precipitation effects

The partial effect of 5% decrease in precipitation is evaluated in this section (scenario II). A decrease of 5% in rainfall could drop the net revenue per hectare by 2%. However, with irrigation as an adaptation option, the situation could be reversed. Thus, net gains could be achieved in net revenue (Figure 5-9).

Figure 5-9: The partial effects of a 2^0C increase in temperature and 5% reduction in precipitation on net revenue



5.4.2.2 Seasonal effects analysis

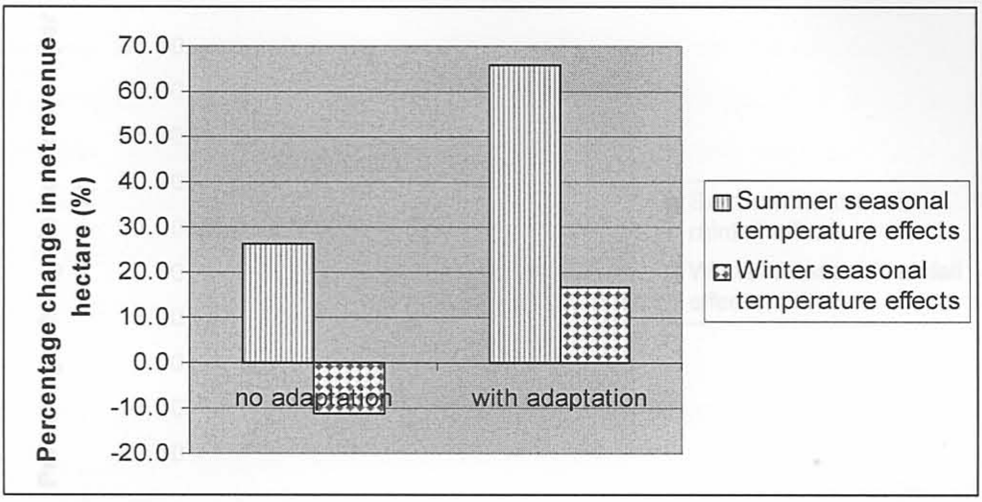
The seasonal effect analysis evaluates the impact of changing only one season temperature or precipitation on net revenue by keeping all others factors constant. In this section, seasonal temperature and precipitation effects are analysed with and without adaptation options.

5.4.2.2.1 Seasonal temperature effects

The seasonal effect of 2^0C increase in temperature for summer and winter respectively, is evaluated in this section (scenario III and scenario IV). Figure 5-10 depicts the results.

With no adaptation, increasing winter temperature by 2^0C will reduce net revenue by about 11%. This is consistent with the fact that current winter temperature is close to the critical point; therefore additional warming will impact negatively on net revenue. On the contrary, further warming in summer is expected to increase net revenue per hectare by 26%. For both seasons, adaptation will have significant positive effects on net revenue.

Figure 5-10: Impact of a 2^0 C increase in winter and summer temperature on net revenue



5.4.2.2.2 Seasonal precipitation effects

This section evaluated the seasonal rainfall effects of 5% decrease in precipitation in both seasons respectively (Scenario V and VI).

Again, the results confirmed that adaptation in form of irrigation is an effective option to reduce the harmful effects of climate change. Furthermore the magnitude of the impacts of climate change differs from one season to another. In fact a 5% decrease in rainfall will reduce the net revenue hectare by 4% and 1% in winter and summer, respectively (Figure 5-11).

5.4.2.2.3 Combined seasonal effects of rainfall and temperature

In this section we simultaneously raise temperature by 2^0C in and reduce rainfall by 5% in each season (scenario VII and scenario VIII). Overall, the change in climate during winter season, characterised by a dryer and hotter winter, will have a negative impacts on net revenue hectare of about 15%. On the other hand, a dryer and hotter summer would be beneficial. The benefits from higher temperature will compensate harmful effects of a decrease in rainfall, inducing a total net benefit of 28%.

