PRODUCTION FUNCTION ANALYSIS OF THE SENSITIVITY OF MAIZE PRODUCTION TO CLIMATE CHANGE IN SOUTH AFRICA

by

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Submitted in partial fulfilment of the requirements for the degree

MSc Agric (Agricultural Economics)

in the
Department of Agricultural Economics, Extension, and Rural Development

Faculty of Natural and Agricultural Sciences

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Pretoria

July 2005

ACKNOWLEDGEMENTS

I would like to thank the institutions and individuals that contributed to the success of this study. The Agricultural Research Council for providing the data and all the assistance for this study. I would also like to thank Professor Rashid Hassan[1] for his patience and tremendously supervising me in undertaking this study.

I am very grateful to all my friends and especially to my family (Mama, Baba, Nkanyezi, Nyanga, Phesheya and Phakade) for supporting and encouraging me at all times. I dedicate this work to my dear late grandmothers MaNdlovu and MaMadlala.

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ABSTRACT

Production function analysis of the sensitivity of maize production to climate change in South Africa

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Abstract

Abstract

Maize production accounts for about 40% of the entire area cultivated in South Africa and is highly sensitive to climate variability. Maize is thus conservatively a staple food for more than 70% of the South African population whilst the maize industry stimulates the economy directly by providing secondary industries with over a billion worth of business each year. This study used the production function approach to evaluate likely impacts of climate change on maize production in South Africa. Data for this study have been obtained from experimental research sites in the 19 main maize producing regions in South Africa. The estimated coefficients of the production function model were used to derive measures of elasticity and optimal climate damage points as well as to simulate partial and total impacts of changes in levels of climate variables on maize yield. The Inter-Governmental Panel on Climate Change (IPCC) benchmark predictions of global warming for Southern Africa indicates that with the doubling of carbon dioxide in the atmosphere, a hotter and drier climate for the western semi-arid regions of Southern Africa and a hotter and slightly wetter climate for the eastern sub-tropical regions of Southern Africa are anticipated. Results indicated that rainfall and net solar radiation diffused within the maize crop have a non-linear and significant impact on average maize yield. Solar radiation rather than temperature was included in the regression analysis as temperature measures did not perform well. The results illustrated that increasing rainfall levels in all three main growth stages (sowing to emergence, juvenile to tassel initiation, and tassel initiation to grain filling growth stages) would increase maize yields whilst increases in solar radiation particularly during tassel initiation to grain filling would decrease maize yield. These results suggest that farmers could adopt a number of adaptation options including manipulation of planting dates,

introduction of heat tolerant maize varieties and other options to mitigate the negative impacts of highlighted increases in solar radiation levels. Results also showed that for the semi-dry regions of South Africa, early growth stages of the maize crop would be mostly affected by decreases in rainfall whilst for the wet eastern regions the forecasted drier conditions would affect mostly the late maize growth stages. To capture the cumulative impact of increasing solar radiation and rainfall amounts marginally across all growth stages, a climate simulation analysis whereby the two main IPCC warming scenarios predicted for the Southern Africa region were used. In the partial effects analysis rainfall and solar radiation changes were simulated separately for each growth stage at a time, whereas in the total effects analysis rainfall and solar radiation changes were simulated simultaneously across all growth stages. Results of these analyses suggest that the west semi-dry regions of South Africa might benefit from the forecasted decreases in both rainfall and solar radiation, especially if sensitivity of the maize crop during its second growth stage is mitigated through the introduction of irrigation. This study also illustrated that maize production in the wet east regions might benefit in all its three growth stages from the forecasted increases in rainfall and solar radiation, especially if sensitivity of the first growth stage is reduced through the possible shifting of planting dates to mitigate the effects of increased rainfall forecasted for this region. One should note however, that the maize crop has the ability to agronomically adapt easily to drier conditions. Other attributes which further assists the resistance of the maize crop to climate changes, include extensive conservation soil tillage farming practices which could be applied to optimise soil infiltration rates whilst minimising evaporation rates, thus reducing soil erosion. The above results highlight the need for investments in improving the adaptive capacity of farmers, especially small-scale farmers who are severely restricted by their heavy reliance on natural climate factors and at the same time lack complementary inputs and institutional support systems. The existence of institutional support systems may assist farmers in further understanding anticipated climate changes and available conservation agricultural practices e.g. cost effective irrigation control systems. Other adaptation options include improved capacity of all the stakeholders involved in maize production (farmers, processors, marketers, exporters etc.) to better the ability to cope with the adversities of climate change through the use of farm planning, available crop insurance systems with regards to floods and droughts, improved weather and climate monitoring and forecasting. At a regional scale, extensive agricultural planning and risk reduction programmes may assist with spreading losses over larger regional areas, which may serve to reduce overall risk to growers. One important limitation of this study was that the analyses focused on the experimental sites only and hence did not consider all maize production areas across the country (which includes sites under small-scale farming). Also, the model adopted for this study also did not include the effects of carbon dioxide fertilisation and price movements, which are crucial. In conclusion, then, there is an urgent need for the South African National Department of Agriculture to look at how maize farmers (and especially small-scale farmers) could be assisted in adapting their traditional cropping methods to the forecasted changes in climate, whilst taking into consideration all the options presented above.

CHAPTER 1: INTRODUCTION

1.1 Background and motivation of the study

The climates of Africa range from humid equatorial regimes, through seasonally arid tropical regimes, to sub-tropical Mediterranean-type climates. All these climates exhibit differing degrees of temporal variability, particularly with regard to rainfall and temperature. Understanding and predicting these inter-annual, inter-decadal and multi-decadal variations in climate has become the major challenge facing most African climate scientists in recent years. The work of examining climate variability, especially rainfall, has also been set in the wider context of the emerging understanding of human-induced climate influences that are referred to as climate change (Hulme et al., 1999).

The scientists of Working Group II of the Intergovernmental Panel for Climate Change (IPCC) have predicted that increases in greenhouse gas concentrations will result in a rise in both mean temperature of about 2^0C and precipitation levels by the middle of the next century, causing a significant climate change throughout the world (IPCC, 1996b). These changes in temperature and precipitation will result in adverse changes in land and water systems that will subsequently affect agricultural productivity (Dinar et al., 1996; Kurukulasuriya and Rosenthal, 2003). As the threat of climate change gains momentum, the importance of exploring the relationship between agricultural performance and long-term climate effects through variables such as temperature, rainfall and atmospheric carbon dioxide concentration levels, especially in developing countries, is growing. Numerous factors influence the performance of agriculture; among these, climate change is gradually being recognised as a key element in shaping the form, scale, size and time-frame of agricultural productivity.

The News Highlights Report of the Food and Agricultural Organisation (FAO) (FAO, 2001) has observed that in Sub-Saharan Africa, long-term climate change would negatively affect agriculture, as well as threaten food security for the world's most vulnerable people. This report further indicated that climate variability and especially climate extremes, which are more difficult to plan for, might become more frequent, putting additional stress on fragile farming systems. Moreover, climatic and agro-ecological zones would shift, forcing farmers to adapt and threatening natural vegetation and fauna. This would further mean that the current imbalances in food production between tropical, sub-tropical and cool temperature regions could increase. Research has also shown that, specifically in tropical regions (in which, incidentally, most of the poor countries are situated), impacts on agricultural productivity are expected to be harmful. Experts have also predicted major reductions in agricultural production and increases in poverty levels in tropical regions, as livelihood opportunities for people engaged in the agricultural sector will increasingly become susceptible to anticipated climate pressures (Kurukulasuriya and Rosenthal, 2003).

Droughts have been found to be one of the main production constraints in Southern Africa. Research focussing on South Africa, Lesotho, Swaziland and Zimbabwe has reflected concerns about the droughts that have afflicted these countries in the years 1984/85 and 1991/92. These droughts have had a significant impact on the production of maize – the staple crop of Southern Africa (CIMMYT, 2001). Maize, together with wheat, represents more than 80% of the total cereal area under production in South Africa. The maize industry also stimulates the economy directly by ensuring a livelihood for more than a million South Africans, whilst providing secondary industries with over R1.5 billion's worth of business each year. Nutritionally, maize products are also an essential part of the South African diet – 35% of the carbohydrates, 15% of the fat and 31% of the protein requirements in the South African diet are supplied directly by maize products. White maize is the staple food for a large section of the population in South Africa, whilst yellow maize is mainly used as animal feed. Despite this dependency on maize, the economics of maize production, especially in the summer grain areas of South Africa, has deteriorated during the past decades. This has been partially due to the fact that the price of production inputs has risen more rapidly than the producer price of maize itself (Meyer, 1998).

The First National Communication under the United Nations Framework Convention on Climate Change for South Africa have also highlighted maize production amongst others as an area of highest vulnerability to climate change, emphasizing the economic assessments of the potential impacts of climate change on this sector (www.unfccc.ntl/national communications, 2004). However, only very few studies have been conducted to analyse the impacts of climate change on South African agriculture. These studies included the study by

Erasmus et al. (2000), which looked at the effects of climate change on the Western Cape farming sector using a mathematical programming model. This study however, considered only impacts on large commercial farmers in the need for Western Cape.

Another study by Poonyth et al. (2002) studied the economic impact of climate change on agriculture in South Africa, specifically analysing the sensitivity of different crops to climate change using an econometric approach (the Ricardian model). The said study employed time series data, which mainly captured weather fluctuations rather than long-term climate shifts and also did not consider the impacts of climate change on the more vulnerable small-scale farmers in South Africa. Schulze et al. (1993) also assessed the potential production of maize under different climatic conditions and concluded that under elevated carbon dioxide and temperature conditions, there is an overall increase in potential maize production even though there are places in which yield of maize decreases. Du Toit et al. (2001) conducted a study in which the CERES crop growth simulation model was used to analyse the vulnerability of maize production to climate change in the nineteen main maize-producing sites in South Africa. This study indicated that South African maize is characterised by variations in yield that are mainly due to fluctuations in seasonal precipitation. The said studies however, were not able to analyse and measure the economic impacts of climate change.

Deressa (2003) and Gbetibouo (2004) utilized cross-section data that reflect climate variations and applied the Ricardian approach to analyze the impact of climate change on South African sugarcane production and field crops, respectively. Maize as a crop was not studied by either, however. Although Schulze et al. (1993) and Du Toit et al. (2001) studied the impact of climate change on maize production, these studies were based on agronomic models and made no attempt to examine the economic impacts of potential changes in climate. The lack of research work assessing the economic impacts of climate change on maize production in South Africa, presents an important limitation for formulating appropriate policy measures and response strategies to mitigate negative climate change impacts on the poor through the production of this basic food staple for the majority of South Africans and especially the poor. The present study therefore made an attempt to analyse and measure the economic impact of climate change on maize production in the country. The study focussed mainly on selected significant factors including soil condition, rainfall, solar radiation for the various physiological growth stages of the maize crop. The study applied the production function approach to the same experimental data employed in the crop simulation analysis of Du Toit et al. (2001). The use of a production function model will further our understanding of designing adjustment strategies that could assist both commercial and small-scale maize producers in adapting to the adverse impacts of climate change, whilst improving their export abilities.

1.2 Objectives of the study

The main objective of this study is to develop and apply a farm-level production function model to measure and analyse the economic impact of climate change on South African agriculture, using maize production as a case study.

Under this main objective, the following specific objectives will be pursued:

1. To develop and apply a production function model to assess the sensitivity of maize production to climate change in the nineteen main maize-producing sites in South Africa;

2. To assess and highlight results from the above production function approach and the results obtained from applying the CERES crop growth model to the same data set, which has been used to assess the vulnerability of maize production to climate change in the same nineteen maize-producing sites (Du Toit et al., 2001).

3. To use the results of the estimated empirical model to inform policy design, research and extension in planning potential effective adaptation options to mitigate negative climate change impacts.

1.3 Approach and methods

To achieve the above objectives, the study adopted a production function approach using experimental cross-sectional data to determine and examine the sensitivity of maize crop yield to climate variables (rainfall, temperature and solar radiation) controlling for the effects of key production inputs such as fertiliser, labour and machinery. This approach will look specifically at the three main maize growth stages, (i.e. the sowing to emergence growth stage, end of juvenile to tassel initiation stage and end of tassel initiation to grain filling stage) in the nineteen main maize-producing sites of South Africa.

1.4 Organisation of the study

The study is organised into six chapters. The next chapter provides an overview of agriculture in the South African economy and contribution of the maize industry to the national economy while discussing the influence of climatic patterns on maize production. The role of small-scale producers in the maize sector and South Africa's climate change policy initiatives are also assessed. Chapter 3 reviews past approaches and studies undertaken to measure the sensitivity of agriculture as a whole and maize production in particular, to climate change. Chapter 4 describes the methodology adopted and data used to conduct the intended analysis. The econometric procedures used to estimate model parameters and results of the empirical analyses are presented and discussed in Chapter 5. The final Chapter draws conclusions and implications of the study.

CHAPTER 2: Maize Farming and Climate Change in South Africa

2.1 Introduction

This chapter provides an overview of the agricultural sector and maize production trends in South Africa. It underscores the importance of agriculture to the South African economy and, more specifically, its contribution to the Gross Domestic Product (GDP), external trade, employment and food supply and security. Thereafter it describes maize farming in South Africa, focusing on maize production regions, production trends and consumption patterns. A discussion of South African agricultural policies focusing on maize policy changes and maize subsidies will then draw attention to the existing economic vulnerability of small-scale farmers, which in turn contribute to the maize sector's vulnerability to climate change**.** In the final section of this chapter, climatic patterns of South Africa, and the sensitivity of agriculture in general, and the maize industry in particular to climate change are explored.

2.2 Importance of agriculture to the South African economy

South Africa covers an area of 1.2 million square kilometres. Approximately 84% of this is used for agriculture and forestry; of this area in turn, approximately 80% is mainly used as natural grazing. The vegetation varies widely from the semi-desert of the north-western Karoo to the highly productive grasslands of the high rainfall areas located in the Mpumalanga, Eastern Cape and KZN regions. In comparison with other countries in Sub-Saharan Africa, South Africa has a very small amount of high-quality arable land (15.8 million hectares) of which only 1.29 million hectares (i.e. a mere 8%) are under irrigation (Jooste and Van Zyl, 1999). The agricultural sector encompasses primary agricultural activities, input (e.g. seed, fertiliser etc.) and financial sectors and agro-processing firms. Together with the agro-food sector, the agricultural sector contributes between 14% and 20% to the GDP, remaining the main source of employment in rural areas and an important earner of foreign currency (Stats SA, 2002).

The gross value of agricultural production also plays a significant role in the economy, to which field crops and animal products have been the major contributors, between 35.85% and 42.94%, respectively, whilst horticultural products have gradually but substantially increased their contribution to the gross value of production from 1960 to 1994 (Jooste and Van Zyl, 1999). Table 2.1 shows that the total gross value of agricultural production has increased substantially from R14.7 million in 1960 to R22 million in 1975. It also shows a significant decrease in the value of agricultural production from R22 million to R17 million between 1975 and 1993.

Table 2.1: Gross value of agricultural production (R Million)

Years	Field Crops		Horticultural Crops		Animal Products		Total
	Rand Million	%	Rand Million	%	Rand Million	%	Rand Million
1960/61	6,289.70	42.63	2,163.80	14.67	6,298.30	42.70	14,751.80
1975/76	9,527.50	41.73	4,005.30	17.54	9,296.20	40.72	22,829.00
1993/94	6,110.10	35.85	3,615.60	21.21	7,317.80	42.94	17,043.50

Source: Jooste and Van Zyl (1999)

The agricultural sector also has strong economic and employment linkages with other sectors of the economy, such as the manufacturing (particularly agro-based industries), thus contributing substantially to economic growth. The National Department of Agriculture (NDA) reported that natural catastrophes, such as the recent floods, which destroyed parts of the Northern Province and Mpumalanga in February 2000, and countrywide droughts in the 2003/2004 summer seasons, have had a strong impact on the economy as a whole. The floods, for instance, resulted in the GDP growth rate dropping by 1%, as most of the crops were flooded and as less yield were obtained (NDA, 2001). It should be pointed out that, although the percentage appears to be small, a 1% drop in the growth rate of total income (GDP) is not by any means a negligible impact. This demonstrates the importance of the agricultural sector; such that, any factor affecting agriculture will evidently influence the rest of the economy as well. Studies on the economy-wide impacts of agriculture indicated that a 1 % growth in the South African agriculture induces more than 1% growth in non-agricultural sector (Poonyth et al., 2000).Similarly the agricultural sector's income and employment multipliers indicate that investments in the agricultural sector induce a remarkable effect on the overall economy. For example, a 1% growth in agricultural production would result in a 1.23% to 1.46% growth in aggregate production in the South

African economy as a whole (Van Rooyen et al., 1998; Van Zyl, 1998; Mc Donald et al., 1997).

The agricultural sector's purchases of goods such as fertilisers, chemicals and implements form backward linkages to the manufacturing sector, while forward linkages are formed through the supply of raw materials to industry. Two thirds of South Africa's agricultural output is used as intermediate input in almost all sectors of the economy (NDA, 2001). In substantiation of this claim, we will now explore the specific contributions of the agricultural sector to the GDP, to the external trade balance and to employment.

2.2.1 Contribution of agriculture to total output (GDP)

The contribution of agriculture to the overall economy is much greater than suggested by the quoted figures of its shares in the GDP (NDA, 2001). The GDP annualised percentage change[2] of the agricultural sector has been fluctuating between 7.9% in 1994 and 4% in 2002, with drastic falls in 1995 and in 1998 (Table 2.2). These fluctuations have been attributed to a number of external factors, which mainly include competition in the global agricultural markets and climatic conditions experienced during these periods. The stability of the manufacturing, electricity and water, transport and communications sectors can be observed from their annual percentage changes (Stats SA, 2002).

Presently the agricultural sector accounts directly for 4% to 5% of the GDP. However, droughts and low crop yield negatively affected the national income by as much as 0.5% to 2% (NDA, 2001).

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[2] **Annualised percentage change** refers to the growth rate per year from the previous year and compounded to the annual rate (Mohr, 1998).

Table 2.2: Annualised percentage change in Gross Domestic Product by sectors

Years	Agriculture forestry and fishing	Manufacturing	Mining and Quarrying	Electricity and Water	Construction	Transport and Communications	General Govt. services
1994	7.9	2.7	0.5	5.8	2.9	4.6	1.0
1995	-19.9	6.5	-3.1	2.0	3.6	10.6	0.8
1996	24.0	1.4	-0.8	10.8	2.0	6.1	1.9
1997	0.9	2.7	1.7	3.9	3.4	7.6	0.8
1998	-6.8	-1.9	-0.8	1.6	2.6	6.7	-0.4
1999	5.1	-0.3	-1.1	1.8	-2.4	7.1	-0.7
2000	7.6	5.1	-2.3	0.7	2.7	7.0	-0.9
2001	-1.7	3.0	-1.5	1.3	5.5	6.9	-0.5
2002	4.0	4.0	-0.6	1.5	2.1	6.2	0.8

Source: Stats SA (2002)

2.2.2 Contribution of agriculture to the external trade balance

Table 2.3 below shows that, in terms of export earnings, agriculture has contributed between R36 410 million (1985) and R163 180 million (1999) annually to the external trade balance. It further reveals that the share of agricultural exports in the country’s total exports has in fact increased from about 8% before 1994 to almost 10% by 1996 – an impressive performance, given the size of South Africa’s total exports in the mining sector and agricultural products. The share of processed agricultural products within the country’s total agricultural exports has also increased from 34% to 50%, further strengthening its linkages to this industry (DBSA, 2001). The growth of the trade balance surplus can further be attributed to faster growth in exports than in imports, which has been triggered by the integration of this sector into the international market.

