Global Environmental Change 18 (2008) 666–678

Contents lists available at ScienceDirect

Global Environmental Change

journal homepage: www.elsevier.com/locate/gloenvcha

South African crop farming and climate change: An economic assessment of impacts

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ARTICLE INFO

Article history:
Received 19 March 2007
Received in revised form
12 June 2008
Accepted 16 June 2008

Keywords:
Agriculture
Climate change
Ricardian model
South Africa

ABSTRACT

This paper assesses the economic impact of the expected adverse changes in the climate on crop farming in South Africa using a revised Ricardian model and data from farm household surveys, long-term climate data, major soils and runoffs. Mean annual estimates indicate that a 1% increase in temperature will lead to about US$ 80.00 increase in net crop revenue while a 1 mm/month fall in precipitation leads to US$ 2.00 fall, but with significant seasonal differences in impacts. There are also significant spatial differences and across the different farming systems. Using selected climate scenarios, the study predicts that crop net revenues are expected to fall by as much as 90% by 2100 with small-scale farmers been most affected. Policies therefore need to be fine-tuned and more focused to take advantage of the relative benefits across seasons, farming systems and spatially, and by so doing climate change may be beneficial rather than harmful.

1. Introduction

Statistical evidence, though limited, suggests that South Africa has been getting hotter over the past four decades. Kruger and Shongwe (2004) analysed climate data from 26 weather stations across the country. Of these, 23 showed that the average annual maximum temperature had increased, in 13 of them significantly. Average annual minimum temperatures also showed an increase, of which 18 were significant. In general, their analysis indicates that the country's average yearly temperatures increased by 0.13 °C per decade between 1960 and 2003, with varying increases across the seasons: fall 0.21 °C (March–May), winter 0.13 °C (June–August), spring 0.08 °C (September–November) and summer 0.12 °C (December–February). There was also an increase in the number of warmer days and a decrease in the number of cooler days.

The country's average annual rainfall is 450 mm/year, well below the world's average of 860 mm, while evaporation is comparatively high. Rainfall is also distributed unevenly across the country, with humid, subtropical conditions in the east having as high as 1000 mm rainfall and dry, desert conditions in the west with less than 100 mm. Potential evaporation is estimated at 1500 mm/year, resulting in only 8.5% runoff with a combined runoff of 42 mm/year compared with the average for Africa (139 mm/year) and the world (330/year). Not only is the runoff in the country very low, but it is also variable from year to year and from region to region (DWAF, 2002, 2004; NDA, 2001). Moreover, only 10% of the country receives an annual precipitation of more than 750 mm and more than 50% of South Africa's water resource is used for agricultural purposes (NDA, 2001).

Climate change resulting in further higher temperatures and worsening rainfall patterns, together with the already scarce water resources in the country are expected to have a significant effect on all sectors of the economy. For example, anecdotal evidence suggests that climate change could lead to a fall of about 1.5% in the country's gross domestic product (GDP) by 2050—a fall roughly equivalent to the total annual foreign direct investment in South Africa at present (see DEAT, 2006). Moreover, climate change and the resulting loss of biodiversity could do irreparable damage to the country's tourism industry, which is worth an estimated Rs 100 billion per annum (about US$ 15 billion) (see UCT, 2008).

But agriculture is most vulnerable to these changes because it is highly dependent on climate variables such as temperature and precipitation, and also because of (i) the semi-arid nature of the country with increased farming on marginal lands, (ii) the frequency of droughts, and (iii) the scarcity of water, which is exacerbated by a high spatial variability of rainfall. In addition to being the main source of food for the country's population of 46.9 million, the sector contributes about 2.9% to the GDP (or about 12% if backward and forward linkages are taken into consideration), 13% (or 30% considering backward and forward linkages) of employment, and a major source of foreign exchange contributing about 10% of total value of exports in 2000 (NDA, 2000;

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doi:10.1016/j.gloenvcha.2008.06.003

StatsSA, 2005). Both commercial farming and especially subsistence farming will be affected by adverse climate change. The impact is also expected to vary across the different agro-ecological zones, administrative demarcated provinces and the different agricultural systems in the country.

Adverse effects of climate change on agriculture would have severe implications not only for South Africa but also for the southern African region because South Africa is the region's major source of food. For example, 50% of the maize (the main staple) in the Southern African Development Community (SADC) region is produced in South Africa. Adverse effects in South Africa could therefore destabilise the whole region.

In spite of these concerns, not many studies have been undertaken in South Africa on the economic losses and social welfare impacts that would result from climate damage to agriculture. The existing studies in South Africa cover either a few crops or small parts of the country and mostly examine how individual crops behave in control experiments, addressing largely grain crops and of those mainly maize (Schulze et al., 1993; Du Toit et al., 2002; Kiker, 2002; Kiker et al., 2002). The study by Du Toit et al. shows that in the dry western areas crop production will become more marginal, while in the high potential eastern areas, there may be a slight increase. Poonyth et al. (2002) use a Ricardian model to explore the agricultural sector's performance with respect to climate change and conclude that rising temperatures will be detrimental to agriculture, and the effects will be even worse if farmers do not adapt appropriately. The focus of Poonyth et al. study was commercial farming. However, the riskier sector is subsistence farming, as these farmers have very little ability to adapt (see also Deressa et al., 2005; Gbetibouo and Hassan, 2005).

Moreover, one of the most significant impacts of climate change is likely to be on the hydrological system, and hence on river flows and water resources in the country. This is especially important given the semi-arid nature of the country, where water resources are very sensitive to climate variability and change. The studies by Poonyth et al., Deressa et al., and Gbetibouo and Hassan have the same limitation as earlier Ricardian studies of agriculture in that they do not include water supplies in the analysis (see Mendelsohn and Dinar, 2003; Darwin, 1999).

Using cross-sectional data for the 2002/2003 farming season, this study extends those done by Poonyth et al., Deressa et al., and Gbetibouo and Hassan, by using a revised Ricardian model that incorporates relevant hydrological variables in the analysis to assess the economic impact of climate change on agriculture in South Africa. The estimated Ricardian model is then used to predict the range of impacts on the agricultural sector under various climate change scenarios. An assessment is also undertaken on differences in spatial impacts and on the different agricultural systems.