Figure 5-11: Impact of 5% decrease in winter and summer precipitation on net revenue

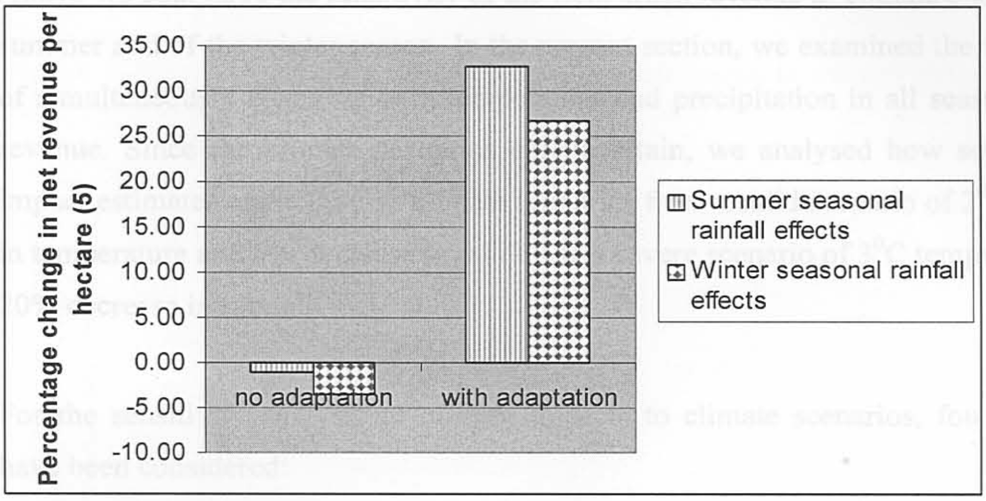
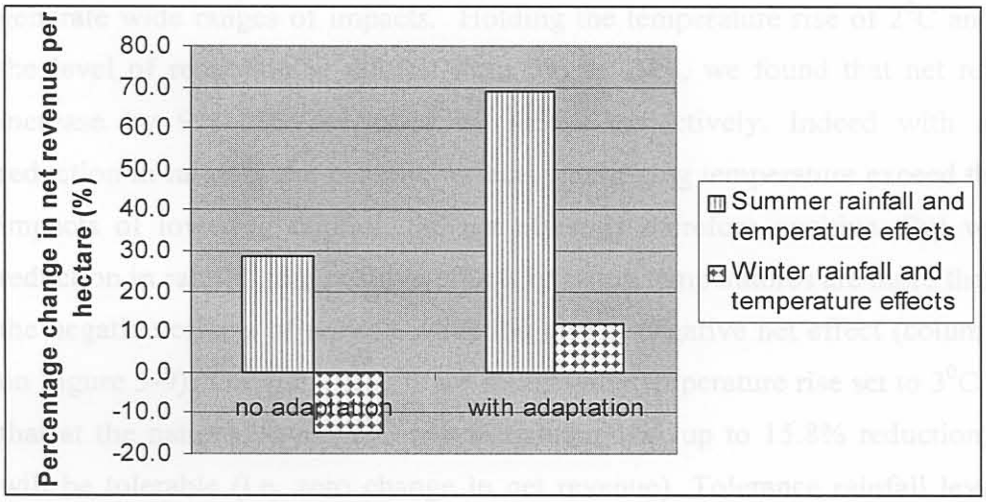


Figure 5-12: Cumulative seasonal impacts of a 2^{0}C increase in temperature and a 5% decrease in rainfall for summer and winter



5.4.2.3 Total effects

Above we compared the sensitivity of the field crops revenue to climate change of the summer and of the winter season. In the present section, we examined the total effect of simultaneously changing both temperature and precipitation in all seasons on net revenue. Since the climate scenarios are uncertain, we analysed how sensitive the impact estimates are to diverse climate scenarios from a mild scenario of 2^0C increase in temperature and 5% decrease in rainfall to a severe scenario of 3^0C temperature and 20% decrease in rainfall.

