CHAPTER 3 : LITERATURE REVIEW ON CLIMATE CHANGE AND AGRICULTURE

3.1 Introduction

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

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

3.2 The Process of climate change

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

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

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

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

3.3 Climate change effects on agricultural productivity

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

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

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

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

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

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

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

3.4 Economic and social impacts of climate change on agriculture

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

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

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

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

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

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

3.5 The distribution of climate change impacts

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

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

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

3.6 Policy implications of climate change: Mitigation and Adaptation

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

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

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

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

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

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

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

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

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

3.7. Measurement of climate change impacts on the agricultural sector

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

3.7.1 Structural modelling of the Agronomic Response

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

3.7.1.1 Agronomic-economic models (AEM)

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

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

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

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

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

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

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

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

3.7.1.2 Agro- Ecological Zones models

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

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

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

3.7.2 Observed Response Models: Cross sectional methods

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

3.7.2.1. The Ricardian Approach

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

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

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

The Ricardian method has received a number of criticisms. The approach assumes that the way that farmers respond to alternative climates over space is the same way that farmers will respond in the long run to those same climates over time. However, this assumption may not hold if important variables that are likely to be correlated with climate have been omitted. In fact, farms may differ greatly within the area of analysis. The differences may not be due to climate but other factors such as farm management due to different level of education etc. Thus the main issue of this method is how to control for unwanted variations. Darwin (1999) also pointed out that this method does not take into account water supply and availability. The Ricardian method estimates assume that the only limiting factor to agriculture is the climate. However, the problem of water cannot be handled properly without using a sophisticated hydrological-economic model (Mendelsohn, 2001b). Another criticism of the method is that it treats price as constant (Cline, 1996). By holding prices constant, the Ricardian model underestimates damages and overestimates benefits. According to Sanghi *et al*. (1998) the Ricardian method is more reliable for estimating impacts of small changes in climate because of the assumption of unchanged relative crop prices. In fact it is reasonable to assume constant prices. Due to the predicted moderating effects of climate change on international market, aggregate world supply will not change by much. Finally, the Ricardian method is criticized for assuming implicitly zero adjustment costs and therefore yields a lower-bound estimate of the costs of climate change (Quiggn and Horowitz, 1999).

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

3.7.2.2 The Future Agricultural Resources Model: FARM

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

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

3.8 Empirical studies of climate change impacts on agriculture

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

3.8.1 Climate change impacts literature in developed countries

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

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

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

3.8.2 Studies on climate change impacts on Agriculture in developing countries

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

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

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

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

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

3.8.3 Studies on climate change impacts on Agriculture in South Africa

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

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

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

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

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

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

Conclusion

The above literature review on climate change and agriculture highlighted some general findings. First, the agricultural sector is vulnerable to climate change physically and economically. Due to climate change, agricultural supply will be affected. Consequently this will induce a reallocation of resources within the agricultural sector and a change in the price of agricultural commodities, altering the structure of the economy of numerous countries and the international trade pattern.

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

Specifically in South Africa, climate impact' studies on agriculture are limited, focused mainly on maize and applied mainly the experimental approach. Although the experimental approach has the advantage of reliable results in terms of relationship between yield and climatic variables, the present study will not adopt this methodology due to the complexity and high data requirements and its failure to take into account farmers' adaptation strategies. Indeed adaptations to climate change are a crucial element in climate change issues and could not be ignored. The Ricardian approach, on the other hand, can be easily adopted to evaluate country level as well regional level impact, and with modifications it can be used to address farmers' adaptations strategies. Thus, the present study will accordingly apply the Ricardian model to measure the economic impact of climate change on filed crops in South Africa.

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

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

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

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