The rest of the paper is organised as follows. Section 2 presents the analytical framework for assessing the economic impact of climate change on South African agriculture. Empirical model specification and data used are discussed in Section 3 while the estimated models of climate impacts including an assessment of climate scenarios are presented and discussed in Section 4. Section 5 concludes and suggests policy implications.

2. Analytical framework for economic impact of climate change on agriculture

Two major economic approaches, the agronomic–economic and the cross-sectional models, have been employed to study the interactions between climate, water and agriculture. The agronomic–economic approach begins with calibrated agronomic models and predicts outcomes, using economic simulations. The cross-sectional approach compares the choices and performances of existing farms with different soil conditions and facing different climate conditions. An advantage of cross-sectional analysis is its inherent assessment of farmers' adaptation. One of the cross-sectional models is the Ricardian approach, which links farm values to climate (see Mendelsohn and Dinar (2003) for further discussion).

2.1. The Ricardian method

The Ricardian method follows Ricardo (1817, 1822) because of his original observation that land rents reflect the net productivity of farmland, which is influenced by many factors including the climate. Farm value (V) consequently reflects the present value of future net productivity. The principle is captured in the following equation (Mendelsohn and Dinar, 2003):

$$V = \int P_{LE} e^{-\delta t}\, dt = \int \left[\sum P_i Q_i(X, F, Z, G) - \sum RX \right] e^{-\delta t}\, dt \qquad (1)$$

where the variables are defined as follows: P_{LE} is the net revenue per hectare, P_i is the market price of crop i, Q_i is the output of crop i, F is the vector of climate variables, Z is the sets of soil classification, G is the set of economic indicators such as market access and access to capital, X is the vector of purchased inputs (other than land), R is the vector of input prices, t is the time and δ is the discount rate.

The farmer is assumed to choose X to maximise net revenues given farm characteristics and market prices. The Ricardian model, following Eq. (1), is a reduced form model that examines how the set of endogenous variables, F, Z and G, affect farm value. The model is based on the observed response of crops and farmers to varying climate. That is, it uses actual observations of farm performance in different climatic regions (Mendelsohn et al., 1994; Mendelsohn and Dinar, 1999; Sanghi et al., 1998; Kumar and Parikh, 1998; Ouedraogo, 1999; Mendelsohn, 2001). 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.

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

The standard Ricardian model relies on a quadratic formulation of climate:

$$V = \beta_0 + \beta_1 F + \beta_2 F^2 + \beta_3 Z + \beta_4 G + u \qquad (2)$$

where u is an error term. The quadratic functional form for climate captures the expected non-linear shape of the relationship between net revenues and climate. When the linear term is negative and the quadratic term is positive, the net revenue function is U-shaped, and when the linear term is positive and the quadratic term is negative, the function is hill-shaped. Several other shapes are possible depending on the relative signs of the linear and quadratic terms (see Kaufmann, 1998). However, based on agronomic research and previous cross-sectional analyses, it is expected that farm values will have a hill-shaped relationship with temperature and also precipitation. That is, for each crop there is a known temperature or precipitation where that crop grows best across the seasons (see Mendelsohn and Dinar, 2003).

Given Eq. (2), the marginal impact of each of the climate variables (f_i) on farm net revenues is evaluated at the mean of each of the variables as follows:

$$E\left[\frac{dV}{df_i}\right] = E[\beta_{1,i} + 2 \times \beta_{2,i} \times f_i] = \beta_{1,i} + 2 \times \beta_{2,i} \times E(f_i) \quad (3)$$

These marginal effects can be evaluated at any level of climate. But the focus is on showing effects at mean climate levels in South Africa and therefore the use of the mean of the climate variables ($E(f_i)$) for the estimation (see Kurukulasuriya et al., 2006).

2.2. Revised Ricardian method

Given that land markets are imperfect and agricultural farm values in the developing world are also weakly documented, net farm revenue per hectare (V) is used as the response variable instead of land values. This follows the approach by Sanghi et al. (1998) and Kumar and Parikh (1998) for India. Net revenue as a response variable incorporates all possible adaptation in agriculture activities (see Kurukulasuriya et al., 2006). But one main shortcoming is that it excludes other possible adaptation outside the agriculture sector incorporated in land values and therefore may overestimate damages from climate changes as noted by Mendelsohn et al. (1994). But this overestimation may not be very high given that the focus here is on the agriculture sector and land in the rural developing world has very limited alternative uses outside agricultural activities.

Moreover, farm net revenue is the sum of the net revenues from crops, livestock and other farm activities. In this analysis, however, the focus is on crop net revenues. It is important to note that a complete assessment of the impacts needs to include revenues from livestock and other farm activities. There is the possibility of substitution or complementarities between and among these different farm activities (as possible adaptation options) as climate warms so it is important for this to be reflected in such impact analysis. However, the extent to which each of these activities responds to climate variables may be different. Such separate analyses are therefore important for formulating effective policy.

Early Ricardian studies of agriculture (Mendelsohn et al., 1994, 1996) have been criticised because they did not include irrigation and other sources of water in the analysis (Darwin, 1999). These studies relied solely on a district/province/county's climate to predict agricultural outcomes. However, such defined area-specific climate does not provide a good indication of the availability of either surface or groundwater because these supplies often come from watersheds that extend far beyond a district/province/county (Mendelsohn and Dinar, 2003). Given the importance of water in agricultural outcomes, it is necessary to estimate the total flow of water to a given geographical area in order to assess the true impact of climate change on agriculture.

To address this shortcoming, Mendelsohn and Dinar (2003) used a revised Ricardian approach (using relevant hydrological proxies) to assess the way other sources of water, surface water, ground water and irrigation (W), affect the value of farmland and the climate sensitivity of agriculture in the United States. This revised approach is what is adopted by the present study.