Table 2.3: Contribution of agriculture to the external trade balance in South Africa

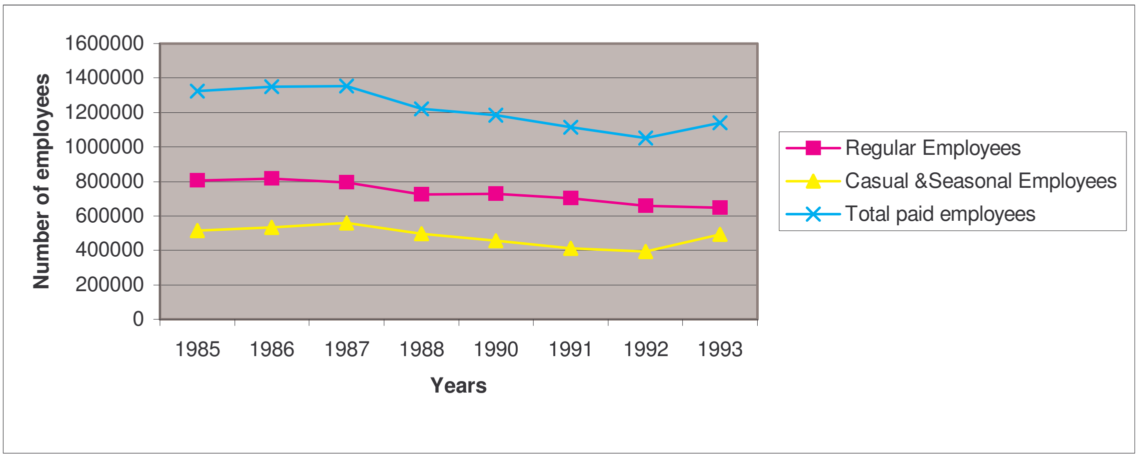
Year	Total exports (Rm)	Total Imports (Rm)	Net export (Rm)	Agric exports as % of total exports	Agric imports as % of total imports	% of trade balance apportioned to agriculture)
1985	36 410	22 731	13 678	6.5	5.7	0.8
1986	41 327	26 863	14 464	7.3	5.5	1.8
1987	42 762	28 672	14 089	7.5	5.3	2.2
1988	49 360	39 483	9 876	7.6	5.2	2.3
1989	58 728	44 741	13 986	9.7	4.6	5.1
1990	60 770	44 141	16 628	8.7	4.9	3.7
1991	61 146	44 195	16 951	8.9	5.5	3.2
1992	69 196	52 594	16 602	7.8	8.5	-0.7
1993	80 938	59 078	21 859	6.8	6.4	0.3
1994	90 328	79 541	10 786	8.8	6.1	2.7
1995	101 503	98 512	2 990	7.9	6.9	1.1
1996	126 044	115 537	10 507	9.2	6.6	2.6
1997	143 814	129 907	13 906	8.5	6.6	1.9
1998	156 184	146 805	9 379	8.6	6.4	2.2
1999	163 180	147 091	16 089	8.8	6.1	2.7

Source: Stats SA (2001)

2.2.3 Contribution of agriculture to employment

The agricultural sector provides employment for about one million workers, making up 11% of total formal sector employment in the country (Figure 2.1). Many of these workers live on commercial farms, and their children receive education in farm schools. This form of agriculture thus provides both a livelihood and housing for a further 6 million family members. In addition, there are about 240 000 small-scale farmers who provide a livelihood for more than 1 million of their own family members, whilst there are also occasional, seasonal employment opportunities for about 500 000 people in the sector every year (Vink and Kirsten, 1999).

Figure 2.1: Farm employment in South Africa (1985-1993)



Source: Kirsten and Van Zyl (1996)

2.2.4 Food supply and food security in South Africa.

South Africa has only 14 %percent of the total surface area available for crop production, and of this area only 1 million hectares are under irrigation. High potential land comprises of a mere 21.9 percent% of total arable land, with natural grazing deteriorating at a fast rate whilst nature conservation areas are highly threatened. The most important restriction on agricultural production is the availability of water. Recent droughts in addition to policy changes within the sector have worsened the situation (NDA, 2001).

Despite all these restrictions, South Africa is self sufficient in the production of most major crops. In the 1980s, it was self-sufficient in terms of all important field crop products (except rice) and horticultural products, achieving above 100 points on the self-sufficiency index[3] for certain field crops and above 160 for horticultural products. Since 1984, South Africa has experienced a strong growth in agricultural exports and an analysis of its trade performance reveals a comfortable surplus on the agricultural balance of payments, with exports growing at a faster rate than imports (Kirsten and Van Zyl, 1996).

The other essential role of agriculture is to ensure a secure supply of food to the consumer at reasonable prices. However, food supply involves more than merely agricultural production.

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[3] **Self Sufficiency Index (SSI)** refers to total production divided by total local consumption multiplied by 100.

An effective food distribution system is as important, especially to the rural poor. It is thus essential for South Africa to maintain a competitive agricultural sector that is able to meet the demand for basic foodstuffs.

Agricultural production in South Africa increased at a rate of 3.1% per annum between 1955 and 1990, while the population increased at a rate of 2.8% (Meyer, 1998). For the period 1990 to 1998, the nominal value of agricultural production increased at an average annual rate of 13.7%, whilst consumer price indices increased by an estimated 9.7% over the same period, indicating an increase in the real value of agricultural production of 4% (NDA, 2000). Thus the agricultural sector has succeeded in increasing production although South Africa does experience shortages in certain agricultural products and therefore needs to import them.

The increasing exposure of commercial farmers to market forces has also set in motion large structural adjustments within the agricultural sector. Recently, there has been significant reduction in field crop production, especially maize. However, according to Breitenbach and Fenyes (2000), economic growth between 4% and 6 % currently observed in South Africa can stimulate consumption to such an extent that food shortages could be expected in the long run.

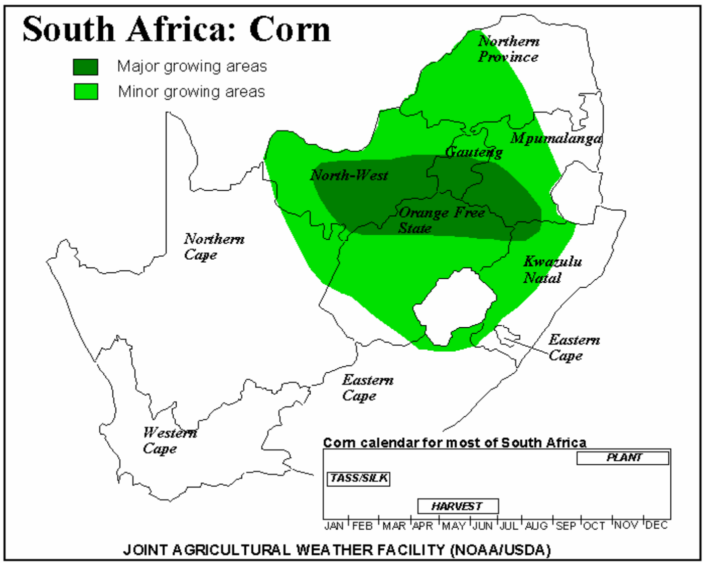
2.3 Maize farming in South Africa

The following sections will look at maize production in South Africa, highlighting major maize producing regions. This is followed by discussions on maize production trends and maize consumption patterns in the country.

2.3.1 Maize production regions in South Africa

South Africa's maize-producing regions include the provinces of the Orange Free State (OFS), North-West (NW), Gauteng, KwaZulu Natal (KZN), Mpumalanga (MP) and the Northern Province (NP), with parts of the North-West, OFS, Mpumalanga and Gauteng being the major maize-growing areas (Figure 2.2).

Figure 2.2: South Africa's main maize producing areas



Source: USDA (1999)

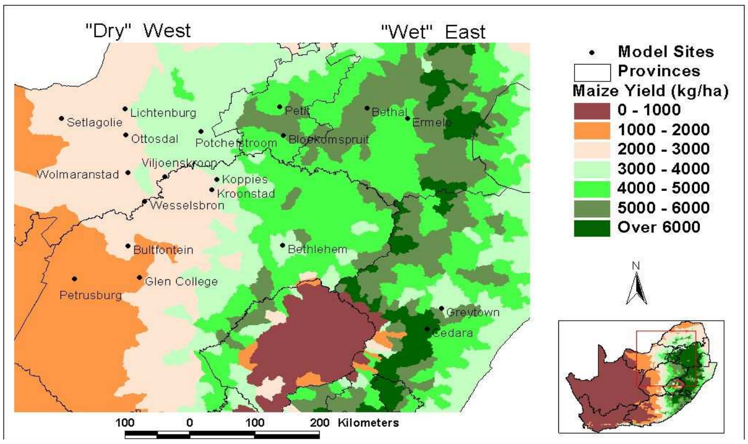
These maize-producing areas can be further divided into the dry west and the wet east. Currently, the dry western areas contribute about 60% of all maize produced, while the wet eastern areas contribute contributes the remainder of this total (Figure 2.3).

Moreover, areas further to the west of the country (such as the south-western Orange Free State, for instance) have been found to be too dry for maize production, whilst areas to the east of the maize region (KZN) are already being used for the production of speciality crops like sugarcane (Du Toit et al., 2001).

The maize-producing regions are distinguished from each other mainly by yield (kg/ha) and by the production practices they employ to optimise production under the current climate (Figure 2.3).

Figure 2.3: The "Dry" Western and the "Wet" Eastern maize-producing areas of South Africa

Source:



Jooste and Van Zyl (1999)

Some of these production practices are illustrated on the map above, and are described below.

- The dry western areas, which make up the main maize-producing region, are characterized by water-limited production practices. For example, the rows of plants are more widely spaced (150 cm apart), and lower densities (2.0 plants per m^2) are used to ensure that each maize plant has access to soil moisture by minimising competition from other plants. Furthermore, the maize crop is mainly planted at the beginning of the rainy season (around the middle of November) to reduce the need for irrigation.
- In contrast, in the wetter eastern areas, the higher precipitation allows more dense planting, with rows planted 90 cm apart and 3.0 plants per m^2. Furthermore, the maize crop is planted during the rainy season (early October), (to maintain and accelerate the sowing to emergence growth stage) and although this management strategy uses more water, it provides higher average yield.
- As a rule of thumb, for both dry and wet areas experts estimate that a harvest of 2 000 to 2 500 kg/ha is the necessary 'break-even' point to ensure the economic viability of a crop (Du Toit et al., 2001).

2.3.2 Maize production trends in South Africa

Maize is of major importance for the South African economy. In 2000, maize yielded over 15% of the gross value of all agricultural products, while accounting for about 40% of the entire cultivated area in the country. South Africa meets its annual maize consumption requirements entirely from domestic production, which has been steadily increasing over the years. Local consumption of maize is about 7.5 metric tonnes per year, but the country often produces surpluses that are exported, mainly to neighbouring countries in the SADC region (NDA, 2001).

Interestingly, despite the growth in production, the entire area used by maize farming has in fact declined from 3.8 million hectares in the mid-eighties to approximately 3 million hectares in 1996/1997 (Table 2.4). For the past decade, an average of approximately 8 million tons of maize has been produced every year. Although the area planted has declined during the same period, the relative stability of production can mainly be attributed to the fact that the yield has increased over the years as production technologies have improved.

Yellow maize yield were normally higher than white maize yield, with yellow maize being at its lowest in the drought year of 1991/1992 and it's highest in the 1993/1994 production year. The highest yield of white maize has been achieved from 1994 to 1996, indicating higher yield during this period; this can be attributed primarily to the fact that white maize is used mainly for human consumption and yellow mainly for animal feed (Table 2.4).

During the drought years (1991/1992 and 1994/1995), even though there were brief declines in the yield, commercial maize producers were able to recover quickly due to government subsidies and grants instituted through the Maize Board and through other government policies. These policies existed until 1996-1997, after which the Maize Control Board ceased to operate; this was significant, as "free agricultural trade policies" were introduced at the time (Essinger et al., 1998).

Table 2.4: Maize production trends in South Africa (1989/90-1998/99)

Production years	Area Planted (1000 ha)	Yield (tonnes/hectare)		Production (1000 tonnes)	
		White Maize	Yellow Maize	White Maize	Yellow Maize
1989/90	3 816	2.22	2.59	4 362	3 982
1990/91	4 176	2.23	2.49	3 830	3 996
1991/92	4 377	0.67	1.06	1 252	1 703
1992/93	4 661	2.23	2.78	4 416	4 661
1993/94	3 526	2.83	3.35	5 759	6 308
1994/95	3 761	1.51	1.47	2 120	2 286
1995/96	4 023	3.07	2.75	5 836	3 858
1996/97	3 560	2.57	2.47	4 614	3 874
1997/98	3 567	2.43	2.32	4 384	2 694
1998/99	3 868	2.26	2.39	4 141	2 574

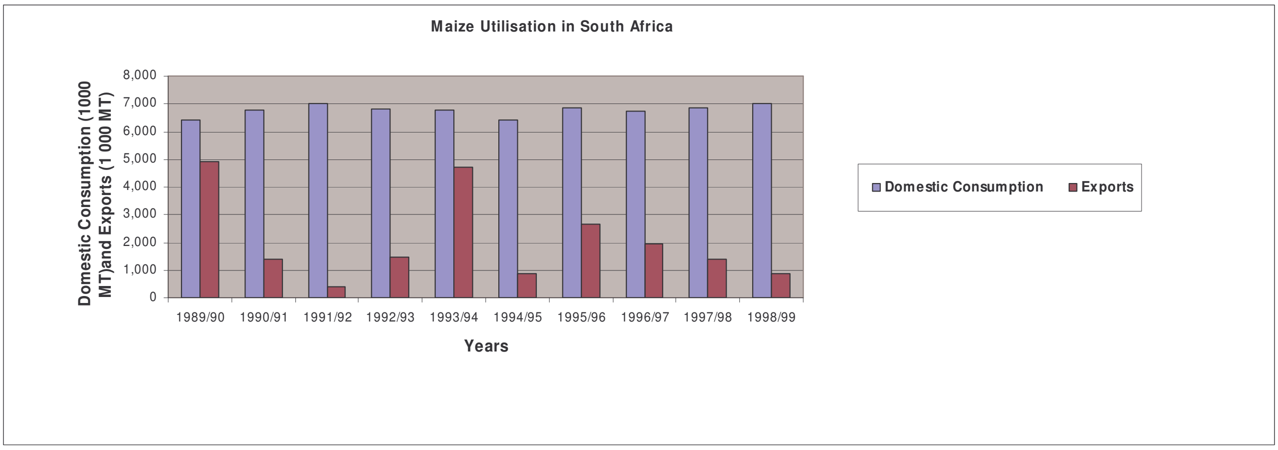
Source: NDA (2001)

2.3.3 Maize consumption patterns in South Africa

The local consumption requirements in 1999 were estimated at 7.5 million tons, made up of 4.4 million tons of white maize and 3.1 million tons of yellow maize. From 1989/1990 to 1998/1999, exports fluctuated between a high of 4 909 000 MT and a low of 890 MT (Figure 2.4). Such exports of maize and maize products, mainly to Zimbabwe, Japan, Zambia, Malawi, Mauritius, Kenya and Mozambique, illustrate the importance of maize as an earner of foreign revenue for South Africa (NDA, 2001).

According to the NDA (2001), there was a marginal increase in the domestic use of maize during the years 1989/1990 and 1991/1992. During that same period (1989/1990 to 1991/1992), however, exports decreased as the supply of maize decreased due to (1991/1992) droughts and political instability in country. However, large amounts of maize were again exported when South Africa experienced a bumper maize crop in 1993/1994 (Figure 2.4).

Figure 2.4: Maize utilization in South Africa (1989/90-1998/99)



Source: NDA (2001)

2.4 South Africa's Agricultural policy and the maize industry.

In the following sections, the South African agricultural policy will be discussed. In these sections, the role which the government has played in controlling food prices, access to the use of natural resources, agricultural finance, labour, and local markets will be investigated. Thereafter, the impacts of the South African agricultural policy on the maize industry will be investigated by looking at the role played by the maize boards, whilst the overall deregulation process of the maize industry will be discussed. This will be followed by discussions on the role which has been played by small-scale farmers in the maize production industry. In this section, the vulnerability of these farmers to both policy changes and potential climate change impacts will be highlighted. Lastly, new climate change initiatives taken by the South African government will be reviewed.

2.4.1 The South African Agricultural Policy

The importance of agriculture to the South African economy requires sound government policies. The agricultural sector has however, experienced a long history of state intervention, which reached its highest point around 1980 with a host of laws, ordinances, statutes and state regulations. Agricultural policy in many cases still affect all aspects of agriculture, which include prices of products, access to the use of natural resources, finance, capital, labour, and local markets. This also has contributed to the segregation and inequalities between commercial farmers and small scale farmers (emerging farmers) of South Africa (Meyer, 1998; Essinger et al., 1998; Jooste and van Zyl, 1999; and Beyers, 2001).

The early part of the 1930s saw initial steps towards changing South Africa's agricultural policy aimed at the territorial segregation of white and black farmers. These agricultural policies saw the former homeland states pressurising their farmers to produce more food whilst investment towards large-scale development projects under expatriate management was also increased. The 1960s saw the commercialisation of white farming through the adoption of modern mechanical and biological technology, resulting in consistent growth in output within a policy environment heavily favouring white commercial owner operated farms (Essinger et al., 1998).

In the maize sector, the state intervention was triggered by the collapse of buying power in 1929 which saw maize prices drop, which then threatened the stability of the domestic maize industry. With the introduction of the Mealie Control Act of 1931 it was stipulated that maize traders had to export a percentage of the maize they purchased each year. This was an attempt to rid South Africa of surplus maize and to drive local producers in asking for prices above export prices. In 1935 the Maize Board (then the Mealie Industry Control Board) was established and the government laid out the framework for a one-channel market and their control over the maize industry. At this time government also offered export quota certificates to stabilise volatile prices.

In 1937, the Marketing Act was introduced and later followed by the Agricultural Marketing Act of 1968 which imposed levies on producers to subsidise export prices of maize in South Africa. This law also allowed for the purchases and sales of maize by the Board and required maize producers to report their net return monthly. By 1941, the Maize board was the main body to set maize prices which were later based on production costs due to droughts and floods in the country. However in 1968, what had been instituted under the Maize Board (1935) became law with the Agricultural Marketing Act. This Act provided white commercial maize farmers with considerable power to influence prices and marketing arrangements through different control boards. Networks of agricultural support institutions for research and extension services were also put in place to implement public sector involvement in white South African commercial agriculture (Ngqaweni et al., 1998; and Jooste et al., 1999).

2.4.2 The Maize Board and the deregulation of the Maize sector

The Maize Control Board regulated the grain industry in every aspect of marketing from the price producers receive, to financing storage facilities, to purchases for millers, and the exportation of the crop itself. All sales and purchases were made through this Board; The Board also provided informational services, inspection services, and laboratory functions whilst setting grades and standards for the maize industry. The Board continued to regulate the marketing of major agricultural commodities until 1997 (Essinger et al., 1998).

Changes in the late 1980's saw the political economy of South Africa transforming the agricultural policy, leading to the lifting of a number of controls. These included a decline in the budgetary allocation which supported white farmers between 1987 and 1993. This period also saw a shift from settlement schemes and large scale projects as the major instruments of agricultural development (especially in the former homelands) to an approach based on the provision of farmer support services which included extension services, and access to credit and markets (Kirsten et al., 1995). In 1987, the Maize Board and the government took another step towards deregulation, as it was decided that farmers could sell grain to other sources besides the Maize Board. The Maize Board also changed from a cost of production system to a pool price system that fixed the selling price based on a domestic market (Essinger et al., 1998).

In 1994, with the new government of national unity, the New Marketing Bill of 1994 was introduced which led to the termination of the old Marketing plan. It stopped the one channel domestic market, prices were no longer fixed under statutory regulations, and little control was held over silos that stored grain. In April 1997, the Maize Board changed its mandate to that of only supplying market information and administering levies (The Maize Board Annual Report, 1996).

2.4.3 The role of small-scale farmers in maize production in South Africa

The most recent challenge faced by small-scale farmers in developing countries is the decline in worldwide relative prices for traditional export commodities. These have been compounded by the increasing costs of inputs at farm level due to structural adjustment programmes.[4] These structural adjustments have removed subsidies and increased supply costs, which have, among other things, led to the deterioration of government maintained rural infrastructure. All of the above have resulted in reductions in profit margins (Poonyth et al., 2000).