For the sensitivity analysis of climate impacts to climate scenarios, four scenarios have been considered:

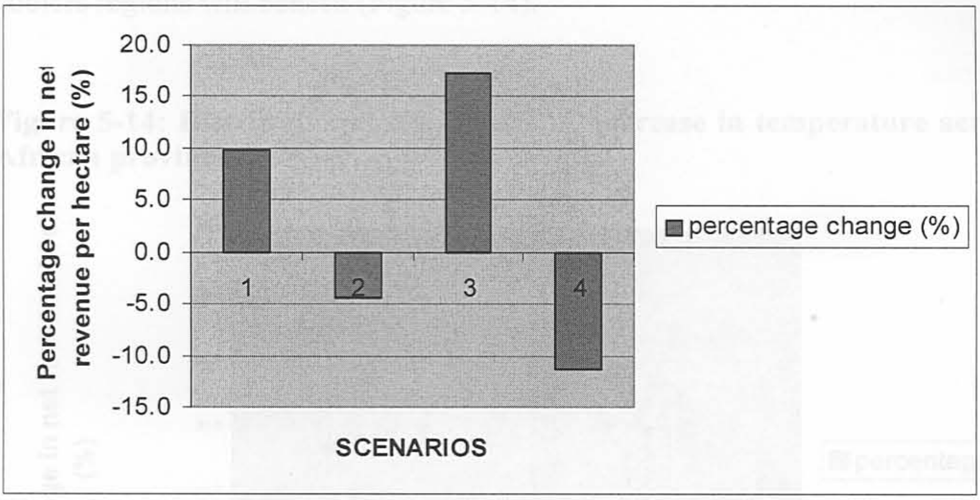
Scenario IX: An increase of 2^0C in temperature and 5% decrease in rainfall
Scenario X: An increase of 2^0C in temperature and 20% decrease in rainfall
Scenario XI: An increase of 3^0C in temperature and 5% decrease in rainfall
Scenario XII: An increase of 3^0C in temperature and 20% decrease in rainfall

The results show that differences among climate scenarios are important and these can generate wide ranges of impacts. Holding the temperature rise of 2^0C and changing the level of reduction in rainfall from 5% to 20%, we found that net revenue will increase by 9% and decreased by 4.5%, respectively. Indeed with a marginal reduction in rainfall, the benefits' effects from rising temperature exceed the negative impacts of lowering rainfall, the net effect is therefore positive. But with further reduction in rainfall, the positive effects of rising temperatures are more than offset by the negative effects of rainfall reduction giving negative net effect (columns 1 and 2 on Figure 5-9). The same results are found with temperature rise set to 3^0C. We found that at the national level, 2^0C rise in temperature; up to 15.8% reduction in rainfall will be tolerable (i.e. zero change in net revenue). Tolerance rainfall levels drop to 13.6% reduction in rainfall at 3^0C.

On the other hand, holding reduction in rainfall by 5% and changing the level of rise in temperature from 2^0C and 3^0C, we found that net revenue increased by 9% and by 12%, respectively. Thus, these results confirmed the fact that higher temperatures are beneficial for the field crops in South Africa. Moreover, the increase in temperature

(+2^{0}C or +3^{0}C) has not put the level of temperature (27^{0}C = 25+3) close to the limit tolerance temperature of the crops, which is 35^{0}C (columns 1 and 3 on Figure 5-13).

Figure 5-13: The sensitivity of climate change impacts on net revenue across different climate change scenarios



Note

1: An increase 2^{0}C in temperature and 5% decrease in rainfall
2: An increase 2^{0}C in temperature and 20% decrease in rainfall
3: An increase 3^{0}C in temperature and 5% decrease in rainfall
4: An increase 3^{0}C in temperature and 20% decrease in rainfall