Mendelsohn and Dinar (2003) noted that water comes to farms in the form of precipitation, which is already reflected in the Ricardian model. However, because surface and ground water can be remote from the farm, the climate at the farm may give little indication of the total amount of water accessible to the farm. Irrigation is also expected to change the relationship between crops and climate. For example, irrigation may allow crops to grow well in warmer temperatures. This will help control the expected negative effects of warmer climates on crop production and crop net revenues. These other sources of water (W) are tested in the model in linear and quadratic terms.

The revised Ricardian model for South Africa is indicated in Eq. (4):

$$V = \beta_0 + \beta_1 F + \beta_2 F^2 + \beta_3 Z + \beta_4 G + \beta_5 W + \beta_6 W^2 + u \quad (4)$$

The set of economic indicators such as market access and access to capital (G) is not assessed in this current analysis in order to focus attention on the extent of the impact of the less controlled variables of climate, soils and hydrology indicators.

Given the possibility of different impacts in the different parts of the country and different agricultural sub-sectors, the impacts are also examined across the agro-ecological zones and the nine provinces in the country using their respective estimated marginal impacts of climate.[1] This is based on the assumption that the estimated climate relationships for the different types of farmers are the same across the nine provinces and different agro-ecological zones. This follows the approach used by Kurukulasuriya et al. (2006). A more explicit spatial analytical approach is discussed by Polsky (2004) and Polsky and Easterling (2001), but the size of the data is not large enough to undertake such explicit analysis. There is also an assessment of whether the impacts are significantly different for irrigated and dryland farms (by assuming that the choice of either of these farming systems is exogenously determined), and also for large-scale and small-scale farms.

In spite of addressing the issue of the impact of other sources of water on farm net revenues, other shortcomings of the Ricardian approach have been identified (see Kurukulasuriya et al., 2006 for a full discussion). Among them is the assumption of constant prices. The argument is that the Ricardian price schedule will overestimate the positive welfare effects of climate change since it underestimates damages and overestimates benefits (Cline, 1996; Darwin, 1999; Adams et al., 1999). For globally traded goods, such as agricultural products, price changes are not likely to be a problem as local gains and losses in production are expected to offset each other for a small net change in global output (Reilly et al., 1994; Mendelsohn and Nordhaus, 1999). But a dramatic reduction in the productivity of African agriculture could affect African wage rates. In order to capture this effect, a more complete analysis should include models for local labour markets as well as land productivity (Kurukulasuriya et al., 2006).

The Ricardian approach also does not measure the effect of different levels of carbon dioxide across space which may be relatively important in farm productivity and therefore farm revenue. But this is not a problem in this study since carbon dioxide levels do not systematically vary across South Africa (see Kurukulasuriya et al., 2006). Another drawback of the model is that variation in climate that is observed across space may not resemble the change in climate over time. In this case, the analysis will not be able to evaluate such an effect. But given the lack of long-term data limitations in the country, cross-sectional analysis provides the best approach of assessing such impacts.

However, one main advantage of the Ricardian empirical model is the inclusion of adaptation responses by farmers to local climate, which are incorporated in the estimation of the value of land. The model reflects the cost to farmers of introducing

[1] There are four main agro-ecological zones in the country which incorporates the nine administrative demarcated regions as follows: arid zone (Eastern, Free State, Gauteng, Limpopo, Mpumalanga and North West Provinces); desert zone (Northern Cape Province); sub-tropical wet zone (KwaZulu-Natal Province) and Winter rainfall zone (Western Cape Province).

a new crop as climate warms, such as costs of seeds, equipment and land preparation, and the benefits. Thus, the model provides a more optimistic result than the generally pessimistic results found with purely agronomic studies (see Polsky, 2004 and Mendelsohn et al., 1994 for full discussion).

3. Data and empirical model specification

The analysis uses cross-sectional data at the household and district levels on farm activities, climate, soils and hydrology. These four sets of data are discussed below.

- *Farm household data*: A farm household questionnaire was used to collect information on selected households in sample districts in the nine provinces in the country on their farm activities. The sample also incorporates all the agro-ecological regions in the country. The questionnaire attempted to capture information on pertinent variables required to calculate net farm revenues and to explain the variation in net farm revenues, land values and income across representative sample districts, and agro-climatic regions in the country. The periods of interest were the summer farming season (April/May 2002–September/October 2002) and winter farming season (October 2002–April/May 2003) of the 2002/2003 farming season. The questionnaire also aimed to capture farmers' knowledge about, attitudes to and perception of climate variation and climate change. The former information is what is used in this analysis.
  In total, 416 farm households were interviewed in 17 districts across the nine provinces. Of these, 53% were large-scale farmers and 47% were small-scale farmers, and 29% were involved in crop farming only with maize as the major crop, 27% in livestock farming only, and 44% in mixed farming. The average farm size ranged from 50 to 1537 ha for large-scale farmers and 1 to 40 ha for small-scale farmers.
- *Climate data*: Two main climatic data were used—satellite temperature and ARTES precipitation (wetness) data. The satellite data come from the Department of Defense in the USA (Basist et al., 2001; Kurukulasuriya et al., 2006). The Defense Department data come from a set of polar orbiting satellites that pass over the entire earth between 6 a.m. and 6 p.m. everyday. The satellites are equipped with sensors that detect microwaves that can pass through clouds and detect both surface temperature (Weng and Grody, 1998) and surface wetness (Basist et al., 2001). The African Rainfall Temperature Evaluation System (ARTES) data are created by the National Oceanic and Atmospheric Association's (NOAA) Climate Prediction Centre of the USA (World Bank, 2003). The ARTES data are based on ground station measurements of precipitation, minimum temperature and maximum temperature.
  The rationale for using these two different sources as proxies for climate is twofold. First, the ARTES dataset is at the provincial level as opposed to the satellite data that are at the district level, so the provincial data will pick up other characteristics in addition to the climate effects. It therefore becomes less clear whether the results reflect temperature effects or some other explanatory factors. Second, in the case of satellite wetness, this measure is an index which has temperature in it somewhere. It is not clear how to make climate predictions with such an index. So the best option is to use the ARTES precipitation data (Kurukulasuriya et al., 2006).
- *Soil data*: These were obtained from the Food and Agriculture Organization (FAO). They provide information on major and minor soils by districts in the country (FAO, 2003). The FAO classifies soils into 26 major units and 107 sub-categories based on soil texture (coarse, medium or fine) and the slope of the land. Three slope classes are distinguished: (a) level to gently undulating, with generally less than 8% slope; (b) rolling to hilly with slopes between 8% and 30%; and (c) steeply dissected to mountainous, with more than 30% slope. The major soil categories are measured as the proportion of total soil composition in the country. For simplicity of analysis, this study tested for the influence of only the major soil categories in the country (see more details in FAO, 2003).
- *Hydrology data*: These were provided by the University of Colorado, Boulder, and the International Water Management Institute (IWMI) as part of the GEF Africa-wide study. Using a hydrological model for Africa, estimates were provided for flow and runoff for each of the sampled districts (Strzepek and McCluskey, 2006).