Small-scale farmers in South Africa produce and export comparatively few crops; these include mainly maize, cotton and other vegetables. The average amount of land allocated to smallholder farming in rural South Africa is between 0.2 and 1 hectare per capita, compared to 2.5 hectares per capita in commercial farming areas. Of the nine South African provinces, the greatest proportion of land used by small-scale agriculture is in KZN, the Northern Province, the Northwest and the Eastern Cape Province (Ngqaweni et al*.*, 1998).

Some 240 000 small-scale maize farmers in South Africa supply local and regional markets, where large numbers of informal traders make their living. Furthermore, there are an estimated 3 million small-scale maize farmers, located mainly in the communal areas of the former homelands, who primarily produce to meet their families' nutritional needs. Effectively, then, these small-scale maize farmers, who depend for their survival on maize farming and related industries, comprise more than half of the country's provinces and about 40% of the country's total population (NDA, 2001).

There are three classes of small-scale maize farmers. The first of these are small-scale commercial emerging farmers who export most of their produce, whilst continuing to improve their production practices by introducing and applying improved technology, seed, pesticides, fertilisers, herbicides etc. The second group of small-scale farmers (emerging commercial farmers) are those whose produce is consumed locally, and who still use some of

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[4] Since 1994, the South African agricultural sector has seen a number of structural adjustments, which include drastic changes in export and import policies, trade policies, and the removal of government subsidies, especially on farm production inputs (fertiliser, seed, extension services etc.).

the traditional methods as part of their production practices. The third group consists of maize subsistence growers. It is this last group of relatively resource-poor farmers, which has been identified as being the most vulnerable to climate variability, as they depend for assistance on government subsidies, on the infrastructures of non-governmental organisations and on other entities in times of droughts and floods. These farmers also seldom apply any form of technological improvements to their production practices, e.g. they seldom use hybrid maize seeds, fertilisers and chemicals unless these are provided by the government or by non-governmental organisations.

A number of questions have arisen over the years, concerning the survival of these small-scale maize farmers. The following two are the most important of these:

- Can small-scale maize farmers survive alongside their more technically and institutionally advanced and more organised large-scale commercial counterparts?
- Can these relatively resource-poor rural maize farmers in South Africa be brought back into the mainstream maize economy, through policy support of increased smallholder agricultural production for the market?

According to a study by Ngqaweni et al. (1998), small-scale agriculture does potentially have a comparative advantage for the use of rural resources in selected agricultural activities. Increased attention is urgently required from policy-orientated and technology-orientated researchers, as is increased agricultural and infrastructural investment in high-potential areas that can accommodate small-scale farmers. However, changes in the political economy have generally not affected small-scale farmers of South Africa, as they have always been outside government policies. This can be seen in their production activities, the problems that they still encounter in accessing the export market, and other market-related problems. The policies of the past have also seen commercial farmers receiving a number of grants and subsidies through the Maize Board in response to climate-related factors for many years, thus improving their stability and encouraging the use of adaptive measures. This has enabled primarily white commercial farmers to adapt faster to climate changes, and consequently to survive in the world export markets, but it has left small-scale farmers more vulnerable, especially in times of drought and floods. It is thus imperative to assess the economic impacts of climate change on maize production in a way that includes this sector of small-scale farmers.

2.4.4 South Africa's climate change policy initiatives

The South African government has begun to realise the impact which climate change will have on the different spheres of the economy and especially on small-scale farmers. This realisation that climate change will definitely affect the country is evidenced by the initiation of the following policies and measures:

- National Department of Agriculture's Strategic plan for South African agriculture has outlined sustainable resource management as one of the three core strategies where issues of adaptation to climate change and sustainable development are to be dealt with.
- The Department of Water Affairs and Forestry (DWAF) has released a National Water Resource Strategy (March 2004). This strategy also includes an analysis (currently being conducted by the Water Research Council) of the impacts of climate change on South Africa's water resources. Institutionally, water and climate impacts are investigated under the Disaster Management and the Strategic Planning Directorate of DWAF. Under this directorate is the functional unit Policy & Strategy Co-ordination (Water Resources) which has been tasked to investigate the adverse impacts climate change and vulnerability may have on water resources.
- The DWAF's working for water (WfW) programme aims to sustainably control invading alien species through the process of economic empowerment and transformation. In doing this, the programme is highlighting the importance of adaptation to climate change by controlling alien species whilst preserving water and optimising the use of natural resources.
- South Africa as a signatory to the United Nations Framework Convention on Climate Change (UNFCCC) submitted South Africa's first national communication study on climate change at the 9th Conference of Parties in Milan, Italy, December 2003. This National Communications Report included chapters on the national GHG (greenhouse gases) inventory, systematic observations and research, projections,

policies and measures, response strategies and adaptation options. Also, with the second national communications study underway, an update of the GHG inventory chapter is also underway.

- The National Environmental Management Act of 1998 has been amended to take into account changes, which have been made in legislation, with respect to pollution and waste management, environmental impact assessments and other general environmental issues. In this Act, the contribution of air pollution (resulting in high CO_2 emissions) and waste disposal (resulting in methane emissions) have been recognised as high contributors of greenhouse gases.
- Department of Environmental Affairs and Tourism (DEAT) has formulated a Vehicle Emissions strategy, outlining vehicle specifications for compliance with the requirements of unleaded petrol. This follows from the Department of Minerals and Energy's (DME) plan to phase out leaded petrol by 2006.
- A Designated National Authority (DNA) for the Clean Development Mechanism (CDM) has been established. This authority, which will be the focal point for the CDM's operation in South Africa, has been approved by parliament, and the DME has been appointed as the leading department in this regard.
- Other related national policy processes include the DME's White Paper on clean and renewable energy (currently awaiting the Minister's approval), the electricity distribution industry's regulatory draft bill and the draft energy bill.
- The Disaster Management Act (Act 57 of 2002) has established a framework and structure for preparedness for disasters in South Africa. This Act gives guidance on how adaptive capacity to disasters of vulnerable ecosystems/communities, and not just response strategies should be undertaken. The disasters experienced in South Africa and the region include climatically induced events (i.e. floods, droughts).
- The National Air Quality Management Act has been approved (February, 2005) after an extensive stakeholder participation process.
- The National Climate Change Response Strategy for South Africa conducted by DEAT was approved by parliament in October 2004.

- The National Department of health (Vector Borne Diseases Directorate) and the Medical Research Council of South Africa are currently undertaking a research programme to assess climate change impacts and malaria risks in Southern Africa.
- The Department of Science and Technology (DST) has been investigating the viability of the bio-diesel industry in South Africa. In partnership with the National Treasury, the DME and the Department of Trade and Industry, the DST in 2003 commissioned research from the CSIR on the commercial aspects of bio-diesel production in South Africa. DST now has ownership of the completed study report, which looks at the technical, economic and agricultural issues surrounding the production of bio-diesel in South Africa.
- DST assisted by CSIR has also been mandated by the Interdepartmental Climate Change Committee and the National Climate Change Committee to lead a Technology Needs Assessment (TNA) in relation to climate change. This Assessment is being undertaken to develop a national policy on technology transfer thus to address climate change in South Africa (Sense 18, 2004).

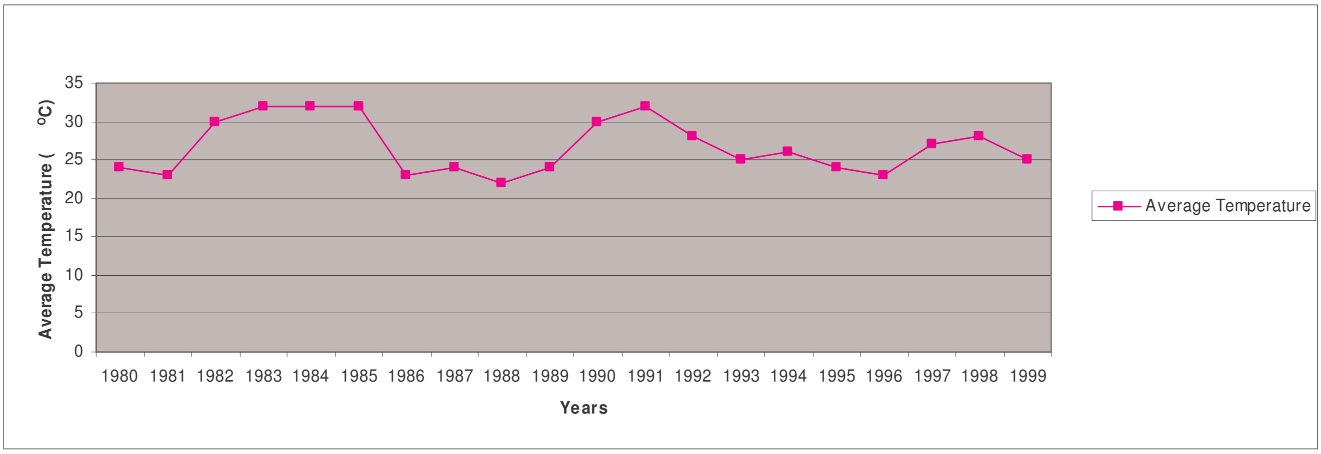
2.5 The impact of climate change on maize farming in South Africa

In the following section, climate patterns and their impacts on maize production will be discussed. Thereafter, three important climate variables which play a significant role in maize production are investigated; these include rainfall, temperature and solar radiation.

2.5.1 Climate patterns and maize production in South Africa

South Africa stretches between the 22nd and 34th degrees of southern latitude and hence is part of the subtropical zone; however, its temperatures are rather low in comparison to other regions within this latitude.

Figure 2.5: Average temperature patterns for South Africa (1980-1999)

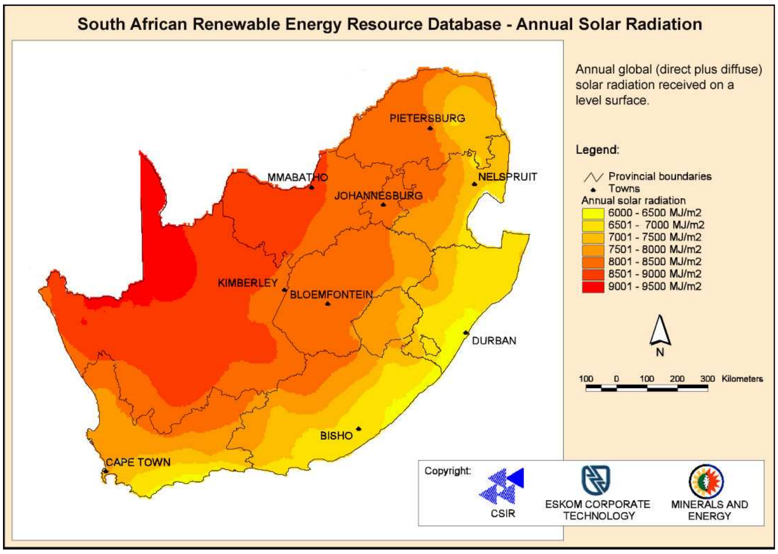


Source: SA Weather Bureau (2000)

Figure 2.5 above illustrates how average annual temperatures have fluctuated slightly over the years from 1980 to 1999. The drought periods of 1981 to 1985 and 1990 to 1992 can be observed with high average temperatures between 30 ^{0}C and 33 ^{0}C.

Temperature and solar radiation are the two weather variables that have a direct and significant effect on crop production. Under well-watered conditions and ample nutrition, in the absence of pests and diseases, maize yield is closely related to the amount of radiation intercepted by the crop. The amount of radiation incident on the crop and the proportion of the radiation that is actually intercepted by the plants are important determinants of maize yield. Therefore, leaf canopy development is influenced by ambient temperature, which determines the leaf area index of the crop, and thereby determines the proportion of the incident radiation which is intercepted. It has been shown that the duration of the grain-filling period is decreased with increasing temperature and that the shorter grain-filling period is often associated with lower grain yield (Muchow et al., 1990). However, Sinclair et al., (1999) observed that while the duration of the grain-filling stage was shorter at higher temperatures, grain yield were unchanged by coincidentally higher incident radiation at higher temperatures.

Figure 2.6: Annual solar radiation for South Africa



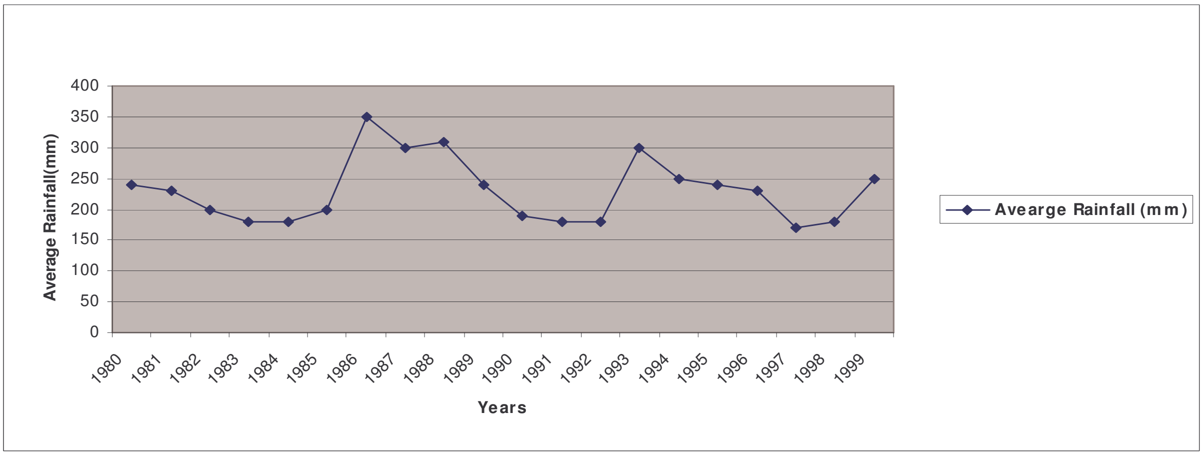
Source: SA Weather Bureau (2000)

Figure 2.6 above illustrates the annual solar radiation for South Africa received at surface levels. Parts of the Northern Cape, the Orange Free State, the North-West, the Northern Province and Gauteng have high annual solar radiation figures ranging from 8 000 MJ/m^2 to 9 500 MJ/m^2.

South Africa has three main rainfall regions: a winter rainfall area in the south-western corner of the country, an all-year rainfall area along the southern coast region, and a summer rainfall area over the remainder of the country. Rainfall is thus distributed unevenly over the country, with humid subtropical conditions prevailing in the east and dry desert conditions in the west. Moreover, South Africa is periodically affected by severe and prolonged droughts (1981 to 1985 and 1990 to 1992) that are often terminated by floods (1987 and 1993) (Figure 2.7).

As a semi-arid country, freshwater is the most limiting natural resource, given that about 65% of the country receives an average of less than 500 mm, which is generally regarded as the minimum for rain-fed cropping (Figure 2.7). This condition is further worsened by evapo-transpiration, especially in areas with relatively low rainfall and a high amount of sunshine. Only about 10% of the country receives more than 750 mm rain per annum (SA Weather Bureau, 2000).

Figure 2.7: Average rainfall patterns for South Africa (1980-1999)



Source: SA Weather Bureau (2000)

Since scientists have recognized that, for various reasons, the climates of the world are likely to change considerably in the future, efforts have been under way to estimate the economic impact of these projected changes in climate on important sectors such as agriculture (maize, rice and other grains). Countries highly dependent on the agricultural sector could also see rapid deterioration in the livelihood of their citizen as a result of climate change (Matarira et al., 1994).

For countries depending on crops like maize, growth of maize plants has been found to be significantly affected by changes in climate (especially by increased temperature and reduced precipitation) and CO_2 enrichment, although the interactions of these factors on baseline crop growth are often complex. As a result, it has been found that maize yield decreases are caused primarily by temperature increases, which shorten the duration of crop growth stages. The new fluctuating weather patterns in South Africa could therefore also have a strong negative impact on the maize economy. Also, the projected climate change could cause maize yield to decrease dramatically under dryland conditions in some regions (in some case up to 30%), even under full irrigation (CIMMYT, 2003). This clearly shows how dependent maize production is on climatic factors, especially rainfall; it also highlights how sensitive agriculture as a whole is to climate variability.

2. 6 Conclusion

This chapter has provided an overview of agriculture and maize production trends in South Africa. It has highlighted the importance of agriculture in the South African economy, and more specifically, its contribution to the Gross Domestic Product (GDP), external trade and employment. It was emphasized that this sector, together with the agro-food sector, remains the main providers of employment in rural areas and important earners of foreign currency. Strong economic and employment linkages exist with other sectors of the economy, whilst the agricultural sector contributes highly to economic growth (GDP and overall external trade). Maize farming in South Africa has also been investigated with particular reference to the main maize production regions. The past production trends of yellow and white maize have been compared, whilst the discussion of maize consumption patterns has focused on total domestic consumption (1989 to 1997) and export figures (1989 to 1997), calling attention to marginal increases and decreases in these figures due to droughts, floods and political instability in the country. South African agricultural policy, role of small-scale farmers, and the impacts of maize policy changes on these farmers and the effects of maize subsidies, which have tended to exclude mainly the small-scale farmers, have all been reviewed. In this regard, the discussion has underscored the economic vulnerability of small-scale farmers who form an integral part of maize production in South Africa. South Africa's climate change policy initiatives have been introduced to illustrate how the various South African government departments are incorporating these issues into their policy formulation strategies.

In the final section of this chapter, climatic patterns for South Africa have been discussed, focusing specifically on the sensitivity of South African agriculture in general and the maize industry in particular to climate changes. Temperature, solar radiation and rainfall have been identified as the most important climatic variables affecting the different growth stages of the maize crop, as they contribute significantly to increases in maize yield. In the following chapter, relevant studies will be reviewed to understand how the impacts of climate change on crop production, especially maize, have been studied and assessed and the analytical approach to be followed in this study will be defined.

CHAPTER 3: Review of the Relevant Literature: Approaches and methodologies for measuring the climate sensitivity of agriculture

3.1 Introduction

This chapter starts by defining climate change and its impacts, then investigates adaptations to and mitigation of climate change and the role of the Intergovernmental Panel for Climate Change (IPCC). The basic integrated assessment model for climate change, which has been developed to analyse the potential harmful effects on agriculture is described. This is followed by a discussion of models and approaches, which have been used to assess the sensitivity of agriculture to climate change. A detailed review is undertaken of the literature and studies with regard to the impact of climate change on agriculture and maize production. This review is provided to identify gaps in the existing knowledge and areas where further research is needed.

3.2 A definition of climate change

Climate is referred to as the prevalent long-term weather conditions in a particular area. Climatic elements include precipitation, temperature, humidity, sunshine and wind velocity and phenomena such as fog, frost, and hail storms (edugreen.teri.res.in/explore/glossary.htm). Thus, climate change can be defined as any change in climate over time, whether due to natural variability or human activity (IPCC, 2001). The Reports by the United Nations Framework Convention on Climate Change (UNFCCC) define it as "a change of climate as 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".

Climate change is caused by increases in the atmospheric concentration of so-called greenhouse gases (GHGs). The build-up of GHGs is rapidly changing how the atmosphere absorbs and retains energy. These GHGs include: carbon dioxide (CO_2) (from burning fossil fuels), methane (CH_4), nitrous oxide (N_2O) (created by agriculture, land use and changes in land use where these gases are emitted), ozone (O_3) (generated mostly by fumes from car exhausts) and chlorofluorocarbons (CFCs) (IPCC, 1997). The increase of these GHGs in the atmosphere further prevents infrared radiation escaping from the earth's atmosphere into space, causing what is called 'global warming'. This acceleration of global warming by humans is referred to as the enhanced greenhouse effect or anthropogenic climate change (Tuibello et al., 2000).

In 1988, the United Nations Environment Programme (UNEP) and the World Meteorological Organisation (WMO) jointly established the IPCC, as concerns over climate change impacts became a political issue. The main purpose of the IPCC is to assess the current state of knowledge on the various aspects of climate change, including scientific, environmental and socio-economic impacts, as well as response strategies. The IPCC is also recognized as the most authoritative scientific and technical voice on climate change, and its assessments have profoundly influenced the negotiators of the UNFCCC and its project-based Kyoto Protocol.[5] The IPCC continues to provide governments with scientific, technical and socio-economic information relevant to evaluating the risks of and developing an effective response to global climate change.