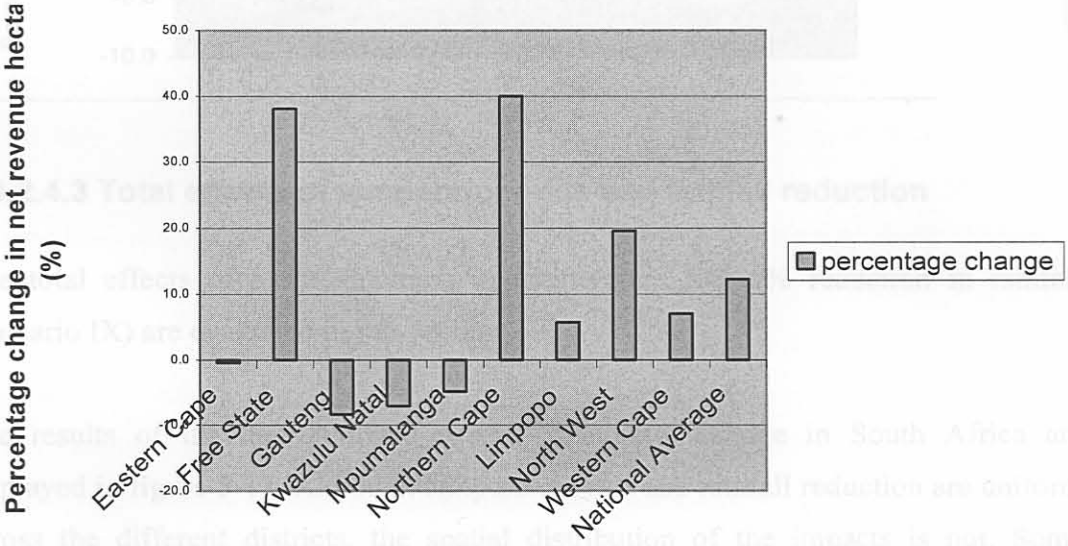
5.4.2.4 Distributional effects

The expected effects of climate change on the agriculture sector will not be uniform across continents, within continents and even within countries (Mendelshon and Williams, 2002). To assess how different provinces will be affected by climate change in South Africa, we applied a mild scenario of an increase of 2^{0}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. In the following analysis, every location and every season is expected to experience the same climate change from their current condition.

5.4.2.4.1 Partial effects of rise in temperature

The partial effects of 2^{0}C increase in temperature (scenario I) across South Africa differ from region to region. The already hot regions of Gauteng, Kwazulu Natal, and Mpumalanga will suffer damages of about 10% reduction in net revenue whereas the coolers regions will benefit (Figure 5-14).

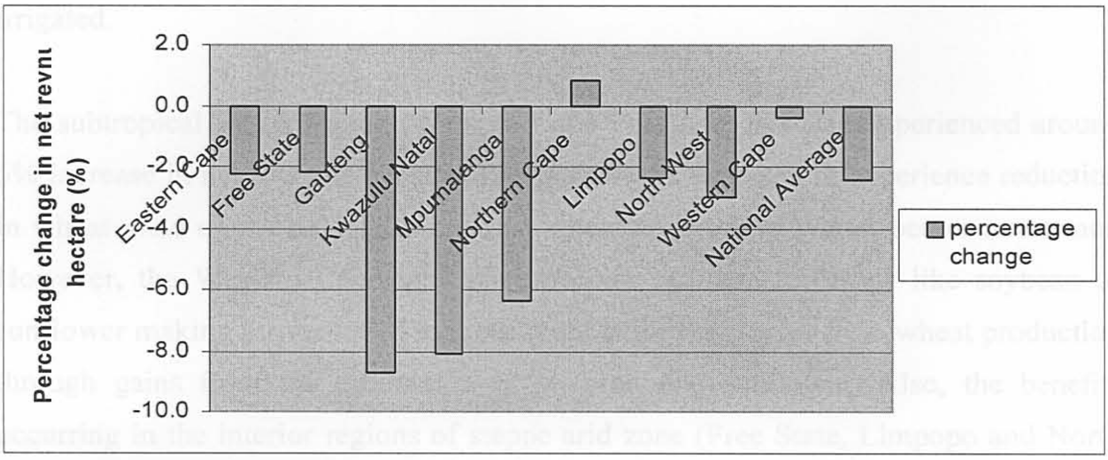
Figure 5-14: Distributional effects of 2^0 C increase in temperature across South African provinces



5.4.2.4.2 Partial effects of reduction in Rainfall

All regions in the country will suffer damages from the partial effect of 5% decrease in precipitation (scenario II) except the Northern Cape province. As outlined earlier, current rainfall patterns in the country are below optimum. The apparent positive effect of reduced rainfall on field crops in the Northern Cape (a desert area) reflect the fact that agriculture production in this province is highly dependent on irrigation. This confirms again the effectiveness of irrigation as an adaptation strategy (Figure 5-15).