3.1. The empirical model

Eq. (4) is estimated for South Africa using seasonal means for summer (December, January and February), fall (March, April and May), winter (June, July and August) and spring (September, October and November).[2] Given that there are two major farming seasons in the country, we also examine the marginal impacts of temperature and precipitation for the summer farming season (December–May) and the winter farming season (June–November) using Eq. (3). The rest of Section 3 discusses each of the variables in the model.

3.2. Description of dependent and explanatory variables

3.2.1. Net crop revenue per hectare

The dependent variable (V) in Eq. (4) is measured as crop net revenue per hectare of cropland as opposed to per hectare of farmland, which would include farmland under livestock and poultry production, and other farm activities such as forestry (see Table 1 for summary of variables included in the models).

In simple terms, net revenue is gross crop revenue (which is the product of total harvest and price of the crop) less total cost of production. If more than one crop is grown on the same land then it is the sum of the products of the crop harvested and their prices less their associated cost of production. Total harvest of crops includes harvest used for household consumption, livestock feed and harvest sold. The cost element is mainly total variable costs (TVCs), which in this case include the depreciation or maintenance cost of fixed assets such as buildings, machinery, etc. TVCs include expenditure on transport, packaging, marketing, storage, post-harvest losses, fertilizer, pesticide, seeds, water use, labour and other depreciation costs of the use of light and heavy machinery. Other costs include rent paid on the farmland, interest paid on loans, etc. What is excluded from the estimation of the cost is household labour because of the high possibility of overestimation.

From the sample of 416 farm households, crop net revenues were estimated for 272 farm households. The rest were mainly in livestock farming or did not harvest any crop in the period of interest. Some households also did not indicate other cost elements and therefore were also excluded. Excessive estimated net revenues which were judged to be outliers were also excluded from the dataset.

[2] Other ways of incorporating climate variables in the model include using annual means, monthly means and the means of the two identified farming seasons (summer and winter) in the country. All these alternatives were tested but the 3-month averages for summer, fall, winter and spring were found to be more relevant for the analysis.

Table 1
Summary statistics of variables in the model

Variable	*N*	Mean	S.D.	Minimum	Maximum
Crop net revenue per hectare (US$)	191	305.525	573.2045	−884.26	2388.555
Summer temperature	195	21.04021	1.885267	17.42128	25.11124
Fall temperature	195	16.45474	1.953028	12.95221	19.52127
Winter temperature	195	11.91574	2.121216	8.943912	15.44466
Spring temperature	195	17.35215	2.064975	14.07367	20.7483
Summer precipitation	195	86.47312	40.70835	5.224444	127.3267
Fall precipitation	195	50.39756	13.68931	24.09667	68.70222
Winter precipitation	195	23.24021	10.15982	7.175556	34
Spring precipitation	195	61.10941	21.05057	17.35556	85.84666
Temperature—annual mean	195	16.69071	1.83374	13.41389	19.74844
Precipitation—annual mean	195	55.30507	18.54841	20.43583	78.60667
Soil vertisols	195	0.114872	0.245232	0	0.8
Soil acrisols	195	0.067692	0.175077	0	0.6
Soil arenasols	195	0.204615	0.425997	0	1.6
Soil xerosols	195	0.196923	0.580607	0	2
Mean runoff	195	10.40746	9.828292	5.33E−05	27.58459
Irrigated farms (1/0)	195	0.466667	0.500172	0	1
Farm type (large-scale farms (1/0))	195	0.482051	0.500964	0	1

The estimated net crop revenue per hectare across South Africa for the 2002/2003 farming season was US$ 306. As expected, irrigated farms had the highest net revenues of US$ 467, large-scale farms US$ 358, small-scale farms US$ 254 and dryland farms had the least at US$ 159.

3.2.2. *Climate variables: temperature and precipitation*

The long-term mean temperatures and precipitation indicate that summer periods, as expected, have the highest temperatures followed by spring and fall then winter. The long-term mean annual temperature was about 17 °C with a minimum of 13 °C and a maximum of 20 °C, with summer periods having as high as 24 °C. The highest long-term average rainfall per month was also experienced in the summer and the lowest in winter (see Table 1), with long-term average rainfall of 55 mm/month, a maximum of 98 mm/month and a minimum of 20 mm/month.

3.2.3. *Soils*

Out of the 26 major soil categories defined by the FAO, about 10 are found in South Africa. The major soil types defined by the proportion of land in the country include *luvisols*, *arenosols*, *xerosols*, *planosols* and *vertisols*. One should note that although these soils seem to be more prominent in the country, this does not imply that they are also important for crop-farming activities. Only four soil types seem to be relevant and therefore tested in the model: *acrisols*, *arenosols*, *vertisols* and *xerosols* (Table 1).

3.2.4. *Hydrology*

Two relevant hydrology variables, runoff and flow, were tested in the model. The runoff variable seems to better explain changes in crop net revenues than the flow variable. The mean runoff is estimated at about 10 mm/month (see Table 1).