At the 1992 Earth Summit in Rio de Janeiro, many countries signed the UNFCCC, committing themselves to "the stabilisation of GHG concentrations in the atmosphere at a level that would prevent dangerous interference with the climate system" (Article 2 of the UNFCCC, 1992). As a result, there is a growing literature on the relationships between adaptation, mitigation and climate change (GEF, 2003).

Mitigation of and adaptation to climate change are the two main pillars of climate change policy. Both pose significant analytical and policy challenges, and thus their respective discussions have evolved at different paces. On the one hand, mitigation of climate change refers to:

> "The stabilization of greenhouse gas (GHG) concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system which would enhance global warming. Such a level should be

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[5] The so-called 'Kyoto Protocol' is an international agreement reached in Kyoto at the Third Conference of the Parties (COP 3) to the UN Framework Convention on Climate Change in 1997. The Protocol established specific targets and timetables for reductions in greenhouse gas emissions to be achieved by the framework's signatories. Although the United States and 83 other countries have signed the Protocol, many countries, including the U.S., have yet to ratify it.

> achieved within a time frame sufficient to allow ecosystems to adapt naturally to climate change, so as to ensure that food production is not threatened whilst at the same time enabling economic development to proceed in a sustainable manner" (Article 2, Convention on Climate Change, 2002: 6).

Research on mitigation measures is also well under way, with the analyses continuously being refined; understanding the mitigation of climate change is also likely to increase further once measures are implemented on a worldwide scale. Programmes are already being implemented, such as the Global Environment Facility (GEF) Projects, the Kyoto mechanisms,[6] and other bilateral and multilateral agreements.

Adaptation to climate change, on the other hand, has been seen by many scientists and policy makers as a powerful option to reduce the negative impacts of climate change and climate variability, especially in developing countries (Barnett, 2001). Studies on the potential for adaptation are linked to the assessment of climate change impacts and the related concept of vulnerability (Antle, 1995). Vulnerability to climate change is referred to as a function of both the sensitivity of a system to changes in climate and of its ability to adapt to such changes (Barnett, 2001; O'Riordan and Jordan, 1998). The IPCC's Third Assessment Report (IPCC, 1997), for example, highlights the high level of vulnerability of Africa to climate change because of its limited adaptive capacity, which is further constrained by numerous factors at the national level. These factors may include national governments' inability to assist, prepare and strengthen all the vulnerable sectors of its economies. The number of vulnerability studies is increasing, whilst adaptation measures are not as well researched. As a result, most information about adaptation is still embedded in work about the impacts of climate change in general, whilst a greater understanding is needed of society's adaptive potential to better comprehend the consequences of unabated climate change (Fankhauser et al., 1999).

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[6] The three flexible mechanisms of the Kyoto Protocol of 1997 under the United Nations Convention on Climate Change are the project-based activities of the Clean Development Mechanism and of the Joint Implementation Mechanism and Emissions Trading (www.unfccc.int)

3.3 Climate prediction models

Climate prediction models are designed mainly for studying climate processes and for projecting how climate responds to human-induced forces. The most complex climate prediction models in current use are called Global Climate Models or General Circulation Models (GCM's). GCM's are based on a physical law describing the dynamics of the atmosphere and oceans, and are expressed in mathematical equations. These equations further incorporate numerical representations of the physical processes of radiation, turbulent transfers at the ground-atmosphere boundary and cloud formations (Rosenzweig, 1989; Barron, 1995).

These models are based on five prognostic variables, namely: temperature, humidity, surface pressure and two dimensions of wind (tail and head winds). They are used in different controlled programme simulations, usually perturbed by changes in CO_2, until they reach an equilibrium level. In addition, these calibrated models can be used to assess situations that do not yet exist and thus impact analyses of future climate changes have mainly been based on these types of analyses. In these analyses yield changes can further be either extrapolated to an aggregate effect, as for example in crop simulation models, or introduced into an economic model, which in turn estimates aggregate damages to the agricultural sector (Mendelssohn et al., 2000).

Manabe and Weatherfeld (1975) at the Geophysical Fluid Dynamics Laboratory (GFDL) in Princeton, New Jersey undertook the first GCM studies (Sanghi et al., 1998). Other studies have also used GCM's to project changes in climate with respect to different climate scenarios (Dhakhwa et al., 1996; Tuibello et al., 1999; Hewitson, 1998; Erasmus et al., 2000).

Lastly, the use of these calibrated models plays an essential role in understanding the potential responses of plant vegetations and ecosystems to simultaneous changes in atmospheric CO_2 and other climate variables. Specific alterations in plant growth and plant populations can be incorporated into simulation models to evaluate scenarios concerning the effects of changes in climate. Climate prediction models are particularly useful with regard to the complexities of climate-crop interactions, and may be the only practical approach available for assessing the impacts of climate variability on agro-ecosystems. The results obtained by climate prediction models can further be used in economic models to assess the impacts of climate change on different sectors of the economy, e.g. agro-economic models can be used for this analysis.

3.4 Measuring the climate sensitivity of agriculture

Two main approaches have been developed to assess the climate sensitivity of the agricultural sector, i.e. to measure how agriculture will be affected if the particular components that make up the general climate of a region change by a certain amount (FAO, 2000):

- Structural modelling of agronomic responses, based on theoretical specifications and controlled experimental evidence, and
- Reliance on the observation of responses of crops and farmers to climate variations.

3.4.1 Structural modelling of agronomic responses

This approach is based on controlled experiments where detailed data are needed to represent the responses of specific crops and crop varieties to different climatic conditions. The main aim of this approach is to improve our understanding of how crop management can be undertaken under different climatic conditions. With this approach, representatives of farms or crops are modelled in a very basic way. This also includes the modelling of farming decisions by implicitly incorporating a crop response function. However, such modelling and representation of crops and farm operations tends to give results that differ from the actual experiences on farms operating under real world conditions.

Broadly speaking, there are two main types of structural modelling of agronomic responses, namely, integrated assessment models and crop-growth simulation models. The latter furthermore include agro-ecological zone analysis and agro-economic approaches (which are also referred to as production function approaches).

3.4.1.1 Integrated assessment for climate change

In the IPCC's Third Assessment Report (IPCC, 2001c), integrated assessment is defined as:

> "an interdisciplinary process that combines, interprets, and communicates knowledge from diverse scientific disciplines which include natural and social sciences to investigate and understand causal relationships within and between systems" (IPCC, 2001c).

It is generally agreed that there are two main principles of integrated assessment, namely:

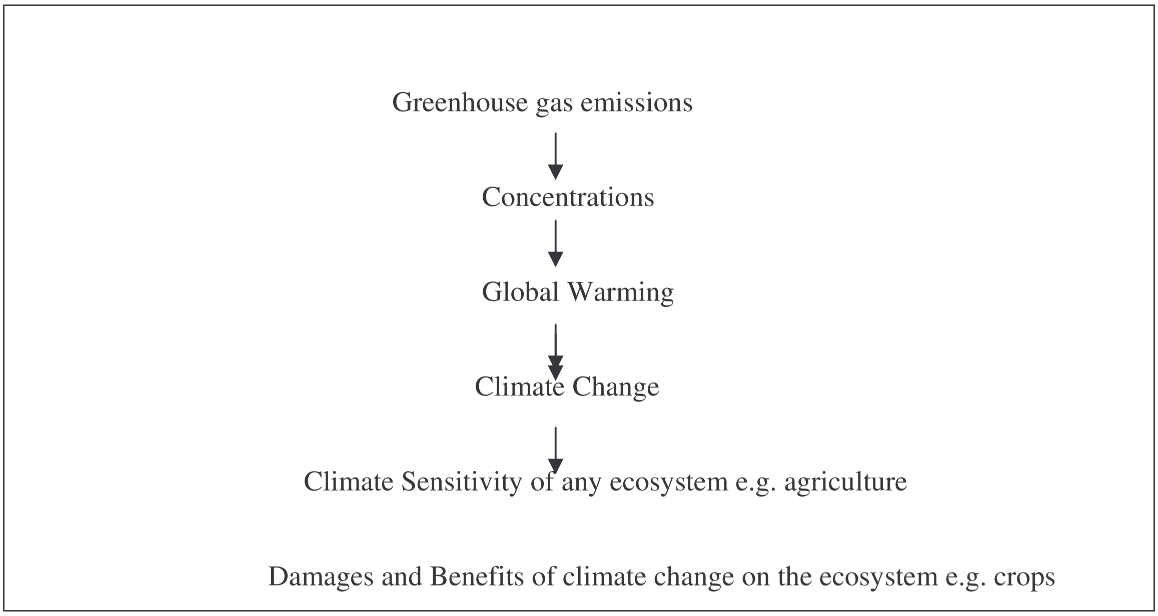
(i) Integration of information obtained through a range of relevant disciplines, and,
(ii) The provision of information suitable for decision-making.

The main objectives of integrated assessment of climate change include:

- Compiling available knowledge in order to evaluate what has been learned from the various disciplines,
- Assessing policy implications and research needs, and
- Promoting a better understanding of and informed decisions on how countries and regions contribute to climate change, and how they are affected by it.

Figure 3.1 illustrates a basic integrated assessment model of climate change, which begins with the assessment of GHG emissions and its future concentrations, the identification of the effects of these concentrations on global warming, the determination of climate change patterns and the climate sensitivity of an ecosystem, and lastly the determination of future impacts on agriculture for example.

Figure 3.1: Basic integrated assessment model



Source: **FAO (1999)**

The main research activity in the integrated assessment model involves the development of methods for linking knowledge across various domains or disciplines, whilst emphasizing the importance of feedback mechanisms, nonlinearities and uncertainties to climate change (Easterling et al., 1994). This makes integrated assessment a primary tool for studying climate change impacts, as it takes into consideration all of the following:

- Anticipated impacts of climate change,
- Current and future patterns of climate variability,
- Current and future non-climatic developments,
- Anticipated interactions between climate related impacts and non-climatic developments, and
- Likely autonomous and planned adaptation measures to both climatic and non-climatic impacts (Mendelssohn, 2000).

This approach has also been able to account for adaptation and welfare impacts, which other approaches have failed to account for (Mendelssohn et al., 1994). In the area of agriculture, the integrated assessment of climate change remains a key link in measuring the climate sensitivity of agriculture. It has a very important role to play in enhancing our understanding of the range of possible future climatic changes, their impacts and the interactive effects with respect to agriculture.

The basis for such assessments has mainly been an understanding of the climate system, its relation to climate change and its impacts on the sea level, the atmosphere, the oceans, the terrestrial biosphere, glaciers, ice sheets and land surface. In order to project the impact of human perturbations on the climate system, it is necessary to calculate the effects of all the key processes operating in the components of these climate systems and the interactions between them.

Integrated assessment models for climate change have also begun to compare the costs and benefits of controlling climate. However, there remains a great deal of uncertainty about many of the components of these models, and one of the most uncertain phenomena is the impact of any specific climate change on human welfare. The possibility of adverse impacts on people has led to a number of conclusive agricultural impact studies mainly in the US, Brazil and India (Mendelssohn et al., 1996).

However, there are some outstanding challenges faced by integrated assessment models, which are, in general, widely recognized. These challenges include the following:

- Improving our understanding of the biggest long-term driving factors: technological change and population growth;
- Building better tools to represent impacts and adaptation, and to describe and analyse policies that can facilitate adaptation;
- Providing useful representations of uncertainty, including low-probability extreme events, and blending of “softer” with “harder” information;
- Supplying methods that represent and assess policies as implemented in reality, rather than in idealized form;
- Promoting richer tools to study collective decision-making and choices of key agents other than the audience, moving beyond the naive implication that assessments are addressed to a unitary decision-maker with the authority to make the relevant policy decisions; and

- Developing assessment tools relevant over long-term horizons: putting climate change in the context of other changes over a 50 to 100 year period (including discontinuities).

In addition, a number of serious unresolved questions still exist that are more general in character, with regard to the appropriate scope and audience for assessments, the relationship between assessments and policy-makers, and the extent to which assessment tools can be generalised across issues (http://sedac.ciesin.org/mva/iamcc.tg/TGsec5-2.html).

3.4.1.2 Crop simulation models

Agronomists have developed and calibrated models which forecast yield for specific crops and for different weather patterns (Poonyth et al., 2002). Crop simulation models that have been widely used include the Crop Environment Resource Synthesis (CERES) and the Erosion Productivity Impact Calculator (EPIC). These simulation models are based on climate prediction models and are thus able to simulate short- and long-term biophysical processes in agro-ecosystems (Downing et al., 2000).

Crop simulation models that use these Global Circulation Models are also closely linked to agronomic science and hydrological conditions, and they are currently the only methods capable of including carbon dioxide fertilisation in agronomic analyses. They are thus able to impose climate change scenarios on current agricultural systems whilst including a variety of planting times, crop varieties, harvest dates and tilling and irrigation methods (Sanghi et al., 1998).

Soil-crop-climate interactions are considered in detail in crop simulation models, as they are able to predict crop growth as a function of genetics, climate, soils and management practices (Dhakhwa et al., 1996; Rosenzweig and Parry, 1993; Muchena, 1994; Du Toit et al., 2001). These complex climate predictions are mathematical representations of atmospheric, ocean and land surface processes involving interactions between mass, momentum, energy and water. Thus, the use of crop simulation models further allows the user to include weather factors (through climate prediction models) and to evaluate the effects of alternative scenarios on crop development and yield.

However, even though these models are based on agronomy, they still fail to incorporate crop growth in relation to the actual behaviour of farmers. The two approaches commonly used for analysing the impacts of climate change on agriculture based on this group of crop simulation models are discussed hereunder, namely:

- Agro-ecological zone analysis, and
- Agro-economic approaches.

3.4.1.2.1 Agro-ecological zone analysis (AEZ)

In 1992, the Food and Agricultural Organisation (FAO) developed the ecophysiological process method to measure the climate sensitivity of crops in different agro-ecological zones in developing countries. The AEZ approach, also referred to as the Crop Suitability Approach, was developed to assess potential production capacity across the ecological zones that determine crop suitability areas.

This AEZ approach provides a standardised framework for characterising climate, soil and terrain conditions relevant to agricultural production whilst its matching procedures are used to identify crop-specific limitations in terms of the prevailing climate, soil and terrain resources under assumed levels of input and management conditions. It also provides a framework for various applications, which include productivity, the extent of land with rain-fed or irrigated cultivation potential, estimates of the population-supporting capacity of land in particular areas, and multi-criteria optimisation of land resource use and optimization (Deressa, 2003).

A yield biomass simulation model is used to simulate crop yield for each of the assessed agricultural zones. A land resources inventory is used to assess all feasible agricultural land-use options for specific management conditions and the levels of input required to quantify the expected production of relevant cropping activities. The inventory includes information on climate, soils and land reform, as this is necessary for the supply of water, energy, nutrients and physical support to crops. The availability of a digital global database of climatic parameters, topography, soil, terrain and land cover has also allowed for revisions and improvements in the calculation procedures for this methodology. The revisions and improvements include:

- The selection and definition of additional crop or land utilization types (LUTs) relevant to temperate and boreal climates,
- The extension of land utilisation definitions to cover irrigated conditions,
- The expansion of a crop-ecological adaptability inventory,
- The application of soil-specific moisture regimes to calculate the lengths of growing periods,
- The application of FAO's digital soil map,
- The application of a gridded monthly average and a historical year-by-year resource database,
- The application of the digital elevation model to compile a terrain-slope database and the integration of terrain slopes with soil resources database, and
- The assessment of agro-climatic crop suitability grid cells and the expansion of land suitability assessment procedures for irrigated crop production.

These improvements have led to the formation to the following AEZ framework, which includes:

- Land utilisation types (LUTs),
- A land resource database,
- Matching of crop yield and LUT requirements,
- Assessment of crop suitability and land productivity, and
- Applications for agricultural development planning.

Adaptation to and technology adoption in respect of impacts that are specific to climate change can be captured in the AEZ model by generating static scenarios with changes in technological parameters. Economic analysis, such as revenue optimisation or cost minimisation, can be linked to the AEZ through linear optimisation estimation procedures; thus, it is possible to undertake sensitivity analyses on economic variables within such linear programming models.

However, Mendelssohn and Tiwari (2000) argue that the large temperature categories reflected in the climate zones in the AEZ approach make it difficult to capture subtle changes within a zone, whilst the calibration of price effects remains crude. They also observed that the existing application of this approach predicts large price changes along with small changes in aggregate supply, suggesting that there may be problems with the calibration of the underlying economic model.

3.4.1.2.2 Agro-economic approaches

Agro-economic approaches, which include the production approach, are based on an empirical or experimental production function whereby relationships between agricultural production and climate change are measured. These approaches may begin with a crop model that has been calibrated from carefully controlled agronomic experiments where crops are grown in the field or laboratory setting under different possible future climates and carbon dioxide levels to predict changes in yield in response to changing climate. The predicted yield is then entered into economic models that predict aggregate crop outputs, prices and net revenue (Kurukulasuriya and Rosenthal, 2003).

This approach is among the most powerful tools for analysing the interactions of the crop-management-climate-soil system. They may include the use of environmental variables such as temperature, rainfall and carbon dioxide as part of the inputs in a production function, which can then be estimated. Thus, based on the estimated production function, changes in yield induced by changes in environmental variables can be measured and analysed in testing sites. The estimated changes in yield caused by changes in environmental variables can also be aggregated to reflect the overall national impact. Alternatively, they can be incorporated into an economic model to simulate the welfare impacts of yield changes under various climate-change scenarios (Adams, 1989; Kumar and Parikh, 1996; Lal et al., 1999). Moreover, with this approach the response of crops and farmers is based on actual responses under current operating conditions rather than on an idealised view of how crops and farmers are likely to respond.

Even though a number of quantitative studies on both the national and the global level have followed the agronomic economic approaches to estimate the impacts of climate change, some problems have been experienced with this production approach in developing countries. These problems relate to uncertainties about future economic development, technical progress in farming systems and political stability. As a result, only a few of the agronomic efforts have considered the implications of projecting impacts into the future (Deressa, 2003; Mendelssohn et al., 1994). This approach also fails to capture changes in farmers' behaviour in response to climate change, which may include the introduction of new crops, changes in land use, use of technology as an input, and the overall adoption of new technologies through government or other forms of interventions (Mendelssohn, 1994; Poonyth et al., 2002). Furthermore, given the high cost of such controlled experimentation, estimates of impacts have, with few exceptions, been limited primarily to grains and to only a few locations around the world (Kurukulasuriya and Rosenthal, 2003).

3.4.2 Reliance on the observed response of crops and farmers to varying climate

Methodologies, which rely on the observed response of crops and farmers to climate variations, are very important in the assessment of climate sensitivity, as they provide estimates of the potential effects, whilst production differences across regions can also be thoroughly explained to estimate the potential impacts of climate change. These methodologies may include the following:

- Ricardian approaches (cross-sectional approaches), and
- Economy-wide models (Computable General Equilibrium [CGE] approaches).

3.4.2.1 The Ricardian approach

During the past few years, two new methods, each based on the analogous region concept, have been developed to account for farmers' adaptations to global climatic change. One of these two new methods called 'Ricardian' by Mendelssohn et al. (1994), econometrically estimates the impact of climatic and other variables on the value of farm real estate. The Ricardian approach to estimating climate-induced impacts on agriculture was proposed as an alternative to crop simulation approaches. This cross-sectional model analyses farm performance across climate zones by assessing the observed responses of both crops and farmers to climate variations (Mendelssohn and Tiwari, 2000; Kumar and Parikh, 1998). In the United States, for instance, it has been applied in climate sensitivity studies of agriculture by Mendelssohn et al. (1994, 1996 and 1998). Sanghi et al. (1999) have applied this approach in Brazil, whilst Kumar and Parikh (1998a) have applied it extensively in India.

Lastly, Poonyth et al. (2002), Deressa (2003), and Gbetibouo (2004) have briefly used a similar approach for different crops in South Africa.