Figure 5-15: Distributional effects of 5% reduction in rainfall across South African provinces



5.4.2.4.3 Total effects of temperature rise and rainfall reduction

The total effects of a 2^0C increase in temperature and 5% reduction in rainfall (scenario IX) are evaluated in this section.

The results of the distributional effects of climate change in South Africa are displayed in figure 5-17. Although temperature rise and rainfall reduction are uniform across the different districts, the spatial distribution of the impacts is not. Some provinces will experience gains while others will experience severe damages. The winners are the Free State, Northern Cape, North West, Western Cape and Limpopo. The losers are Eastern Cape, Gauteng, Kwazulu Natal and Mpumalanga. With the exception of Limpopo, the winners are from the western part (cooler and dryer regions) of the country and the losers from the eastern part (warmer and wetter zones) of the country (Figure 5-16 and Table 5-6).

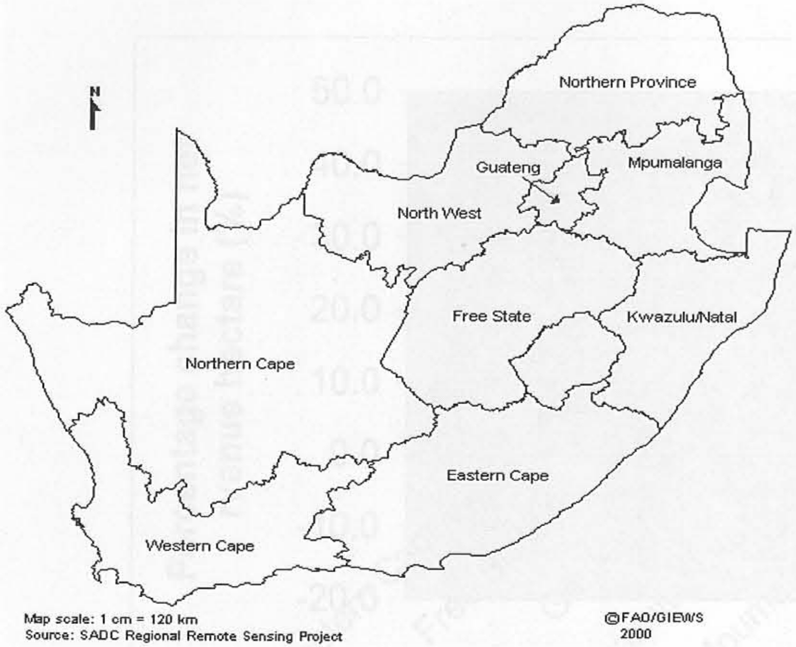
The benefits that occur due to rise in temperature and lower rainfall are somehow controversial. One would have expected that the Northern Cape Province characterized by the desert agro-ecological zone with lower rainfall region to experience damages instead of benefits. However, these results may be due to the fact farmers in a arid situations could be less sensitive because they have already adapted to harsher climatic conditions and have developed other alternatives such as irrigation to manage their unfriendly environment. Therefore 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.

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 2^0C 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 extend, 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).

Figure 5-16: South Africa provinces delimitation



Source: FAO/GIEWS (2001)