3.3. *Estimation procedure*

A STATA statistical and econometric package was used to estimate the revised Ricardian model Eq. (4) for South Africa (StataCorp, 2003). Typical of most cross-sectional regressions are the problems of (i) endogeneity, (ii) heteroscedasticity in the error terms, (iii) multicollinearity among explanatory variables, and (iv) the impact of outliers.

The problem with endogeneity was dealt with by estimating a reduced form of the net revenue model rather than the structural model.

The problem of multicollinearity is controlled for by dropping the most problematic variables, especially in cases of detecting strong collinearity and where the explanatory variables do not improve on the model and are also not significant. For example, the flow variable and some of the soil variables were all excluded from the model. But multicollinearity is normally an issue of extent rather than absence and so cannot be completely eliminated (Gujarati, 1995). Very obvious outliers, such as for net revenues and some of the winter and spring precipitation, were excluded from the estimation.

To correct for heteroscedasticity, a quantile regression (*qreg*) was estimated instead of an ordinary regression. The *qreg* fits quantile (including median) regressions models, also known as least-absolute value models (LAV or MAD). The objective is to estimate the median of the dependent variable, conditional on the values of the independent variables. This is very similar to ordinary regression, where the objective is to estimate the mean of the dependent variable. In other words, median regression finds a line through the data that minimises the sum of the *absolute* residuals rather than the sum of the *squares* of the residuals as in ordinary regressions. The quantile regression, *qreg*, is an alternative to regular or robust regressions. Unlike *qreg*, ordinary regression or robust regression fits ordinary (linear) regression and is concerned with predicting the mean rather than the median, so both are in technical sense correct. Since both the mean and the median describe central tendencies, the question is always which of these methods best describes the central tendency of the data (see StataCorp, 2003).

Means, and therefore ordinary regressions, are sensitive to outliers, and cross-sectional data have serious problems of this kind. In spite of removing the obvious ones from the dataset, these outliers dominate ordinary regression and produce results that do not reflect the central tendency well. Robust regression is an attempt to correct for the outlier-sensitivity deficiency in ordinary regressions. Both *qreg* and robust regression attempt to correct for the influence of outliers, but robust regression will have smaller standard errors since it is not sensitive to the exact placement of the observations near the median and therefore coefficient estimates may be termed significant even when they are not. Quantile regression, *qreg*, on the other hand is sensitive to this and tries to make the necessary corrections. The *qreg* produces a pseudo-R similar to the R^2 produced by the ordinary regression with the same interpretation (see StataCorp, 2003).

4. Discussion of results

A step-wise approach to the analysis was explored, starting with only climate variables to the inclusion of other relevant variables, to assess the role played by the different set of variables (climate, soils and hydrology) on crop net revenues. The results of the full model (incorporating climate, soils and hydrology variables) are discussed why the estimated models incorporating climate variables only and climate and soil variables only are presented in Appendices A and B.

There is also investigation into whether there are any significant differences in the effects between irrigated and dryland farms on one hand and between large-scale and small-scale farms on the other. That is, in the latter, an assessment is made if scale does matter in climate analysis in the agricultural sector in South Africa. In addition, differences in the agro-ecological zones and provincial effects of climate change were examined. This analysis helps to understand the distribution of winners and losers in the face of climate impacts.

Estimates indicated that irrigation is a significant positive influence on crop net revenues, as is the farm type (represented by the dummy for large-scale farms) in the three sets of models—-with climate variables only; climate and soil variables only; and climate, soil and hydrology variables. That is, irrigated farms are expected to have relatively higher net revenues than dryland farms, and large-scale farms are expected to have significantly higher net revenues than small-scale ones. This is also a confirmation of the significant difference in the estimated net revenues for the two sets of farming systems. When both irrigation and farm type were considered in the models, the significance of the whole model improved, indicating that both variables are important influences on net revenue. However, the irrigation variable was found to be significantly more important than the size of the farm. It follows that even though scale is important, irrigation is even more so. Given this background, we examined different models for irrigation and dryland farms, and large-scale and small-scale ones.

In the rest of the section, we discuss the estimated full model and taking into account the four main types of farm systems (irrigation and dryland, large-scale and small-scale). We also estimate the marginal effects of the climate variables using Eq. (3) to examine the extent of the climate effects on net revenues, and conclude the section by using selected climate scenarios to assess the expected climate impacts on net revenues in 2050 and 2100.

4.1. Estimated full model

4.1.1. Climate variables

The estimated models for the full sample and the four types of farm systems are presented in Table 2. The results indicate the importance of all the three sets of variables in explaining changes in the crop net revenues. This is shown by higher pseudo Rs in Table 2 compared with the climate only model in Appendix A.

The estimated models in Table 2 indicate that climate variables have significant influences on crop net revenues in South Africa. It also shows that to some extent, there is non-linear relationship between climate variables and crop net revenues, especially for precipitation (see Kaufmann, 1998 and Kurukulasuriya et al., 2006). Summer and winter temperatures show an upward trend while fall and spring temperatures show a downward trend. The signs of the temperature coefficients are generally robust in the entire five models and a majority are significant. The upward trend of the summer and winter temperature is a little bit surprising. But given that these two temperatures are part of the summer farming season and winter farming season, respectively, the results indicate that higher temperatures in the early part of both farming seasons (initial growth period of crops) may be beneficial but as it get hotter in the later stages in each of the farming seasons, respectively (fall and spring temperature), it would be detrimental to crop growth. From the point of view of the two faming seasons, temperature indeed indicates a hill-shaped trend. That is, for the two farming seasons, higher temperatures will be beneficial up to a certain extent, after which