The Ricardian approach examines farm performance as measured by land values (rents) and crop revenues across different agro-climatic zones, assessing how long-term farm profitability may vary in response to local climate, while controlling for other factors. It attempts to capture the influence of economic, climatic and environmental factors on farm income or land values, thus further incorporating adaptation techniques by farmers (Mendelssohn et al., 1994).

This approach has the necessary flexibility to incorporate private adoption and freedom of choice with regard to methods and technologies which allows the farmer to modify his operational environment to increase profits, e.g. to change his crops in response to climatic conditions. It can also be adopted to evaluate country level and regional level impacts. As it does not depend on controlled experiments, it thus makes it possible to measure the direct impact of climate changes on farm income or revenue.

Some disadvantages of this approach include the fact that the farms are not controlled, as in the case of scientific experiments. Thus, the failure to control the impacts of important variables, which could explain ultimate variations in farm incomes, is not properly captured. Moreover, as this approach uses uncontrolled experiments and incomplete specifications of farms, agro-ecological zones have been found to result in models that do not capture information on soil quality, solar radiation, CO_2 fertilisation effects and water supply. With reference to water supplies, this approach has also not been able to take into account water usage in crop production and the magnitude of the water supplies on which crops depend (Mendelssohn, 2000).

In their later work, Mendelssohn et al. (2000) have also shown that the value of climatic change is captured exactly by changes in land values if output prices and the prices of other inputs remain unchanged. However, assuming constant output prices is appropriate when changes in the supply of crop and livestock commodities are not likely to affect their prices, whilst assuming constant input prices implies that all inputs are readily available at current prices. It, too, is appropriate when changes in the demand for inputs are not likely to affect prices. Many analysts have regarded these assumptions as the main drawbacks to this approach, as they may result in the underestimation of damages and the overestimation of benefits, as crop prices are treated as constant variables. This is because, firstly, farm-level adaptations made by farmers in response to global climatic change would likely generate supply changes that, in turn, would affect output prices. Furthermore, the supplies of crops may increase or decrease, whilst their prices would decline or rise, respectively, thus supply changes could likely be accompanied by changes in inputs and input prices as well (Rosenzweig and Parry, 1994; Darwin et al., 1994, 1995). Lastly, the Ricardian approach assumes that adjustments made in response to climate changes are costless; this has also tended to lead to biased outcomes and results of this model (Quiggin et al., 2000).

3.4.2.2 Economy-wide models for climate change impact analysis

Computable general equilibrium models form part of economy-wide policy impact assessment models, which explicitly account for all domestic and international value flows, as households (farms) are assumed to own all primary factors of production. Value flows for these models are traced from households (farms) through domestic and international markets to producing sectors and then back to households (farms), thereby providing comprehensive measures of economic activity (Darwin et al., 1995). As a result, the general equilibrium theory is able to take into account all the interactions between markets, as well as the functioning of the individual markets themselves.

Recently, several studies have assessed global climate impacts by using general equilibrium models (Kane et al., 1991; Yates and Strezepek, 1996; Nordhaus et al., 1996). These studies have also shown how it is possible to capture complex economy-wide markets that show the effects of exogenous environmental changes, while providing insights into micro-level impacts on producers, consumers and institutions (Mabugu, 2002).

Some of the problems that have been encountered with the use of general equilibrium models include difficulties in model selection, parameter specification, choice and type of functional forms to use, data consistency and the absence of statistical tests for the model specification.

3.5 Impacts of climate change: Review of empirical studies

The following sections will give reviews of the empirical studies which have been done on the impacts of climate change on agriculture, maize production, and lastly food security and food supply. The review on these studies will show the importance of assessing the impacts of climate change while giving insight into the potential adaptation measures and strategies. These reviews will also give insight into the degree of vulnerability of the agricultural economy to climate change giving further analysis of the additional burdens and production risks that farmers will encounter in the future due to climate change.

3.5.1 Impacts of climate change on agriculture

In the last two decades, analysts have been interested in assessing the impact of weather on crops in order to predict what crops to grow, when to plant and harvest and what the agricultural prices will be each year. With the growing likelihood that accumulating greenhouse gases will change the world's climate, there has been an increased interest in measuring the specific impacts of this climate change too. Evidence suggests that climate change will result in a set of diverse and location-specific impacts on agricultural production. Most studies also indicate that, although the global agricultural supply is likely to be robust in the face of moderate climate change, several variations can be expected. Whilst temperate and polar regions stand to gain in terms of productivity increases from climate change, several developing countries are expected to be the worst affected, suffering significant agricultural production losses and increased ecological and economic stress.

Hulme (1996), for example, used a crop simulation model to show, firstly, how vulnerable the Southern African region is to climate changes and, secondly, the impacts that such changes can have on food security and water resources. Three crop simulation models for maize (CERES-Maize) that have been used to conduct impact analyses in the region were also described by Hulme (1996). His study constructed an index of vulnerability based on national food balances, food production and dependence on food imports and food aid. Results described four ways in which climate will have a physical effect on crops, and these include changes in temperature and precipitation, carbon dioxide effects, water availability and increased frequency of extreme events such as droughts and floods. Changes in temperature and precipitation were expected to alter the distribution of agro-ecological zones, leading to changes in soil moisture and content and the timing and length of growing seasons. Interestingly, the carbon dioxide effects were expected to have a positive effect due to a greater efficiency of water use and a higher rate of photosynthesis. The results showed that South Africa was the least vulnerable, whereas Angola was found to be the most vulnerable country in Southern Africa.

Tubiello et al. (1999) investigated the potential effects of climate change on two locations in Italy (in the counties of Modena and Foggia), using climate prediction models. These potential effects correspond to doubling the effects of atmospheric CO_2 from 350 to 700 PPM on the four different cropping systems of the two locations. Two general circulation models (GCM's) were applied at these two locations to represent the weather input for a crop system simulator, CropSyst. The two GCM's used for this study were the Goddard Institute of Space Studies (GISS) model, developed at the NASA Goddard Institute for Space Studies located near Columbia University in New York City (U.S.), and the GDFL model, developed at the Geophysical Fluid Dynamics Laboratory in Princeton, New Jersey (U.S.). Atmospheric circulation and land surface dynamics with seasonal surface temperatures simulated from the two GCM models were further used by the crop system to simulate future weather figures, which included the effects of elevated CO_2 on crop synthesis and transpiration as its main variables. Six different crops were simulated by these two GCM's, namely: maize, wheat, sorghum, sunflower, soybean and barley. The results from the crop system simulator suggested that elevated atmospheric CO_2 and climate change at both sites would depress crop yield if the management practices, which were currently being used, were not modified. The study also suggested that improved techniques, which would include better adaptation strategies, the use of slower maturing winter cereal cultivars and more irrigation, were needed to increase yield.

Kane et al. (1991) used CGE models to model world agriculture, using 13 regions and 20 commodities. In this study, the regions were linked by trade through global commodity markets. The results showed reductions in crop yield in some regions, when trade adjustments of global patterns in terms of production and consumption were found to be the main factor. Yates and Strezepek (1996) also applied a dynamic CGE model to assess the impact of climate change on the Egyptian economy. This study concluded that the net effect of climate change on per capita GDP was not significant. Nordhaus et al. (1996) used a dynamic general equilibrium model in a regionally and sectorally disintegrated framework to analyse adaptation to climate change in different regions of the world. This study also analysed different national strategies in which climate change policies, such as pure market solutions, efficient cooperatives outcomes and non-cooperative equilibriums were analysed extensively. In this study, it was found that there are substantial differences in the levels of control in both cooperative and non-cooperative policies among different countries, and that the high-income countries may be the major losers from cooperation with low-income countries.

Relatively few studies have focused on rice, which is a staple food crop in Asia. Therefore, in 1989, the U.S. Environmental Protection Agency (EPA) and the International Rice Research Institute initiated a major research project to investigate relationships between climate change and rice production. One component of this project was the quantification of the impact of climate variability on rice production. An agro-economic approach was used in this study. The existing knowledge of the effects of increased levels of CO_2 and temperature were integrated into the crop simulation models used.

Although an increase in CO_2 levels was found to increase yield, it was also accompanied by an increase in global temperature, which reduced yield at a later stage. The ORYZA1[7] crop simulation model predicted that the overall rice production in the region would change by +6.5%, -4.4% and –5.6% respectively under three climate prediction models, which included the models designed by the General Fluid Dynamics Laboratory (GFDL), the Goddard Institute of Space Studies (GISS) and the United Kingdom Meteorological Office (UKMO). These were used to double the CO_2 scenarios. The average of these estimates suggests that rice production in the Asian region may decline by 3.8% under climate changes in the next century. Declines in yield have been predicted for Thailand, Bangladesh, southern China and

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[7] ORYZA1 is an ecophysiological model for irrigated rice production; this model can be used to simulate realistic yield and to assess the impact of planting date, weather and latitude at measured leaf Nitrogen contents (ORYZA model simulations, 2000).

western India, while increases have been predicted for Indonesia, Malaysia, Taiwan and parts of India and China.

According to De Siqueira et al. (1994), in most regions of Latin America and specifically in the Amazon basin, soil erosion is one of the most serious threats to the sustainability of agriculture and forestry. Specifically Brazil, Peru and Honduras are sensitive to flooding, which further negatively affects their agricultural output. A crop simulation model was used to determine the effect of climatic events such as soil erosion on the production of maize, wheat and soybean. The results indicated that wheat and maize production in Brazil would decline over time under simulated climate scenarios, whereas soybean production would either increase or stay the same depending on the climate scenario experienced. The results suggest that adaptation to climate variability through better resistance towards flooding and drought scenarios by farmers would significantly improve yield.

Most regions in Africa are highly populated and most people live below the poverty line. This, together with climate change, is expected to increase food insecurities throughout Africa. South Africa, Zimbabwe and Kenya have been found to be the regions that suffer most seriously from the effects of drought. In some zones, intra-seasonal and inter-annual variability of rainfall also creates a high-risk environment for agriculture (FAO, 1999).
Sivakumar (1992) focused on changing rainfall patterns to assess the impacts on the production of pearl millet, which is a staple food in Niger. He used daily precipitation data from 21 stations between 1921 and 1990, and explored correlations with millet yield and aggregate production. An agro-economic analysis was used to analyse shifts in the patterns of rainfall during the 1965-1988 periods; these shifts had been accompanied by a reduced growing season (reduced by 5-20 days) across the various observed locations. These observations highlighted the impact of declining rainfall on agriculture. This may have serious implications for the sustainability of agriculture and the environment as a whole.

Downing (1992) conducted studies in Kenya and later in Zimbabwe, in which an agro-economic approach was used to assess climate change impacts. In Kenya, potential food production was found to decrease with lower temperatures and lower rainfall, while vulnerable socio-economic groups would face serious difficulties if their already low yield were to decrease further because of insufficient rainfall. In Zimbabwe, shifts in agro-climatic potential would affect national food production and land use. With a 2^0 C increase in temperature, the core agricultural zone would decrease by a third, whilst the semi-extensive farming zone was found to be particularly sensitive to these climate changes.

Muchinda (1994) conducted an agro-economic study on the effects of rainfall changes in Zambia. Recurring droughts were found to have detrimental effects in the country in such a way that the southern zones of Zambia would be less able to support the varieties of maize grown in these parts, which would necessitate large imports of basic foods. Changing rainfall patterns also reduced river flows, which later significantly affected the reservoir volumes for hydropower generation, which in turn is used in crop-processing activities. Mitigation measures were suggested, in which seasonal climate predictions were promoted to assist different government departments and farmer organisations in reducing economic uncertainties, especially at the household level. Water harvesting by means of water tanks, clay-pot irrigation methods and simple irrigation systems that are easy to construct have been suggested to mitigate the detrimental effects of climate change.

Fischer and Van Velthuizen (1996) used a crop simulation model to assess the potential impacts of climate change on agriculture in Kenya. The results showed that climate change, which would include higher carbon dioxide levels and higher temperatures, would effectively increase maize yield in higher altitude regions, given that these areas would become more suitable for cropping.

In South Africa, Dube and Jury (1994) also did a study on the historical context and potential causes and structure of the 1992/93 drought in the KwaZulu Natal region of South Africa. Their analysis used climate prediction models to understand drought-induced meteorological processes. It indicated that, as a result of droughts, increasing westerly winds with surface marine lows and continental highs would prevail over Southern Africa. The widespread occurrence of severe droughts during the past three decades underscores the vulnerability of both developed and developing societies to the ravages of such droughts. Widespread and sustained droughts have periodically afflicted Southern Africa in 1964, 1968, 1970, 1982, 1983, 1984 and 1987, leading to significant decreases in food production, especially of maize and wheat.

Deressa (2003) utilized the Ricardian approach to capture farmer adaptations to varying environmental factors to analyze the impact of climate change on South African sugarcane production. This study took into consideration two production systems, i.e. irrigated and dryland farming systems. Results from this study indicated that sugarcane production in South Africa is more sensitive to future increases in temperature than precipitation as a consequence of climate change. This study also found that even though management options, such as irrigation, are thought to provide an adaptation mechanism in the arid and semi-arid regions under sugarcane farming, irrigation did not reduce the harmful impacts of climate change significantly.

Gbetibouo (2004) conducted a study in which the Ricardian model was also used to measure the impact of climate change on South African field crops (maize, wheat, sorghum, sugarcane, groundnut, sunflower and soybeans) and analysed potential future impacts of further changes in the climate. This study indicated that the production of field crops is sensitive to marginal changes in temperature as compared to changes in precipitation. Temperature increases were found to positively affect net revenue whereas the effect of reduction in rainfall was found to be negative. This study indicated the importance of season and location in dealing with climate change showing that the spatial distribution of climate change impacts and consequently needed adaptations will not be uniform across agro-ecological regions of South Africa.

In early agronomic studies, Neumann (1980) investigated the impacts of climate change on crop production in the United States by using crop simulation models. The results showed that the U.S. Corn Belt would shift north-east for every 1^0C rise in temperature. Similarly, Rosenzweig (1985), using the same methodology, found that climate change would increase winter wheat production in Canada.

Reilly et al. (1993) used an agro-economic model to evaluate the economic impacts of climate change on agriculture in the Unites States. Firstly, three GCM's, which included

GISS (Goddard Institute of Space Studies), GFDL (Princeton Geophysical Fluid Dynamics) and UKMO (United Kingdom Meteorological Office), were used to predict climate scenarios. Thereafter, further analysis was done on the impact of trade and prices, to demonstrate that relative export status would affect the net impact on a country.

Smith and Tirpak (1989), Kane et al. (1993) and Mendelssohn and Neumann (1998) also conducted studies in which they assessed the economic impacts of climate change on agriculture in the United States. Although these studies used different methodologies, which included mainly regional crop simulations and global circulation models, the results nonetheless all showed a decrease in agricultural production, exacerbated by changes in world prices. Results also showed that, as farmers continue to adapt and as forecast information becomes available, U.S. agriculture would become more resilient to climate change effects. In these studies, extreme climate variables (including droughts and floods) were found to have a detrimental effect on agricultural production, leading to reduced agricultural output or crop yield.

Given these anticipated effects in climate variability in both developed and developing countries, we can conclude that maize as a main cereal crop in Southern Africa may be under threat. Also, given that the results of the above research clearly indicated an urgent need for farmers to adapt to climate change, further studies were done. Antle et al. (1995) and later Dinar et al. (1998), for instance, focused on finding both adaptation and mitigation techniques that developing countries' farmers in particular can adopt so as to withstand the changing climate. The methodologies that were used in these studies included different agronomic approaches specified for each region and country. The results showed that adaptation and mitigation techniques include the following: changing seed varieties through technological advancement research and through advanced management practices, creating new water-harvesting strategies and government-farmer interventions. However, these adaptation techniques failed to take into consideration the fact that some farmers simply cannot afford such measures without government interventions. Therefore, due to the limitations of these suggested techniques and methodologies, the effects of climate change on agriculture in developing countries have most likely been both under- and overestimated.

Easterling (1994) did a review study of the adaptability of North American (U.S. and Canada) agriculture to climate change. The most efficient agronomic and economical adaptation strategies were found to be the following:

- Climate adjustments at farm-level,
- Government policies that assist farmers to adapt to climate change,
- International trade policies, which recognise the impacts of climate change,
- The translocation of crops across natural climate ingredients, and
- Rapid introduction of new crops (soybeans and canola) and resource substitutions prompted by changes in prices of production inputs.

South Africa is one of the countries in which government subsidies and controls have been eradicated; this factor needs to be considered when assessing the impacts of climate change and variability (Government Year Book, 1996). Already, according to the Government Gazette on Agriculture (2001), South Africa does not have ideal conditions for crop production, as less than 15% of its land is arable and as serious climatic constraints, such as periodic droughts, have hindered agricultural production. Moreover, the recent droughts in Southern Africa (1992/1993) have renewed concerns about natural or possibly man-made climate change. It also cannot be ignored that a majority of the population in this region still relies on agriculture for food at the subsistence level, and sometimes even at a more advanced level to generate household income.

3.5.2 Impacts of climate change on maize production

Most analysts and scientists agree that agriculture, especially in poor countries, is likely to be the most vulnerable sector and the least capable of adapting to climate change and other environmental disturbances (Antle, 1995).

These projections have already been noticed in Sub-Saharan Africa where climate variability has mainly been experienced through floods and droughts, in 1982 and 1985 respectively (Dube and Jury, 1994). South Africa's first National Communications[8] to the UNFCCC have

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[8] In accordance with Article 12 of the Convention on Climate Change, South Africa as a signatory to the UNFCCC is obliged to report on the following: national inventories of GHGs: SA's vulnerability to climate change and its potential to adapt thereto; systematic observation and research undertaken in this regard;

identified maize as the main crop that would be detrimentally affected by climate variability and change. A number of comparable studies have been done in European countries and in parts of Africa, specifically in Southern Africa, using different approaches to assess the potential effects of climate change on maize production in these regions.

In Europe, Alexandrov and Hoogenboom (2000) investigated the impacts of climate change on maize production in Bulgaria. An agro-economic approach was conducted, whereby GCM's were used to predict different climate scenarios. The results from this study indicated that increased CO_2 levels will lead to global warming, which will further increase droughts and floods in this region. The results also illustrated that, as CO_2 levels continue to increase globally, the threat to agricultural productivity, especially maize production, is unavoidable. In addition, the CO_2 increase was projected to lead to further regional and global changes in temperature, precipitation and other climate variables, but these would be felt more at the regional level due to their intensities at such levels.

In Africa, Fischer and Onyeji (1994) conducted a study to assess the impacts of climate change on maize production in Egypt. They used the crop simulation models of the International Benchmark Sites Network for Agro-technology Transfer (IBSNAT) for this analysis. They took into account the wider impacts of climate change on world commodity trade and the consequent effects on Egypt's economy. They also examined various scenarios, both with and without adaptation strategies, and compared these results with a reference scenario of no climate change. The first scenario assumed no investment in adaptation, the second scenario assumed both small investments and large investments, and thereafter the projected yield from the two scenarios were applied to a Basic Linked System of National Agricultural Models (a general equilibrium model) to simulate the impacts of climate change from 1990 to 2060. The results showed that large investments in adaptation are required to avoid the adverse impacts of climate change on the Egyptian economy, whilst changes in the GDP were found to range from –6.2% (with no adaptation) to +0.7% (with large investments in adaptation).

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projections and policies on climate change, mitigation options and possibilities of adaptation; as well as preliminary needs assessments, education and public awareness programmes (www.unfcc/nationalcommunications/South Africa).

In Southern Africa, studies on the potential impacts of climate change on maize include studies done by Schulze et al. (1993) and later Muchena (1994), who examined the effects of climate change on maize yield and the effects of adaptive measures in different regions of Zimbabwe, South Africa and Lesotho. In these studies the CERES maize model (a crop simulation model) was used to simulate the effects of climate change on yield and productivity under present and future climatic conditions, taking into account the effects of increasing CO_2 levels and the resultant expected increases in temperature.