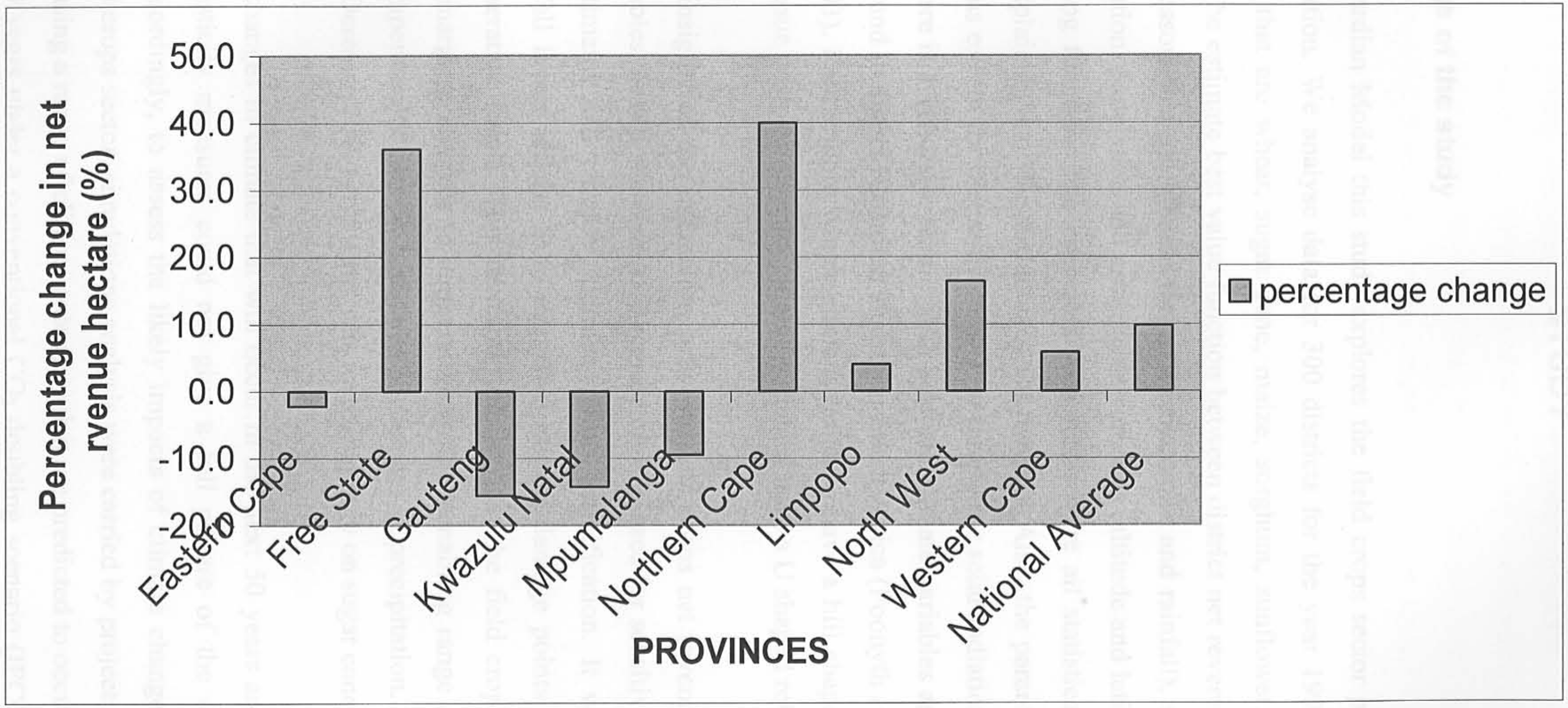
Table 5-6: Current level of provincial rainfall and temperature

Agro-ecological zones	Provinces*	Rainfall Pattern (mm)		Average Temperature (^{0}C)	
		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

Figure 5-17: Distributional effects of 2^0 C increase in temperature and 5% reduction in rainfall across South African provinces



CHAPTER 6 : CONCLUSIONS AND IMPLICATIONS OF THE STUDY

6.1 Findings of the study

Using a Ricardian Model this study explores the field crops sector performance to climate variation. We analyse data for 300 districts for the year 1993 and include seven crops that are wheat, sugar cane, maize, sorghum, sunflower, soybean and groundnut. The estimate best value function between district net revenues per hectare and the regressors that are climate factors (temperature and rainfall), soil indicators, labour, irrigation, population and geographic variables (altitude and latitude) is a non-linear semi-log function. The estimated parameters were all statistically significant and could explain 63% of the variation in net revenue. 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 as found in others Ricardian studies in South Africa (Poonyth *et al.*, 2002 and Deressa, 2003). Furthermore winter climate variables have a hill shaped relationship with net revenue whereas summer climate variables have a U shaped relationship.