Table 2
Full model—climate, soil and hydrology variables

Variable	Dependent variable: crop farming net revenue				
	Col. 1	Col. 2	Col. 3	Col. 4	Col. 5
	Full sample	Irrigated	Dryland	Large-scale	Small-scale
Summer temperature squared	22.11***	62.434	−11.80*	43.637*	36.69***
Fall temperature squared	−50.26***	−154.10*	−17.65**	−98.86	−75.008**
Winter temperature squared	62.9***	186.93**	38.55***	130.61*	95.31***
Spring temperature squared	−20.46***	−50.174	1.796	−30.73**	−38.86***
Summer precipitation	147.77**	628.59	73.87***	−44.41	187.63**
Summer precipitation squared	−0.68**	−2.562	0.0166	−0.449	0.442*
Fall precipitation squared	−0.85	−4.605	−0.515**	1.174	−0.992
Winter precipitation	86.67	471.22	141.03***	−58.27	242.31*
Winter precipitation squared	−0.34**	−1.154	0.3804***	−0.445	1.213***
Spring precipitation	−222.12**	−853.38		9.873	
Spring precipitation squared	1.71**	6.188	1.22***	0.979	−3.438***
Soil acrisols	881.94***	1281.57			978.28**
Soil arenosols	371.96**	989.95	551.74***		
Soil xerosols	−63.05	−262.09		−270.47	15.55
Mean runoff	44.14	130.68	65.18***	−3.254	63.33
Mean runoff squared	−2.28*	−6.77	−3.363***	0.157	−2.715
Constant	1046.71	−909.67	18.24	934.431	−8550.65**
Pseudo-*R*	0.1363	0.1564	0.253	0.194	0.1516
No. of observations	191	91	100	94	97

* Significant at 10%.
** Significant at 5%.
*** Significant at 1%.

the benefit will be negated. The trend for precipitation for summer, fall and winter is hill-shaped, while for spring it is U-shaped. Again, what this indicate in general is that early rainfall in both the summer and winter farming seasons may be beneficial to crop farming in South Africa.

Comparing the irrigated model (col. 2) with the dryland farm model (col. 3), the coefficients of both the summer and fall temperatures are negative in the dryland model. It is also important to note that while most of the climate variables, especially for precipitation, are significant in the dryland farm model, only the fall and winter temperatures are significant in the irrigation model. This may be because dryland farms rely heavily on climate variables as they lack substitutes for rainwater, while irrigation helps to reduce the effect of climate variables on farming activities.

Again in comparing the large-scale (col. 4) and small-scale (col. 6) farms, climate variables are very significant in the small-scale model than the large-scale model (Table 2). This is not surprising since a majority of small-scale farmers rely more on the climate for their activities than large-scale farmers who have better potential to deal with the vagaries of climate by finding substitutes such as irrigation. In fact, of the 1.2 million hectares of land under irrigation (10% of total farmland), only 4% is small-scale irrigation (NDA, undated). This may suggest that whether a farm irrigates or not is more relevant to climate analysis in South Africa than the scale of the farm.

In general, the estimated models in Table 2 indicate that climate variables are very relevant for crop-farming activities in South Africa, and particularly for dryland and small-scale farming activities. The impact of climate variables may also to a large extent be non-linear and irrigation may help reduce the effect of climate variables on crop net revenue. The discussion of the estimated marginal impacts in the next section provides a better understanding on the extent to which climate variables may affect net crop revenues in the country.

4.1.2. Soil variables

Four main types of soil identified as influencing crop farming in South Africa, *acrisols*, *arenosols*, *vertisols* and *xerosols*, were included in the model (see Appendix B and Table 2) to assess how soil variables influence the extent to which climate variables affect crop net revenues.

The results for the full sample in Table 2 (col. 1) indicate that two of the four groups of soils have significant impacts on crop net revenues in South Africa. Both *acrisols* and *arenosols* are expected to have positive impacts on crop net revenues. That is, in general areas in the country where these types of soils can be found have significantly higher net revenues than other areas. This is true for three of the other four models, especially for *arenosol* in the dryland model (col. 3) and *acrisols* in the small-scale model (col. 5). Soil *xerosols*, on the other hand, may have a negative effect on net revenues but this result is not significant.

4.1.3. Hydrology variable (runoff)

The linear and quadratic terms of the runoff variables are included to test the nature and extent of the impact. This also follows the assumption that such an impact is non-linear.

The results indicate that the influence of the runoff variable is non-linear, with a hill-shape in four of the five models, with the exception of the large-scale farms where it is U-shaped (Table 2). The relationship is also more significant in the dryland model. This indicates that access to water other than rainfall may enhance net revenues, particularly for dryland farms mainly because it may affect the texture of the soil and positively affect net revenues. But excessive runoff may be detrimental to net revenues, as indicated by the negative coefficient of the quadratic term (see Table 2).

The above-estimated set of models indicate that the extent and nature of the impact of climate variables on crop net revenues may be influenced by the type of soil and the runoff in a particular farming location in South Africa. Soil *acrisols* and *arenosols* may enhance crop net revenues and therefore reduce the negative effect of climate change on net revenues, while *xerosols* may rather reduce crop net revenues and therefore aggravate the negative effect. Runoff will increase net revenues and also reduce the negative effects of climate, especially for dryland farming. However, to clearly assess climate impacts on crop net revenues, we estimate the marginal effects using the estimated models in Table 2.

4.2. Marginal impact of climate

The estimated marginal effects of temperature and precipitation on crop net revenues using Eq. (3) are presented in Table 3.

Table 3 shows the marginal effects of a 1 °C increase in temperature and 1 mm/month increase in precipitation on crop net revenues for the different types of farmers in the country and also for the summer farming season (summer and fall periods) and the winter farming season (winter and spring periods).

Higher temperatures in the summer farming season would have a negative effect on crop net revenues for all types of farms in the country. More importantly, higher temperatures in the fall will not augur well for crop farming. On the other hand, increases in temperature in the winter farming season will positively affect crop net revenues. The net effects of the seasonal impacts indicate that a 1 °C increase in annual temperatures will lead to an increase in crop net revenue of US$ 80 for the whole country, US$ 191 for irrigated farms, US$ 588 for large-scale farms and US$ 60 for small-scale farms. However, dryland farms will see a fall in their net revenues by about −US$ 50 per hectare. Estimated elasticity indicates that a 1% increase in temperature will lead to 4% increase in net revenues for the whole of South Africa, 7% for irrigated farms, 27% for large-scale farms, 4% for small-scale farms, but a fall of 5% in net revenues for dryland farms (Table 3). The policy lesson from this result is to take advantage of the positive effects of climate change while reducing the negative ones.