Their results showed that maize yield would decline over time even under increasing CO_2 levels, whereas dependence on the intra-seasonal and inter-annual variations of rainfall would increase. Results also showed that a decline in productivity would likely be marginal, as these countries were already facing considerable food security problems and economic instabilities. This study also recommended adaptation measures, such as changes to more drought-resistant varieties of plants, adaptation to new growing seasons, and even the introduction of new irrigation schemes. However, these would be very costly for the farmers in this region.

Matarira et al. (1995) assessed the vulnerability of maize and adaptation options, which could be used in Zimbabwe. They used Global Circulation Models (specifically, the Geophysical Fluid Dynamics model and the Canadian Climate Centre Model) and dynamic crop-simulation growth models (specifically, CERES-maize models). Simulated maize yield were projected to decrease both under dry land conditions and under full irrigation conditions in response to certain climate variations. This reduction in the modelled maize yield was primarily attributed to temperature increases that would shorten the growth stages (i.e. the grain filling stages) of the maize crop.

With reference to adaptation, several potential adaptation strategies were suggested. These included switching to drought-tolerant small maize varieties and utilizing appropriate management activities. It was also found that some farmers might suffer because of relatively severe local climatic changes, while farmers in other areas might benefit through improved yield and higher prices because of favourable local climatic conditions. Nevertheless, it was recommended that further research would be necessary to generate more advanced technologies that would equip farmers to adapt to the effects of climate change and climate variability.

Lastly, Berry and Ortmann (1989, 1990) completed a series of studies using an agro-economic approach to analyse maize yield responses to fertiliser and rainfall variations at Dundee, KZN province, South Africa. Data from a long-term field experiment was used to develop a predictive equation relating maize grain yield to nitrogen (N) and phosphorus (P) applications and total precipitation in different growth stages of the maize plant. These stages included pre-planting, followed by a sequence of non-overlapping physiological growth phases from sowing to maturity. A mixed quadratic (N) and square root (P) polynomial containing linear terms was used to determine the response of maize grain yield to N and P, the fertiliser requirements for maximum profits and the least cost N and P combinations. The effects of low, medium and high levels of rainfall were also investigated. The results indicated that an increased level of precipitation would adversely affect yield response and profitability.

3.5.3 Impacts of climate change on food security and food supply

With anticipated increases in climate variability and its impacts on crop production, both the international and national food security of countries will be seriously threatened. In 1986, the World Bank issued a food security policy paper, in which two essential elements of food security – the availability of food, and the ability to acquire it – were extensively discussed. The availability of food and the stability of supplies were seen to be under threat because of dramatic climate fluctuations (including droughts and floods), as well as because of sharp price increases and seasonal employment which has left people even more vulnerable than before.

Many studies have been undertaken in developed countries to analyse the impacts of climate change on food security. Parry (1990), Rosenzweig et al. (1993) and Parry et al. (1994) have all highlighted the potential effects of climate change on crop yield, world food supply and regions vulnerable to such food deficits. Greenhouse gas-induced climate change scenarios and crop-economic simulations were used to analyse these potential impacts. The analysis further provided estimates of changes in terms of production and the prices of major food crops. Results of the effects of climate change, with adjustments made in farm-level inputs and country-specific trade economic systems, but excluding farm-level adaptations, suggested that there would be disparities in crop production between developed and developing countries as a result of climate change. Given different levels of farmer adaptation, the results of climate change and variability suggested that both minor and major levels of adaptation would help to restore world production levels globally, compared to climate change scenarios with no adaptation, although cereal production would still decrease by 5%. In addition, climate change is expected to increase yield in the high and mid-high altitude areas of the North, whilst decreasing yield at lower altitudes. These studies also suggested that this pattern would become more pronounced as time progresses.

Given the relationship between food security, poverty, climate variability and its impacts, researchers in Southern Africa have started to look at the correlations between these different variables. Hulme (1996), for instance, undertook a study to show how vulnerable the Southern African region is to climate changes, and how these can influence food security and water resources. He constructed an index of vulnerability based on different variables, such as national food balances, food production and dependence on food imports and food aid and the GNP of the relevant countries in Southern Africa. The results showed that the droughts of 1984/1985 and 1991/1992 had a significant impact on maize production in Southern Africa, and that desertification was caused by unsustainable human behaviour (specifically demographic changes, such as the lack of skilled small-scale farmers able to react sustainably to changes in climate and able to adapt quickly to the changing climate). Of the countries in the region, South Africa was found to be the least vulnerable, whereas Angola was the most vulnerable, due mainly to political unrest there. In addition to Hulme (1996), Benson and Clay (1998) also explored the impact of these droughts on national economies in Southern Africa. Benson and Clay's study focused on Namibia, Zimbabwe, Malawi, Lesotho and Botswana. It indicated that less developed countries would continue to be more vulnerable because of their greater dependency on agriculture, poor inter-sectoral linkages, their small non-agricultural sectors and a poor transport infrastructure.

3.6 Conclusion

The studies reviewed above showed the importance of assessing the impacts of climate change on food security and crop production, especially with regard to maize being the staple food for most African countries. Two main approaches were found in the literature with regard to measuring the sensitivity of agriculture to climate change. The first is a structural model of the agronomic response, which is based on theoretical specifications and controlled experiments. This includes integrated assessment models and crop simulation models, the latter of which includes agro-ecological zone analysis and agro-economic approaches. The second approach, in contrast, relies on the observed responses of farmers to climate variations.

Integrated assessment models are used in climate change analysis to link knowledge across various disciplines with climate change impacts. The agro-ecological zoning approach, by comparison, relies on crop models and a land resource inventory to determine potential yields. This methodology is also able to capture adaptation and technology adoption by farmers in response to climate change. The main disadvantage of this methodology has been its inability to capture changes within each zone, given that the calibration of price effects in this methodology is still difficult.

Agro-economic approaches (i.e. production function approaches) are based on empirical and experimental analyses and capture the relationships between yield factors and environmental factors. Mendelssohn et al. (1994) outlined several deficiencies of the agro-economic approach, with the most important being that such models tend to overestimate damages, whereas yield estimates from these controlled experimental models do not incorporate adaptations in the form of modified farming methods. Cross-section methods known as the Ricardian approaches, on the other hand, rely on observed responses of farmers to varying climate. The Ricardian approach employs regression techniques to measure the relationship between land value or net revenue and a set of climatic and social attributes. The main disadvantage of this approach has been that it assumes constant prices.

Studies on the impacts of climate change in Southern Africa have been growing. Recently a few studies looked at the impact of climate change on different crops in the region. These included studies by Schulze et al. (1993) assessing the potential impacts on maize production under different climatic conditions whilst the Agricultural Research Council (ARC) conducted a study on the vulnerability of maize production to climate change in South Africa. Both these studies used crop growth simulation models. Also, Erasmus et al. (2000) studied the effects of climate change on the Western Cape farm sector using a GCM. The limitations of this study was that it looked only at the Western Cape and only focused on one climate variable (i.e. rainfall) to predict various climate change scenarios.

In terms of economic assessments, few studies have started to analyse the economic impacts of climate change on agriculture in South Africa. They include a study by Poonyth et al. (2002), which only looked at climate variability rather than long-term climate changes. On the other hand, Deressa (2003) and Gbetibouo (2004) utilized the Ricardian approach employing cross-section data to properly capture the economic impact of climate change on various crops including maize production. However, both these economic impact studies conducted by Deressa (2003) and Gbetibouo (2004) were not able to highlight the relationship between the agronomical/biological growth aspects of the crops they assessed and climate variations.

Even though the analyses of economic impacts of climate change on South African staple foods (including maize) have started, the anticipated impacts of climate change (as forecasted by the IPCC for the Southern Africa region) on the main growth stages of the maize crop (agronomic/biological growth responses) have not yet been taken into consideration. However, the ARC study applied the crop growth model in which production practices, soil characteristics, maize cultivars, climate and most importantly crop physiological responses to increased CO_2 levels were assessed to analyse vulnerability of maize production to climate change, but the vulnerability of each of the main growth stages (including all maize agronomical aspects) to the forecasted climate scenarios were still not assessed. Therefore, this study will attempt to focus on the vulnerability of the main growth stages to the current and future forecasted climate variations using the same data set from the ARC study.

For this study, the production function approach was chosen as it is the only approach which allows for current observed maize yield in the 19 main experimental sites to be entered into an economic model that will predict likely impacts of the anticipated changing climate. This production approach is also said to be the most powerful approach for analysing the interactions of the crop-management-climate-soil system.

Lastly, this study has adopted the production function approach to assess the relationship between the agronomical growth stages of the maize crop to present and future forecasted climatic conditions using experimental data from the 19 main maize producing sites of South Africa. In assessing both present and future forecasted climatic conditions, where negative climate change impacts are anticipated for each of the growth stage, possible adaptation responses which can be undertaken by farmers will be presented.

CHAPTER 4: Approach and Methods of the Study

4.1 Introduction

This study used cross-section data to analyse the sensitivity of maize yield to both climate variables and production inputs in the nineteen main maize-producing regions in South Africa. The focus is specifically on measuring the impacts of climate variables on the three main growth stages of the maize crop: sowing to emergence (juvenile stage), end of juvenile stage to tassel initiation stage, and from tassel initiation to the grain filling growth stage. The production function model and the technical aspects of production are discussed in the next section. The empirical model is for maize production in SA is then described followed by a discussion of types and sources of the used data.

4.2 The production function and its structural properties

Agricultural production functions measure the biophysical relationship between the physical quantities of output of a crop and the set of inputs used to produce the crop (Ozsabuncuoglu, 1998). The function (f) reflects a technological mapping of the maximum level of physical output (Y) which can be obtained from given levels of factor inputs (X):

$$Y = f\,(X) \qquad (4.1)$$

Production inputs may either be fixed (land, machinery, etc.) or variable (levels of fertiliser, seed, labour, etc.).

Production function parameters can thus be estimated from observed information on input and output quantities in the form of:

- Cross-section data (observations across space within a particular time period),
- Panel data (observations from the same sample or location over many time periods), and
- Time series (data observed over a number of time periods and locations).

Certain assumptions are made in defining and describing production functions to ensure technical validity and feasibility of an economic optimum, i.e. maximum profit or minimum cost, which include the following restrictions on the structure of a production function f (Chambers, 1988):

- f is monoperiodic, requiring that production in one time period is entirely independent of production in preceding and subsequent time periods;
- All inputs and outputs are homogenous, which means that there are no quality differences between different levels of particular input or output;
- f is monotonic in X, which means that increasing the level of any member of X (*ceteris paribus*) can never decrease output Y. This property stipulates that marginal products are non-negative[9];
- f is quasi-concave imposing convexity of the production set and ensuring the law of diminishing marginal rate of technical substitution;
- f is a twice continuously differentiable function.

One rule that must hold for all production functions is the *law of diminishing marginal returns* to ensure existence of an economic optimum. This law implies that adding more of one input while holding others constant eventually results in smaller increments in the level of produced output. Concavity of the production function guarantees this structural property. Another important measure of the structural properties of production functions is the measure of returns to scale, which may be referred to as the *elasticity of production or the elasticity of scale* (Beattie and Taylor, 1985; Chambers, 1988). The *elasticity of scale* measures how output responds to simultaneous changes in input levels. Returns to scale properties of a production function are characterised by means of the degree of homogeneity of a production function. For example, if we consider the general production function f, it is said that the function f is homogenous of degree r if:

$$\lambda^r Y = f\,(\lambda X_1,\ \lambda X_2,\ \ldots.,\ \lambda X_n) \qquad (4.2)$$

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[9] Although in agricultural production there are certain technical circumstances in which higher input levels are harmful to grown crops and hence lead to reductions in output, these are not consistent with economic rationality and hence are excluded possibilities for a well-behaved production function in the economic rationality sense.

Function *f* is said to exhibit increasing, constant or decreasing returns to scale if r is greater than, equal to or less than one, respectively. In other words, this means that increasing levels of all inputs by the constant factor λ will increase the level of output Y (value of function *f*) by the quantity λ^r.

Admissible production functions require that at least one input is a substitute to others in the production of Y. Substitution possibilities between inputs are an economic necessity for determining the alternative combinations of inputs that generate the same level of output. The measure of the degree of substitutability between two inputs when all other inputs are held constant is known as the *elasticity of input substitution*. In conclusion, a well-behaved production function is assumed to be twice continuously differentiable, strictly increasing in X and concave.

4.3 The empirical production function model for maize in SA

To implement the above analytical model to measuring impacts of climate change on maize production in SA, the relationship between maize yield (Y) and the following set of explanatory variables (X) on which data were available for this investigation was specified:

1. **Climate attributes**: Rainfall, temperature and solar radiation in the three growth stages of the maize crop defined above.
2. **Soil factors**, specifically drainage rate and minerals' contents;
3. **External inputs** namely, inorganic fertiliser, labor and machinery

The above listed independent variables include production inputs (fertiliser applied, labour and machinery), which fall under the control of the farmer, as well as climate variables (drainage rate, mineralization of the soil, solar radiation, rainfall and temperature) that are beyond farmer's control.

In the first stage of maize growth (the juvenile stage from sowing to emergence), soil drainage and amount of rainfall are particularly important. Excess rainfall before and after sowing can cause soils to become waterlogged, leading to slow seed germination. On the other hand, excess drought conditions may cause slow or no seed germination.

During the second stage (the end of the juvenile to tassel initiation), the critical climate variables are soil drainage, fertiliser application, temperature and solar radiation. Fertiliser application is critical, as soil nitrogen deficiency may result in stunted plant growth and other undesirable plant deficiencies. Similarly, soil drainage is important for this stage, as soil aeration and highly waterlogged soils may hinder plant growth. Lastly, as the maize plant is a summer crop, it is particularly dependent on mean annual temperatures (above 15.9 ^{0}C) and mean annual global solar radiation (above 244 Wm^{-2}) (Tsubo et.al. 2003).

During the third stage (from tassel initiation to grain filling) solar radiation (which also directly influences day length), rainfall, and drainage are the most important climate variables. For instance, short day lengths might delay the grain filling process. Excessive rainfall may cause maize cobs to rot, whereas drought conditions during this stage may result in tassel desiccation. Finally, good soil drainage is important as it allows the plant to absorb water and minerals when needed (www.cimmyt.org/reports).

4.4 Data used and their sources

To conduct the intended analyses, farm level data on the above listed variables were obtained from the Agricultural Research Council (ARC) experimental sites in the nineteen main maize-producing regions in South Africa. The variables included in the empirical analyses are described in Table 4.1.

The data have been collected by the ARC to conduct the South African Country Study on Climate Change (SACSCC) Vulnerability and Adaptation Assessment for Agriculture. For each of the nineteen sites model simulations were conducted using a number of variables specified in the CERES crop growth simulation models. This has been the main limitation of the ARC study, as all of the data collected from the sites were based on what was required for applying the CERES simulation programme and model.

The data set includes average and standard deviation of yield distributions, and average units of the standard production practices, which included fertiliser applications, labour and machinery use. Data on minimum and maximum climate attributes such as temperature, solar radiation and rainfall were also obtained in addition to drainage rate and mineralization rate.

Table 4.1: Maize production variables included in the empirical maize production model for SA

Data Name	**Definition and Data (Measurements)**
Yield (Y)	Maize yield in Kg per hectare (kg/ha)
Fertiliser (F)	Fertiliser use in Kg per hectare (kg/ha)
Labour (L)	Labour time for operating machinery (hours/ha)
Machinery (M)	Machine time (hours/ha)
Soil drainage rate (DR)	Drainage rate of the soil in each site. This variable takes a value of one if the soil has a soil drainage (porosity) rate < 0.1 and zero if less.
Soil mineralization (MR)	Mineralization rate of the soil refers to the content of minerals in the soil in each site. This variables takes a value of one if the soil has mineralization rate is greater than 0.1ugN and zero if less than 0.1ugN.
Solar Radiation (SR_1)	Solar radiation, measured as a rate at which radiation is diffused by the plant leaves from sowing to emergence (W/m^2).
Solar Radiation (SR_2)	Solar radiation measured as a rate at which radiation is diffused by the plant leaves (proxy for radiation use efficiency); from end of juvenile stage to tassel initiation (W/m^2).
Solar Radiation (SR_3)	Solar radiation measured as a rate at which radiation is diffused by the plant leaves (proxy for radiation use efficiency); from tassel initiation to grain filling (W/m^2).
Rainfall (R_1)	Mean total rainfall (mm) from sowing to emergence
Rainfall (R_2)	Mean total rainfall (mm) from end of juvenile stage to tassel initiation
Rainfall (R_3)	Mean total rainfall (mm) from tassel initiation to grain filling
Temperature (T_1)	Mean daily maximum temperatures (ºC) during sowing to emergence
Temperature (T_2)	Mean daily maximum temperature (ºC) during end of juvenile stage to tassel initiation
Temperature (T_3)	Mean daily maximum temperature (ºC) during tassel initiation to grain filling

Chapter 5: Results of the empirical analysis

5.1 Introduction

This chapter presents and discusses the results of the empirical analyses. It starts by introducing the procedures employed in the specification and estimation of the empirical model. The results of the empirical analyses were then discussed, followed by results of simulations undertaken to evaluate the implications of global warming scenarios, associated with doubling of carbon dioxide levels on maize production sites in South Africa. The same data set was used previously in a study conducted by the Agricultural Research Council of South Africa (ARC), employing the CERES crop growth model to analyse the vulnerability of maize production to climate change**.** The results of this study were then compared with the ARC study results, to ascertain the likely impacts of climate change on maize production in these nineteen maize production regions of the country.

5.2 Specification and estimation of the empirical production function model

The first step in the empirical specification is the choice of an appropriate functional form. Several factors are considered when making this choice, which include a selection of a functional form that obeys certain regularity conditions on the technology structure (i.e. concavity, non-negativity of input and output levels, etc.). The number of data points available for the analysis is another factor which influences the feasibility of alternative technology structure specifications (Gujarati, 1998).

Some functional forms impose certain restrictions on the production structure and require higher degrees of freedom (sample size). According to Ozsabuncuoglu (1998) the Cobb-Douglas and quadratic functional forms are the most commonly used agricultural production functions. Both these forms were feasible for the purposes of this study, given available data. The two functional forms were therefore tested and the results of the econometric estimation were evaluated and compared.

The second step is to choose the appropriate econometric estimation procedure to generate estimates of the selected model parameters. The available data for this study are cross-sectional and has low degrees of freedom. Two problems namely heteroscedasticity and multicollinearity are normally encountered when working with such data.

Heteroscedasticity refers to the unequal spread or variance of the disturbances u_i of a regression model. This violates one of the assumptions of the classical linear regression model, which require that the error terms (u_i) be homoskedastic (i.e. must all have the same variance) for its ordinary least squares (OLS) estimators to be best linear unbiased estimators (BLUE) (Gujarati, 1998). In the presence of heteroscedastic errors, the OLS estimators remain unbiased and consistent but not efficient whilst the OLS procedures result in t and F tests which are highly misleading and which may result in erroneous conclusions.

A number of solutions are used to correct for heteroscedasticity. According to Gujarati (1998), a log-log model may reduce heteroscedasticity compared to a linear model. Also, to correct for heteroscedastic errors, a number of alternative econometric estimation procedures have been developed to use instead of the OLS estimation methods. These include the Weighed Least Squares (which is a special case of Generalized Least Squares) and Maximum Likelihood estimation among others (Dutta, 1975). These estimation methods may be used to allow for consistent covariance matrix of the parameter estimates. Therefore, to remedy the problem of heteroscedasticity in this study, firstly the dependent variable was log transformed, which also compresses the scale in which variables are measured. Secondly, White's heteroscedasticity corrected standard error was specified using the statistical software package E-views to ensure consistency and efficiency of estimators. Therefore, with specified White corrected standard errors, new larger standard errors and smaller estimated t-values were obtained.

The second common problem that is usually encountered with the use of cross-sectional data is multicollinearity. This refers to the existence of linear correlations among some explanatory variables of a regression model. In the presence of multicollinearity, OLS estimation procedures still generate the best linear unbiased estimators but with large variances, covariances, wider confidence intervals, and high R^2 but few significant t-ratios (with smallest variance). Also with multicollinearity, the F- test usually rejects the hypothesis that the partial slope coefficients are simultaneously equal to zero whilst the t-test usually shows that none or very few of the partial slope coefficients are statistically different from zero.