For further insights of the interaction between field crops net revenue hectare and climate variables, firstly, the estimated regression was used for sensitivity analysis by elasticity estimates and climate optimum points identification. It was found that current rainfall levels are far from estimated critical damage points in contrary to current temperature levels. This therefore implies that the field crops 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 finding is in line with Deressa (2003) study that was focussing only on sugar cane.

Hence, the changes in climate that will occur in the next 50 years are not marginal changes; elasticity measures could not give a full picture of the climate change impacts. Accordingly, to assess the likely impacts of climate change on the South African field crops sector, simulations analysis were carried by projecting net revenue per hectare using a range of climate outcomes that are predicted to occur over a period of 30 to 100 years under a conventional CO_2 doubling scenario (IPCC, 2001a). 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 ha) were simulated using the coefficients of 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.

The study suggests seasonal variation in the response of net revenue to climate change. The results show that in summer, the rise in temperature has a positive effect on net revenue hectare, whereas decrease in rainfall reduces the net revenue. For winter, both rise in temperature and reduction in rainfall causes damage for the field crops net revenue. The results also confirmed that adaptation in the form of irrigation is an effective 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. Thus, net gains could be achieved in net revenue (Table 6-1).

Table 6-1: 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	+ 2^0C	-11	26	26	63	12	47
Rainfall	-5%	-4	26	-1	34	-2	27

Furthermore we examined the total effect of simultaneously changing both temperature and precipitation in all seasons on the net revenue. Since the climate scenario are uncertain, we firstly analyse how sensitive the estimates impacts are to divers climate scenarios from a mild scenario of 2^0C increase in temperature and 5% decrease in rainfall to a severe scenario of 3^0C temperature and 20% decrease in rainfall. The results show that differences among climate scenarios are important and these 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 6-2).

Table 6-2: Sensitivity of the impacts of climate change on net revenue to climate scenarios in percentage (%)

Climate change scenarios	Impacts on net revenue hectare (%)
+2^0 C and 5% reduction in rainfall	9
+2^0 C and 20% reduction in rainfall	-4.4
+3^0 C and 5% reduction in rainfall	17.3
+3^0 C and 20% reduction in rainfall	-11.3

Moreover, we also investigated the distributional effects of climate change in South Africa. Although the temperature rise and the rainfall reduction are uniform across the different districts, the spatial distribution of the impacts is not. Indeed, desert region, the interior steppe arid region and the subtropical winter regions will benefit from a 2^0 C and 5% reduction in rainfall, whereas the subtropical wet and the rest of the steppe arid region will suffer damages.

6.2 Limitations and Future studies

The findings of theses studies are based on aggregate district agricultural and climate data. Therefore results must be treated with some caution since important farm level decisions and phenomenon that influence net revenue may have been missed. This calls for further micro-level efforts in modelling agricultural climate change responses. Additionally, the study focused mainly on commercial agriculture hence future studies should take into consideration the subsistence agricultural sector as this sector is most at risk for various reasons and these farmers cannot avail themselves of risk pooling value of markets. With the adoption of the Ricardian approach in the present study, crop dependence on water availability is not fully captured, therefore future studies should also consider integrate water and agriculture since South Africa is a water scarce country. Moreover, although the adjustments to climate change (introduction or intensification of irrigation) are likely to entail economic costs, they are not fully reflected in the Ricardian approach adopted for this study. Thus, a region-specific analysis accounting for the relevant hydrology and institutional framework of water deliveries will be required to evaluate these costs in more detail (Cline, 1996; Quiggin and Horowitz, 1999 and 2003 and Schlenker *et al.*, 2003).

6.3 Conclusions and policy 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. For example, government bodies could provide farmers with good predictions of future climate change as well as information about appropriate adaptations. 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.

Finally, government need to commit itself to designing price and marketing policies that have a potential for reducing the risk and cost implications of the impact of climate change on agriculture in South Africa.

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.

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