The marginal impacts of precipitation on crop net revenues indicate that increases in precipitation will lead to increases in net revenues for all the types of farms except for small-scale ones, with more significant impacts for dryland farms. Again the relative seasonal impacts are important. The summer farming season, surprisingly, indicates that increases in precipitation affect net revenues negatively. This is mainly due to the strong negative influence of the fall period (Table 3). The implication is that the timing of the rainfall is important for agricultural activities. Higher rainfall in the earlier part of the summer farming season would be more beneficial to crop farming than later rainfall in the season. Therefore, shifts in the timing of the rainfall as a result of climate change may be damaging to crop activities unless farmers are aware of these shifts and adjust their farming activities appropriately in the summer farming season. Except for dryland farms, the influence of increased precipitation in the winter season would be positive. The annual estimates indicate that an annual increase of 1 mm/month of precipitation will have a positive effect on net revenues, with the exception of those of small-scale farmers, which indicate a negative value though this result is not significant. As expected, dryland farms may benefit more, as indicated by the significance of their positive effects and relatively higher estimated elasticity of 7. For the country as a

Table 3
Marginal effects of climate

	Full sample	Irrigated	Dryland	Large-scale	Small-scale
1 °C increase in temperature on crop net revenue (US$/ha)					
Summer temperature	952.68***	2695.66*	−507.20*	1892.91*	1570.30***
Fall temperature	−1704.2***	−5182.81*	−605.65**	−3279.3	−2595.2***
Summer farming season	−751.53***	−2487.15	−1112.85***	−1386.4	−1024.85
Winter temperature	1561.95***	4420.82**	997.20***	3052*	2496.52***
Spring temperature	−730.56***	−1742.35	65.63	−1077.3**	−1411.20***
Winter farming season	831.39***	2678.47	1062.83***	1974.73	1085.32
Annual temperature	79.86	191.31	−50.02	588.34	60.48
Annual elasticity	4.36	6.71	−5.33	26.87	4.04
1 mm/month increase in precipitation on crop net revenue (US$/ha)					
Summer precipitation	30.34	210.66	76.88**	−111.31	273.99***
Fall precipitation	−86.09	−447.12	−54.55**	104.41	−112.86
Summer farming season	−55.75	−236.47	22.33	−6.89	161.13**
Winter precipitation	70.97	417.79	158.78***	−76.3444	305.29**
Spring precipitation	−13.18	−152.81	−160.97***	107.9519	−494.34***
Winter farming season	57.79	264.98	−2.19	31.60367	−189.05**
Annual precipitation	2.04	28.52	20.14**	24.71	−27.92
Annual elasticity	(0.37)	(31.2)	(7.33)	(3.25)	(−6.9)

Estimated annual elasticities in parenthesis.
Note: elasticity estimated as

$$\text{Marginal effects} \times \frac{\text{Mean of (corresponding climate variable)}}{\text{Mean of dependent variable (crop net revenue)}}.$$

* Significant at 10%.
** Significant at 5%.
*** Significant at 1%.

whole, an annual net gain of US$ 2 is expected with a 1 mm/month increase in precipitation: US$ 29 for irrigated farms and US$ 25 for large-scale farms, but −US$ 28 for small-scale farms, with corresponding elasticities of 0.37, 3.12, 3.25 and −6.9. It follows that a decrease in precipitation by the same amount will reduce net revenues by similar amounts. The negative impact for small-scale farms is surprising. One reason for this is the relative negative effect of the winter farming season that outweighs the positive effect in the summer farming season.

4.3. *Agro-ecological zones and provincial level marginal impacts of climate*

Using the coefficients of the full sample model in Table 2, the marginal impacts of climate at the agro-ecological and provincial levels are assessed based on their respective means. The results are presented in Table 4. The marginal impact estimates of increased temperature indicate that in general, almost all the agro-ecological zones and administrative provinces will experience positive mean annual impacts. A 1 °C increase in temperature will lead to an increase in mean annual crop net revenue with a range of US$ 22–175, with significant values for the arid agro-ecological zone especially for the Gauteng, Limpopo and Mpumalanga Provinces. This follows the general trend for the whole country as indicated in Table 3. The only agro-ecological zone and province which would experience a negative mean annual impact is the desert or Northern Cape Province of −US$ 93 per hectare. This is expected because of the exceptionally hot climate in this area. Again, this annual estimate hides the significant difference in the seasonal impacts, which is crucial for policy. In Table 4, all agro-ecological zones and provinces experience negative impacts on net crop revenues in the summer farming season while they all experience positive impacts in the winter farming season. These differences are important in the sense that depending on the relative impacts of the two seasons, an agro-ecological zone or province may have a positive or negative impact. This is the particular situation in the desert zone and Northern Cape Province, where even though the trends in the summer and winter farming seasons follow the general trend in the other provinces, the positive winter farming season impact is not high enough to offset the negative summer farming season impact. It is therefore important to take advantage of the positive impact while limiting the negative impacts.

The marginal impact of increased precipitation at the provincial level is, however, not very straightforward and follows the trend for the whole country. The results indicate that some of the provinces in the different agro-ecological zones will experience mean annual benefits while others will experience negative effects (Table 4). With a 1 mm/month increase in precipitation, the Free State and North West Province in the arid zone, the subtropical wet zone of KwaZulu-Natal, the Northern Cape in the desert zone, and the winter rainfall zone of the Western Cape Province will experience negative impacts in the range of −US$ 4 to −29. It follows that a fall in precipitation will rather lead to mean annual benefits for these provinces, though these impacts are not significant except for the North West Province. With the same level of increase in precipitation, the Eastern Cape, Gauteng, Limpopo and Mpumalanga all in the arid zone will experience a positive impact in the range of US$ 3–116, or the same range of negative effects with decrease in precipitation, with significant values for Limpopo. It follows that these provinces will be more affected by a similar decrease in precipitation. Again, there is a significant difference in the impacts in the farming seasons and the specific seasons. Higher precipitation levels will have a positive effect in the summer and winter seasons, but negative impacts in the fall season with both positive and negative impacts in the spring season. What this again indicates is that the timing of the rainfall is important. If it starts early in the summer farming season and also in the winter farming season, then most of the provinces will benefit. But if it does arrive late, especially in the fall period, farmers will not benefit. Such information should help policy makers plan when and how to help farmers, by providing information on the timing of the rain to reduce any such negative effect.