Therefore, the main factors contributing to the presence of multicollinearity include data measurement methods employed and improper model specification. Several remedial measures do exist, especially in terms of improving problems related to the data, which include omitting highly collinear variables or combining cross-sectional and time series data, transforming variables or obtaining additional or new data (Gujarati, 1998).

An inspection of the matrix of correlation coefficients among all regressors provided a test of multicollinearity. It is clear from the matrix of partial correlations presented in Appendix 1, that there is high collinearity among the following regressors:

1. In general, high collinearity was evident between measures of solar radiation in different growth stages (SR1 and SR3) and between measures of solar radiation and temperature (SR and T).
2. High collinearity was also detected between rainfall (for the 1st and the 2nd growth stages) and temperature variables (for all three growth stages) of close to 0.9.
3. Temperature variables also showed high collinearity of close to 0.8 amongst each other.

As a result, variables that showed high collinearity were dropped from the model. This was done iteratively, dropping one at a time, starting from the highest levels of collinearity and re-estimating the model again. The process was repeated until a reasonable statistical performance was reached.

To determine an appropriate functional form to best fit the data three criteria were applied. Firstly, the signs of the estimated coefficients were checked for consistency with prior expectations. This was then followed by an assessment of the statistical significance of the estimated coefficients. Then the power of the regression model was evaluated in terms of the explained variation in the dependent variable, as measured by the adjusted coefficient of determination (R^2).

Upon applying the above procedures, the semi-log functional form was chosen, as it gave the best statistical fit and admissible structure. The best statistical fit and performance was given by the following maize yield response model that regressed maize yield on climate factors:

$$\ln \boldsymbol{Y} = \boldsymbol{\beta}_0 + \Sigma_i \boldsymbol{\beta}_i \boldsymbol{X}_i + \Sigma_i \boldsymbol{\beta}_{ij} \boldsymbol{X}_i \boldsymbol{X}_j + \boldsymbol{u} \ldots\ldots\ldots\ldots\ldots\ldots\ldots (5.1)$$

Where Y refers to maize yield, β_o, β_i and β_{ij} refer to the regression coefficients to be estimated, $X_{i,}$ refer to regressors, which included rainfall for the three maize growth stages (R_1, R_2 and R_3), solar radiation for the three maize growth stages (SR1, SR2 and SR_3), temperature for the three growth stages, fertiliser and dummy variables for soil drainage (SD) and soil mineralization (SM).

The empirical model applied to this study assumed a quadratic relationship between maize yield and climate factors. The quadratic terms were included to reflect nonlinearities in the relationship between maize yield and climate variables (i.e. to capture second order effects of climate variables on maize yield (Dinar et al., 1998, Gbetibouo and Hassan, 2004; Mendelssohn and Dinar, 2003).

5.3 Results of the empirical estimation

In estimating the empirical model, fertiliser application, and the soil drainage dummy variables had initially been included, but they were found to have inadmissible signs and were statistically insignificant and were thus omitted. However, the dummy variable measuring soil mineralization, which reflects the amount of minerals in the soil (and which is obviously highly correlated with fertiliser application) was found to have an admissible sign and to be statistically significant. Again, temperature by growth stages variables were introduced but did not perform well and hence were omitted and replaced by solar radiation variables.

The significance of the solar radiation in maize production should be highlighted as it has a direct and significant effect on maize production as the maize crop is highly dependent on the amount of solar radiation it intercepts. It should also be noted that all the energy used by plants to grow is derived from sunlight, or more precisely, solar radiation which is also directly linked to temperature levels in the atmosphere. According to the IPCC (2001), increases of CO_2 in the atmosphere (which causes global warming) would further reduce the ozone layer hence resulting in increased infra-red light being re-emitted. This high availability of infra-red light means that plants have to intercept and diffuse increased amounts of net radiation through its leaves to convert it to energy. Therefore, an increase in both ultraviolet radiation (together with mean temperatures) in the atmosphere would further accelerate the amount of CO_2 assimilated by the total crop canopy, which also accelerates crop growth (Muchow et al., 1990). Solar radiation is also regarded as a key driver of the maize plant growth processes of photosynthesis, evaporation, transpiration, and soil heating (Tsubo et al., 2003).

The variable on solar radiation levels in the first growth stage was dropped from the estimation because it was found to have high multicollinearity with variables on solar radiation for the other growth stages. Also, the inclusion of quadratic terms that capture second order effects of solar radiation in the second and the third growth stage reduced the statistical insignificance of the other variables in the estimation, and were hence omitted, but were used later for the critical climate damage point analysis.

Given the importance of rainfall and solar radiation as main climate variables which affect maize yield, this empirical estimation focused on assessing the impact of current and anticipated rainfall and solar radiation changes on maize yield. The final semi-log function gave the best statistical fit to the data explaining 79% of the total variation in maize yield as reported in Table 5.1.

Results showed that rainfall variables for all three growth stages were statistically significant and supported a quadratic relationship between rainfall and maize yield. None of the solar radiation variables were significant, however it should be noted that under good conditions and in the absence of pests and diseases, the amount of solar radiation intercepted by the crop especially during the second growth stage should be positively related to maize yields.

During the second growth stage, the maize crop requires both maximum solar radiation levels to allow for proper tassel initiation and maximum water absorption by the crop. On the other hand, during the grain filling growth stage, minimal solar radiation interception and adequate (sometimes minimal) water absorption are required by the maize crop. The soil mineralization dummy was found to positively affect maize yield across all growth stages, indicating the importance of fertile soils which result in positive maize yields.

The rainfall in the first growth stage (sowing to emergence) and the third growth stage (tassel initiation to grain filling) showed a concave (hill-shaped) relationship with maize yields whereas, rainfall in the second growth stage (juvenile stage to tassel initiation) had a U-shaped relationship with maize yields.

Table 5.1: Estimated parameters of the semi-log maize production function

Dependent variable: Maize yields in Kg/ha **Constant = 0**[10]		
Independent variables	**Coefficients (β)**	**t-statistic**
Mineralization rate	0.539	3.23**
Rainfall (R_1)-sowing to emergence growth stage	0.086	2.6*
Rainfall (R_2)-end of juvenile to tassel initiation growth stage	-0.153	-3.9**
Rainfall (R_3)-tassel initiation to grain filling growth stage	0.192	3.8**
Solar Radiation (SR_2)- end of juvenile to tassel initiation growth stage	1.121	0.61
Solar radiation (SR_3)- tassel initiation to grain filling growth stage	-4.277	-2.2
Rainfall $(R_1)^2$	-0.0007	-2.4*
Rainfall$(R_2)^2$	0.000909	4.2*
Rainfall $(R_3)^2$	-0.001	-3.6*
Number of observations = 19	* Significant at 5% **Significant at 1%	Adjusted R^2= 79%

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[10] The constant term in this multiple regression analysis was not included as it proved redundant with the set of independent variables which were estimated. Thus to ensure that the model will still be "unbiased" even with exclusion of the constant term, the adjusted R^2 was thus used instead of a normal R^2.

Measures of elasticity estimate the percentage change in the response variable induced by a percent change in the independent variables. Therefore, the sensitivity of maize yield to changes in climate variables was evaluated in this section by making use of elasticity measures. The calculated elasticities indicated that at mean levels maize yields are highly sensitive to both rainfall and solar radiation changes.

Table 5.2: Estimates of the elasticity of maize yield to climate factors

Rainfall in the first growth stage	0.03
Rainfall in the second growth stage	0.78
Rainfall in the third growth stage	1.34
Solar radiation in the second growth stage	0.62
Solar Radiation in the third growth stage	-2.73

Therefore, the calculated elasticity evaluated at mean values indicated that at current levels of solar radiation, increasing rainfall in all three growth stages would increase maize yields. Also, at current levels of rainfall, calculated elasticities at mean values indicated that increasing solar radiation levels for the second growth stage would increase maize yields whilst increasing solar radiation for the third growth stage would decrease maize yield.

5.4 Optimal climatic conditions for maize production

Comparing critical damage points using the estimated model with optimal ranges of solar radiation and rainfall in various growth stages for maize production based on agronomic knowledge revealed interesting findings on the sensitivity of maize production in South Africa to climate change. Also, all levels of rainfall and solar radiation higher (for concave relationships) and lower (for convex relationships) than the calculated climate optimal point were considered sub-optimal, i.e. result in lower yields.

The critical damage point analyses showed that increasing rainfall levels up to 61.42 mm during the first stage would increase maize yields, beyond which higher rainfall levels lead to yield reductions Table 5.3 and Figure 5.2.

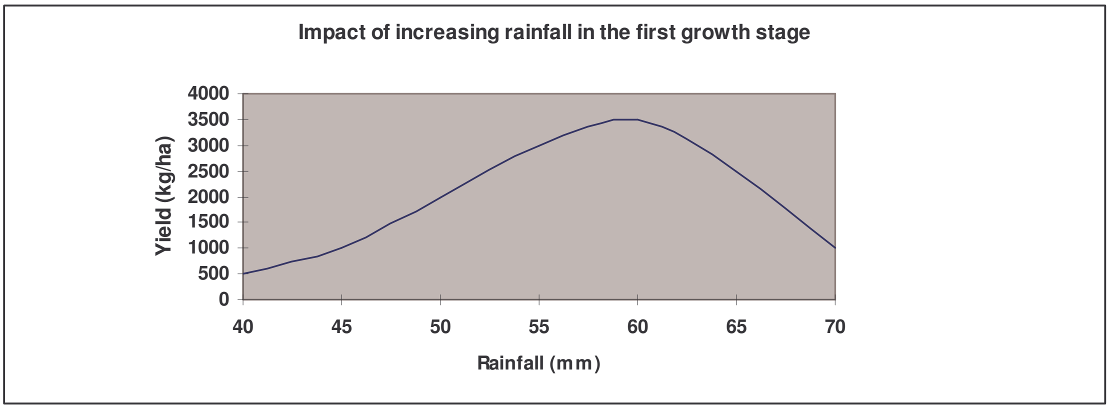
Table 5.3: Critical damage points, average rainfall, and agronomic optimal ranges of rainfall across the 19 main maize producing experimental sites of South Africa

Maize growth stage	**Critical rainfall points obtained (mm) from the model**	**Average rainfall in the 19 main maize producing sites for each of the growth stages**	**Agronomic optimal ranges of rainfall[1] (mm)**
1st stage – Sowing to emergence	61.42 mm Maximum point	61.01 mm	50mm-60mm
2nd stage – Juvenile to tassel initiation	84.06 mm minimum point	88.88 mm	90mm-120mm
3rd stage – Tassel initiation to grain filling stages	96 mm maximum point	88.41 mm	80mm-100mm

1. Source: Agricultural Research Council- Grain Crop Institute (2003).

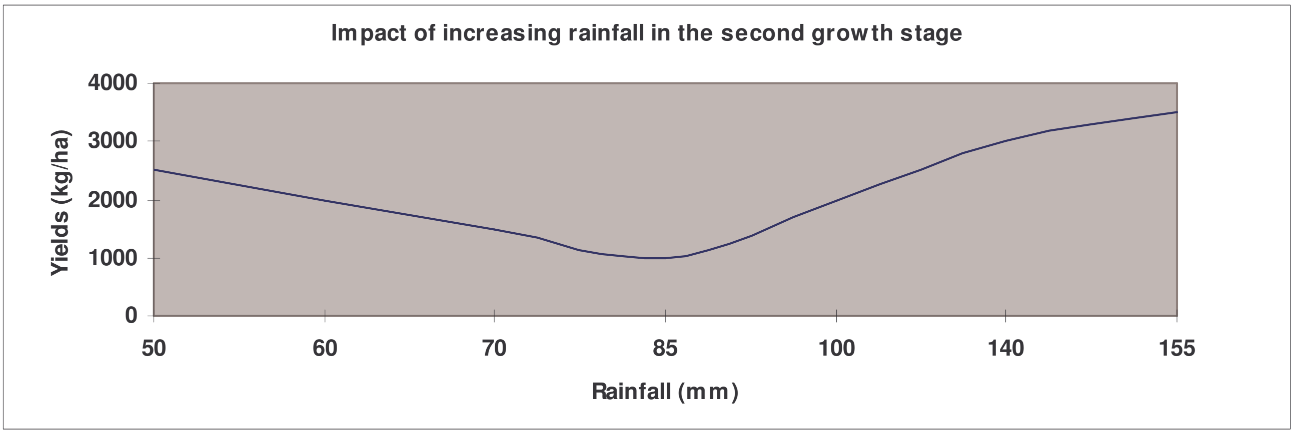
The decline in maize yields above this rainfall level could be attributed to the fact that soils may become waterlogged due to high rainfall levels, leading to slow seed germination. This result is in line with the agronomic optimum values, which ranges from 50 mm to 60 mm. Table 5.3 also shows that the current average level of rainfall during this growth stage is close to the maximum critical damage point of 61.42 mm. This implies that this growth stage is sensitive to marginal changes in rainfall as there is very limited range of tolerance to increased rainfall.

Figure 5.2: Impact of increasing rainfall in the first growth stage on maize yield



In contrast, rainfall in the second growth stage, showed a U (convex)-shaped relationship with maize yield (Figure 5.3). This suggests that rainfall amounts less than 84.06 mm during this stage would decrease maize yields, beyond which higher rainfall levels lead to higher yields. The increase in maize yields due to higher rainfall above this point could be due to the fact that the maize crop needs maximum amounts of moisture at its juvenile to tassel initiation growth stage. Currently average rainfall during this stage of maize growth in South Africa is higher than the critical damage point but lower than the agronomic optimal range (Table 5.3). This implies that this growth stage is sensitive to lower rainfall levels but higher rainfall would be favourable (Figure 5.3).

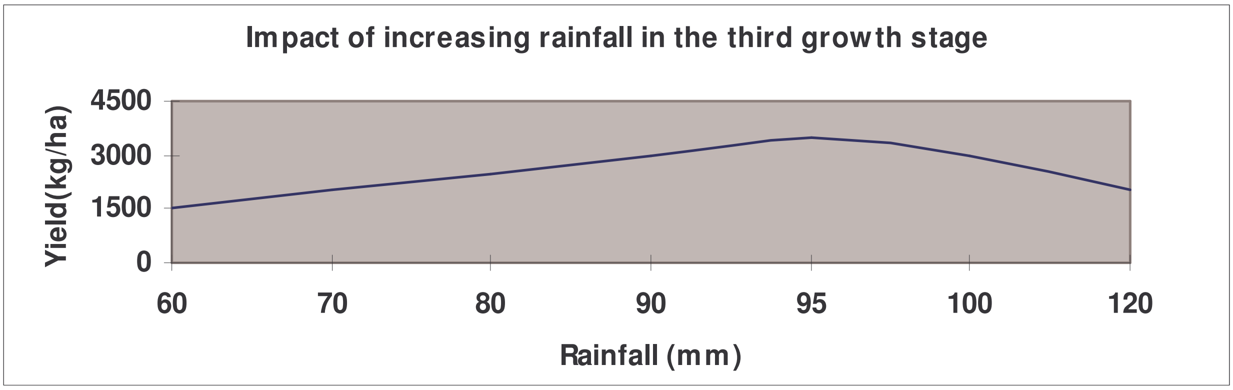
Figure 5.3: Impact of increasing rainfall in the second growth stage on maize yield



A hill-shaped relationship was again obtained between maize yield and rainfall in the third growth stage (Figure 5.4). This indicated that increasing rainfall up to 96 mm during this stage would increase maize yield, whereas more than 96 mm of rainfall would decrease yield. The decline in maize yield beyond 96 mm during this stage could be associated with the fact that, excessive rainfall may cause maize cobs to rot leading to lower maize yields. According to the ARC-Grain Institute (2003) 15 kgs of grain are produced for each millimetre of water consumed.

This result is again in line with the agronomic optimum values, which range from 80mm to 100mm (Table 5.3). However, for this growth stage Table 5.3 shows that the current average value of rainfall during this growth stage is below the maximum critical damage point and hence showing a good range of tolerance to higher rainfall (Figure 5.4).

Figure 5.4: Impact of increasing rainfall in the third growth stage on maize yield



As mentioned earlier, although the quadratic terms of the effect of solar radiation on maize yield were excluded from the final regression model for their poor statistical significance, they have been re-estimated for the critical climate damage analysis. For solar radiation in the second growth stage, the calculated optimal climate point at which maize yield is maximised was 0.31 W/m^2 (Table 5.4). This indicates that increasing solar radiation up to 0.31 W/m^2 during this stage would increase maize yield, whereas amounts beyond 0.31 W/m^2 would affect maize yield negatively (Figure 5.5). This result is not in line with the agronomic optimum values, which range from 0.40 W/m^2 - 0.50 W/m^2 (Table 5.4).

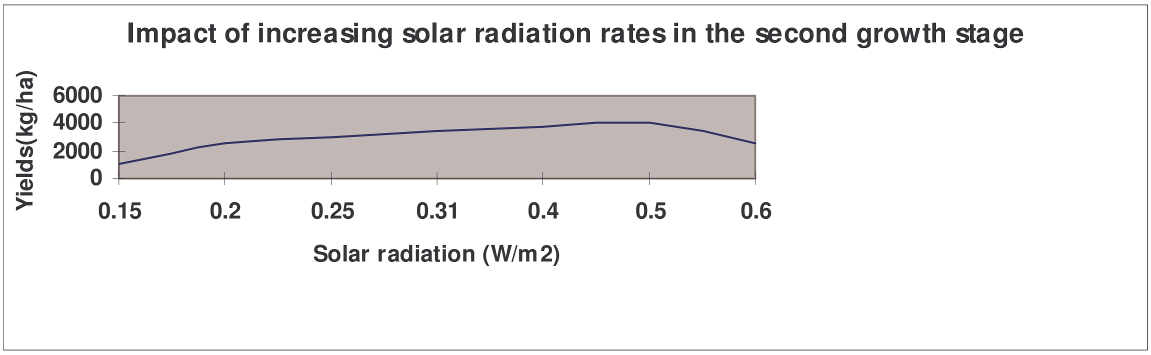
Table 5.4: Critical damage points, average solar radiation, and agronomic optimal range of solar radiation during the last two growth stages of the maize crop across the 19 main maize producing experimental sites of South Africa

Maize growth stage	**Critical solar radiation damage points (W/m^2) determined from the model**	**Average solar radiation in the 19 main maize producing sites**	**Agronomic optimal ranges of solar radiation[1] (percentage day length)**
Solar radiation for the second growth stage	0.31 : maximum point	0.55 at which solar radiation is diffused	0.40 to 0.55 at which solar radiation is diffused
Solar radiation for the third growth stage	0.18: minimum point	0.64: at which solar radiation is diffused	0.35 to 0.50 at which solar radiation is diffused

1. Source: Agricultural Research Council climate database.

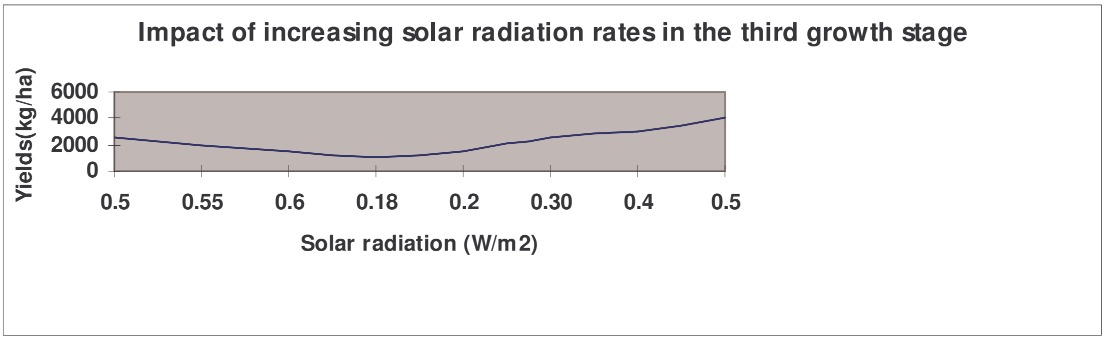
However, the current average value for solar radiation during this growth stage is higher than the maximum critical point but within the agronomic optimum value, which implies that even though current average solar radiation levels may be higher than the critical damage point resulting in lower maize yields, current solar radiation levels are still within the agronomic optimum values for this stage indicating tolerance to marginal increments of solar radiation during this stage (Figure 5.5).

Figure 5.5: Impact of increasing solar radiation in the second growth stage of the maize crop



In contrast, solar radiation in the third growth stage showed a U (convex)-shaped relationship with maize yield (Figure 5.6). This suggests that solar radiation levels diffused less than 0.18 W/m^2 during this stage would decrease maize yields. However, even though solar radiation levels during this stage are currently above the critical damage point they are still not within the optimal agronomic range. This further highlights high sensitivity of this growth stage to high solar radiation levels (Table 5.4 and Figure 5.6).

Figure 5.6: Impact of increasing solar radiation in the third growth stage of the maize crop



The critical damage point analyses revealed interesting variations between the different maize growth stages in terms of its sensitivity to changes in rainfall and solar radiation. It should be noted however, that the cumulative impact of increasing/decreasing both rainfall and solar radiation levels simultaneously across all growth stages should further be agronomically evaluated to give a better picture of the likely impact of climate change on the maize crop, which is what the next section attempts to do.

5.5 Simulation of potential climate change impacts on maize yield

The production function analyses presented above measured the relationship between climate attributes (rainfall and solar radiation) and maize yield in the main production regions in South Africa. The regression estimation results were then used in the previous section to evaluate the likely impacts of changes in climate attributes in each growth stage at a time (partial impact analysis), which did not capture the cumulative impact of changing levels of all climate attributes simultaneously across all growth stages. Furthermore, changes in climate that will occur in the next 50 years are not marginal changes, and thus elasticity measures could not give a full picture of climate change impacts.

Therefore, a climate change impact simulation analysis was carried to capture the cumulative impacts of plausible simultaneous change in rainfall and solar radiation across all growth stages. Following Sanghi *et al* (1998) and Kumar and Parikh (1998) in analysing the impact of climate change on Indian Agriculture, this section used the estimated production function model to simulate the impacts of changing rainfall and solar radiation (proxy for a temperature) on maize yield.

In this approach, both the partial and total impacts on the response variable (maize yield) were simulated by utilising the estimated regression coefficients (Table 5.5.) across the three growth stages. The change in maize yield (i.e. the difference between the actual trends experienced and the climate scenario levels) was calculated for potential benchmark warming scenarios predicted for the Southern Africa region. Firstly, a partial effect analysis whereby rainfall and solar radiation changes were simulated for each growth stage at a time was done followed by a total effect analysis in which rainfall and solar radiation changes were simulated across all growth stages at the same time.

A hotter and drier future climate scenario for the semi-arid to arid western regions of South Africa (60% of the 19 main maize producing sites in this study) and a hotter and slightly wetter future climate scenario for the wet east regions (remaining 40%) were predicted for South Africa (IPCC Third Assessment Report, 2001).

5.5.1 Partial and total effects of a hotter and drier climate scenario

As noted above, this scenario applies only to the arid and semi-arid regions where 60% of the maize is grown in South Africa. The forecasted climate scenario of a 7% reduction in rainfall and a 5% increase in solar radiation applied to the first stage of maize growth leads to a positive response (i.e. percentage increase) in maize yields. This result illustrated some level of tolerance which this growth stage has with respect to rainfall reductions. With respect to the second growth stage, a partial effect of decreasing rainfall by 7% and increasing solar radiation by 5% showed a negative response (i.e. percentage decrease). As explained before, sufficient and increased rainfall amounts during this growth stage are necessary otherwise tassels in which maize cobs develop may be stunted. Lastly, the partial effect scenarios for the last growth stage showed that a hotter and drier climate scenario would positively affect this growth the significantly. This result was not expected due to that at this stage, minimal solar radiation levels are required by the crop to obtain higher yield. However, the positive result may be attributed to that cumulative positive effects of minimal rainfall might exceed the negative effects of increased solar radiation during this stage.

Table 5.5: Sensitivity of maize yields to the forecasted hotter and drier future climate scenario for South Africa's arid and semi-arid regions

Climate Change Scenarios	**Partial impact for the 1st growth stage (%)**	**Partial impacts for the 2nd growth stage (%)**	**Partial impacts for the 3rd growth stage (%)**	**Total impacts on the three growth stages (%)**
7% reduction in rainfall and 5% increase in solar radiation	2	-13	17	4

Furthermore, this study examined the total effect scenario on maize yield of changing rainfall and solar radiation at the same time across all growth stages. With a 7% decrease in rainfall and 5 % solar radiation across all growth stages, there was an overall increase in maize yields. Therefore, the results from Table 5.5 showed that the benefits' effects of rising solar radiation intercepted by the maize crop can exceed the negative impacts of lower rainfall levels, i.e. hotter and drier climate scenario leading to a net gain of 4 percentage in maize yield.

5.5.2 Partial and total effects of a hotter and wetter climate scenario

Table 5.6 shows the percentage changes in maize yield in response to the forecasted climate change scenario for hotter and wetter future climate in the wet east regions of South Africa, where the remaining 40% of the maize is found.

Table 5.6: Sensitivity of maize yields to the forecasted hotter and wetter future climate scenario for South Africa's east regions

Climate Change Scenarios	Partial impact for the 1st growth stage (%)	Partial impacts for the 2nd growth stage (%)	Partial impacts for the 3rd growth stage (%)	Total impacts on the three growth stages (%)
7% increase in rainfall and 5% increase in solar radiation	-3	19	-17	-4

For the partial effect scenario in the first growth stage, a 7% increase in rainfall and a 5% increase in solar radiation showed a negative response (i.e. percentage decrease) in maize yields. This highlighted sensitivity of this growth stage to high water content in the soil during germination of seeds. With respect of the second growth stage, a partial effect of increasing rainfall by 7% and increasing solar radiation by 5% showed the most positive response (i.e. percentage increase). As explained before, increases in rainfall during this growth stage are necessary. Lastly, the partial effects scenarios for the last growth stage showed that a hotter and wetter climate scenario would affect this growth stage negatively. This may be attributed to the fact that, at this last growth stage, the maize crop requires minimal precipitation (rainfall).

Table 5:6 also shows the total effect scenarios on maize yields of changing rainfall and solar radiation at the same time across all growth stages. Therefore with a 7% increase in rainfall and 5 % increase in solar radiation across all growth stages; an overall decrease in maize yields was obtained.

5.6 Result analyses of the CERES Crop-Growth Model and the production function Model

This section reviews the CERES crop growth model simulations conducted by the Agricultural Research Council (ARC) on the same data used by the present study as part of the Vulnerability and Adaptation Assessment for Agriculture, a South African Country Study for Climate Change (SACSCC) (Du Toit *et al.,* 2001). The main findings and conclusions of the two studies are then compared.

For the ARC study, four climate scenario-based models were used for the simulation analysis and these included the climate system model (CSM), genesis model (GEN), Hadley 2 Model with no sulphate forcing (H2n) and the Hadley 2 model with sulphate forcing (H2s). This simulation analysis was repeated for each of the possible four scenarios. Therefore, for each of the nineteen sites, 30 years of simulations (1966-1996) were conducted with the standard production practices of the particular locality. The average, standard deviation and yield distribution were calculated for each of these nineteen points. Data on climate including minimum and maximum temperatures, solar radiation and rainfall were utilised. Other data used in the model simulations included soil classification, crop cultivar traits, production practices, and potential effects of CO_2 on plant physiology, to reflect crop physiological responses to increased $C0_2$ levels in the atmosphere.

Two of the four crop model simulations were altered to reflect experimental $C0_2$ effects for normal (330ppm) and approximately doubled (550ppm) $C0_2$ effects by increasing daily photosynthesis rates and stomatal resistance in conjunction with changes in rainfall. Therefore, the Hadley models with and without sulphate forcing (H2s and H2n, respectively) assessed the impact of increasing CO_2 from 330ppm (normal) to 550ppm for all 19 main maize producing sites. The four climate scenario site-based simulations were also linked to a national-scale Geographic Information System (GIS) database, and simulated for a period of 42 years (1951–1993), which was done to reflect potential crop yield responses at a regional scale.

The results from the H2n and H2s climate models indicated that, with increased CO_2 levels (resulting in drier climates due to decreases in rainfall); yield reductions of 10% to 20% were anticipated. The CSM and the Genesis scenarios were activated to assess the impact of increased rainfall, i.e. opposite scenarios to H2n and H2s. The results from these showed that production levels in the 19 experimental sites would remain the same as current levels with some increases in the dry marginal western production areas.

The ARC analyses predicted that some of the marginal western areas might become unsuitable for maize production under current management strategies, whilst some of the eastern production areas might remain unchanged or even increase production levels. However, it was concluded that some of the negative crop growth effects might be mitigated by the “fertilization effect” of CO_2 gas on plant physiology, even though some of the scientists are currently divided on the scale and longevity of these benefits. Other adaptation options highlighted include moisture retaining farming methods, increased extension education to prevent unnecessary water losses from fields, and changing land use or activities.

The production function analyses of cross-section maize production data used in this study indicated that with the doubling of CO_2 in the atmosphere (from 330ppm to 550ppm), the maize crop will respond differently to the anticipated climate changes at its various growth stages. Partial effect analysis on the impacts of climate change (rainfall and solar radiation changes) on the three main growth stages illustrated that the third growth stage would benefit the most from the forecasted decreases in rainfall and solar radiation forecasted especially for semi-arid to arid regions whilst the second growth stage would be the only negatively affected stage. However, for the wet east regions of the country, the third growth stage was found to be the most negatively affected growth stage due to the forecasted increases in rainfall and solar radiation whilst the second growth stage would be the only positively affected stage.

On the other hand, an analysis of the total impacts of climate change using the two climate scenarios predicted for the Southern African region illustrated that the cumulative benefits effects of rising solar radiation levels can exceed the negative impacts from lower rainfall levels i.e. for a hot and drier climate scenario (forecasted for semi-arid to arid regions) whereas for a wetter and drier climate (forecasted for sub-tropical regions) the results illustrated that the cumulative benefit effects from rising solar radiation levels can slightly offset the benefits of increasing rainfall thus giving negative effects on maize yield.

To compare the findings of the two studies, the CERES model comprised of four simulated climate scenarios, each of which considered various climate and production variables, whereas the production function analysis that forms the core of this study considered two simulated climate scenarios forecasted for the Southern Africa region (i.e. warmer and wetter climate for the sub-tropical regions and a warmer and drier climate for the semi-arid to the arid regions). For the ARC study, the H2n and H2s climate models, which both describe hotter (i.e. increased temperatures) and drier (decreasing precipitation) future climates showed that maize yield levels would decrease in most of South Africa by 10% to 20%, causing serious damages in the more marginal areas of the western production region. In comparison, the production function study obtained different findings for the same scenario showing increases in maize yields for the same western semi-arid regions of the country. The production function study further highlighted that for the same climate scenario the second growth stage would be the only negatively affected growth stage.

Again, in the ARC study, the CSM and the Genesis climate models, which describe hotter and slightly wetter future climate scenarios showed that for the wet eastern parts of the country maize production would either remain the same or slightly increase. On the other hand, the production function study showed decreases in maize yields under the same climate scenario whilst further highlighting that the second growth stage will be the only positively affected growth stage.

Lastly, it can be concluded from the above that even though the ARC crop growth simulations followed a more comprehensive scenario analyses in terms of the maize crop physiology however, it was not able to capture agronomic responses of the maize crop to climate change which were properly captured by the production function approach adopted in this study. Again, the production function approach which is a cross-section analysis of the economic impacts of climate change on maize production is based on the assumption that there is adequate diversity in climatic conditions in the spatial spread of the used cross-section data to reasonably capture and reflect the relationship between climate and maize production.

Chapter 6: Summary, Conclusions and Implications of the Study

This study evaluated the impact of climate change on maize production in South Africa. The empirical analysis presented in Chapter 5 utilized the production function approach, to evaluate the likely impacts of climate change on maize yield.

The study found that maize production in South Africa is sensitive to climate fluctuations especially rainfall and solar radiation. Solar radiation rather than temperature was included in the regression analysis as temperature measures did not perform well. Therefore, to gain further insights into the interaction between maize and climate variables, two approaches were used in this study to evaluate these interactions. The first approach used the estimated model coefficients of the empirical model to derive measures of elasticity and the optimal damage climate points. The second approach used the estimated regression coefficients to simulate the impacts of changes in levels of climate variables on maize yields using two main climate scenarios forecasted for the Southern Africa region.

In the first approach, elasticities were calculated to assess the sensitivity of maize yields to rainfall changes at mean values. Results indicated that at current levels of solar radiation, increasing rainfall in all three growth stages would increase maize yields whereas at current levels of rainfall, results indicated that increasing solar radiation levels for the second growth stage would increase maize yields whilst increasing solar radiation for the third growth stage would decrease maize yield. These results suggested high agronomic sensitivity of the maize crop's growth stages to both solar radiation and rainfall.

The critical damage analyses indicated that current average rainfall values for the 1st growth stage of the maize crop were close to the maximum point implying that this growth stage is sensitive to marginal changes in rainfall during this stage as there was no remaining range of tolerance to increased rainfall. For the 2nd growth stage, current average rainfall was found to be higher than the critical damage point but lower than the agronomic optimal range. This implies that this growth stage is sensitive to lower rainfall levels whilst higher rainfall levels would still be favourable. For the 3rd growth stage, current average rainfall values were found to be far from the maximum critical damage point and hence indicating a good range of tolerance to higher rainfall levels. With respect to solar radiation, critical damage analyses indicated that for the 2nd growth stage, the current average value of solar radiation was found to be higher than the maximum critical point but within the agronomic optimum value, which implied that this growth stage is not sensitive to marginal increments in solar radiation. However, for the third growth stage, the current average value of solar radiation was found to be higher than the critical point and outside the optimal agronomic range further highlighting that this growth stage has no tolerance to higher solar radiation.

To capture the cumulative impact of increasing solar radiation and rainfall amounts marginally across all growth stages, a climate simulation analysis whereby the two main benchmark warming scenarios predicted for the Southern Africa region were used. In this approach, a partial effect analysis whereby rainfall and solar radiation changes were simulated for each growth stage at a time was conducted followed by a total effect analysis in which rainfall and solar radiation changes were simulated across all growth stages at the same time. Results from this approach illustrated that for the forecasted hot and drier climate scenario, the third growth stage would benefit the most from the forecasted climate scenario whilst the second growth stage would be the only negatively affected growth stage for the semi-arid to arid regions. On the contrary, for the forecasted hot and wetter climate scenario, the third growth stage would be the most negatively affected growth stage whilst the second growth stage would be the only positively affected growth stage for the wet eastern regions.

Results of the total effect analysis also illustrated that benefits from increasing net radiation diffusion (solar radiation) could exceed the negative effects of decreasing rainfall across all growth stages for a hot and drier climate scenario forecasted for the semi-arid to arid regions, where 60% of the maize is produced. Again, a hot and drier climate scenario has been found to have positive effects on the first and the last growth stages of the maize crop. On the other hand, this study has found that an increase in both rainfall and net radiation diffused (in a hotter and slightly wetter climate scenario) at the same time could offset the benefits of increasing rainfall thus giving negative effects on maize yield. However, for this hotter and slightly wetter climate scenario, the second growth stage has been found to be the only growth stage which would have positive effects

We can thus conclude that this study has highlighted high agronomic sensitivity of the maize crop to the forecasted changes in climate factors. The results of the study suggest giving high priority to intervention and adaptation strategies that target mitigation of decreased rainfall impacts especially during the second growth stages in the semi arid to arid regions of the country. The study also suggests priority intervention and adaptation strategies that would improve tolerance to higher rainfall especially in the first and the third growth stage in the wet east regions of the country.

A study carried by the ARC using the same data found that the hot and drier future forecasted climate scenario will lower maize yield levels by 10% to 20%, causing serious damages in the more marginal areas of the western production region. At the same time the ARC study concluded that forecasted climate scenario will have a small impact on maize production in the wet eastern region. Both studies illustrated the need for future research which would focus on cost-effective methods of controlling yield-reducing factors associated with both increased and decreased rainfall amounts during various growth stages of the maize crop.

The production function analyses suggest that the west semi-dry regions of South Africa might benefit from the forecasted decreases in both rainfall and solar radiation, especially if sensitivity of the maize crop during its second growth stage is mitigated through the introduction of irrigation. This study also illustrated that maize production in the wet east regions might benefit in all its three growth stages from the forecasted increases in rainfall and solar radiation, especially if sensitivity of the first growth stage is reduced through the possible shifting of planting dates to mitigate the effects of increased rainfall forecasted for this region. One should note however, that the maize crop can agronomically adapt easily to drier conditions. Other attributes which further assists the resistance of the maize crop to climate changes, include extensive conservation soil tillage farming practices which could be applied to optimise soil infiltration rates whilst minimising evaporation rates, thus reducing soil erosion.

These results have implied and highlighted the need for investments into the adaptive capacity of farmers, especially small-scale farmers who are severely restricted by their heavy reliance on natural climate factors whilst also lacking complementary inputs and institutional support systems. The existence of institutional support systems may assist farmers in further understanding anticipated climate changes and available conservation agricultural practices e.g. cost effective irrigation control systems.

Other options may include extensive capacity building of all the stakeholders involved in maize production (farmers, processors, marketers, exporters etc.) with regard to issues like farm planning, available crop insurance systems with regards to floods and droughts, improved weather and climate monitoring and forecasting, and lastly climate change and its economic impacts on maize production in general. At a regional scale, extensive agricultural planning and risk reduction programmes may assist with spreading losses over larger regional areas, which may serve to reduce overall risk to growers.

One important limitation of this study was that the analyses focused on the experimental sites only and hence did not consider all maize production areas across the country (which includes sites under small-scale farming). Also, the model adopted for this study also did not include the effects of carbon dioxide fertilisation and price movements and the effects of the socio-economic impacts of the changing climate factors, which are crucial. In conclusion, then, there is an urgent need for the South African National Department of Agriculture to look at how maize farmers (and especially small-scale farmers) could be assisted in adapting their traditional cropping methods to the forecasted changes in climate, whilst taking into consideration all the options presented above.

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8. APPENDIX 1: Collinearity Test

A collinearity test on data variables was conducted and the following results were obtained:

Table 5.1: Results from a collinearity test

	F	**L**	**M**	**DR**	**MR**	**SR1**	**SR2**	**SR3**	**Ra1**	**Ra2**	**Ra3**	**T1**	**T2**	**T3**
F	1													
L	-0.1511	1												
M	0.44364	**0.788**	1											
DR	0.03144	-0.37	-0.35	1										
MR	0.39367	-0.37	-0.1	0.484	1									
SR1	-0.6011	0.233	-0.25	-0.11	-0.276	1								
SR2	-0.589	0.325	-0.16	-0.13	-0.383	**0.766**	1							
SR3	-0.6036	0.243	-0.23	-0.15	-0.446	**0.692**	**0.916**	1						
Ra1	0.42732	-0.44	0.01	0.11	0.284	**-0.722**	**-0.721**	-0.58	1					
Ra2	0.58788	-0.43	0.09	0.182	0.488	-0.683	**-0.796**	-0.69	**0.91**	1				
Ra3	0.52905	-0.09	0.34	0.088	0.299	-0.472	**-0.792**	**-0.76**	0.66	0.**812**	1			
T1	-0.5671	0.3	-0.2	-0.05	-0.046	**0.743**	0.686	0.648	**-0.84**	**-0.76**	-0.67	1		
T2	-0.5402	0.428	-0.05	-0.22	-0.379	**0.703**	0.693	0.609	**-0.88**	**-0.92**	-0.68	**0.844**	1	
T3	-0.5218	0.355	-0.11	-0.21	-0.348	0.686	0.632	0.593	**-0.85**	**-0.89**	-0.7	**0.854**	**0.983**	1