Table 4
Marginal effects climate at the agro-ecological zone and provincial level

Agro-ecological zone	Province	Summer	Fall	Summer farming season	Winter	Spring	Winter farming season	Annual
1 °C increase in temperature on crop net revenue (US$/ha)								
Arid	Eastern Cape	965.51***	−1682.924***	−717.41***	1407.15***	−667.50***	739.64**	22.23
	Free State	871.46***	−1429.52***	−558.07**	1262.66***	−675.8***	586.77**	28.7
	Gauteng	918.64***	−1610.27	−691.63***	1506.74***	−741.72***	765.02***	73.39**
	Limpopo	1051.72***	−2012.44***	−960.72***	2005.90***	−869.54***	1136.36***	175.63***
	Mpumalanga	975.90***	−1783.15***	−807.25***	1724.47***	−800.53***	923.94***	116.69**
	North West	1035.01***	−1800.38***	−765.37**	1688.94***	−846.05***	842.89***	77.513
Desert	Northern Cape	1132.73***	−1784.21***	−651.48**	1350.61***	−791.69***	558.92**	−92.56
Sub-tropical wet	KwaZulu-Natal	896.50***	−1684.89***	−788.39***	1622.01***	−703.19***	918.82***	130.44**
Winter rainfall	Western Cape	993.67***	−1747.097***	−753.43***	1432.94***	−663.99***	768.95***	15.52
1 mm/month increase in precipitation on crop net revenue (US$/ha)								
Arid	Eastern Cape	50.31	−79.48	−29.17	69.68	−37.37	32.30	3.13
	Free State	32.02	−80.45	−48.43	77.68	−40.51	37.16	−11.26
	Gauteng	−3.65	−81.05	−84.70	80.43	10.1	90.54	5.84
	Limpopo	140.67**	−71.20	69.47***	63.69	−16.97	46.73	116.20*
	Mpumalanga	−5.88	−83.55	−89.43	78.14	16.66	94.79	5.36
	North West	32.77	−71.29	−38.52	81.82	−72.54*	9.28	−29.24**
Desert	Northern Cape	108.88**	−41.60	67.27**	78.8	−162.78**	−83.98***	−16.7
Sub-tropical wet	KwaZulu-Natal	−25.14	−117.05	−142.19*	64.67	71.4	136.08*	−6.12
Winter rainfall	Western Cape	117.37**	−51.91	65.46**	65.26	−134.35**	−69.10*	−3.64

* Significant at 10%.
** Significant at 5%.
*** Significant at 1%.

The estimated marginal impacts of the climate variables indicate that there would be winners and losers from climate change amongst the different types of farmers in the country and the different agro-ecological zones and provinces in the country. One important focus is dryland farmers who generally have negative impacts from increased temperatures. Moreover, seasonal effects may also be different. It is therefore important for farmers and policy makers to take advantage of the gains while trying to limit the losses and by so doing controlling the adverse effects of climate change. It is important to know where the gains are and who the winners will be, so as to provide the necessary support to take advantage of the gains. Similarly, it is important to know who the losers are and where the losses are, also to provide the necessary support to limit the losses. By so doing, the net adverse effect could be reduced. The seasonal differences are important for policy makers, to know when and where to take advantage of climate change. For example, it may be possible to grow some of the current summer crops in the current winter growing areas such as the Western Cape as the climate warms up. Policy makers may therefore need to inform farmers about this possibility. These seasonal differences of the impacts are extremely important if the adverse effects of climate are to be controlled.

4.4. *Forecasts of climate impacts*

We examined a set of climate scenarios predicted by Strzepek and McCluskey (2006) and following the Intergovernmental Panel on Climate Change (IPCC). The study uses synthetic or General Circulation Model (GCM)-based climate change scenarios as input to what is referred to as a Water Balance (WatBal) model to provide insights into the changes in hydroclimatic variables that can be expected under different climate change scenarios. The scenarios represent a range of equally plausible future climates (expressed as anomalies of the baseline 1961–1990 climate) with differences attributable to the different climate models used and to the different emission scenarios that the world would follow. We used three main scenarios derived by Strzepek and McCluskey (2006) using three different models (CSIRO2, HadCM3 and PCM) in conjunction with the A2 emission scenarios plausible for South Africa. We then examined the consequences of these climate change scenarios on net crop revenues in these two periods using the estimated model in Appendix A. The predicted changes for temperature and precipitation plus the impacts on crop net revenues for 2050 and 2100 are presented in Table 5. All three models predict increased temperatures in the range of 2.3–3.9 °C by 2050, and even higher levels of 3.9–9.6 °C by 2100. All three models also predict falls in precipitation in the range of 2–8% by 2050 and 4–8% by 2100.

The estimated climate scenarios impacts indicate that, comparatively, dryland farms will be more affected by increased temperatures and decreased rainfall. Comparing large- and small-scale farmers, the latter will also be more affected (Table 5).

For 2050, given the A2 scenarios, crop net revenues are expected to fall by US$ 5.14–16.26 (or 1.7–5.3%) per hectare for the whole of South Africa, US$ 5.34–20.23 (or 1.2–4.3%) for irrigated farms, US$ 41.63–55.24 (or 26.2–27.7%) for dryland farms, US$ 20.65–49.39 (or 5.8–13.8%) for large-scale farms, and US$ 25.05–204.60 (or 9.9–20.7%) for small-scale farms. The negative effects are expected to increase by 2100, with a fall in crop net revenues ranging from 9% to as high as 90%, with small-scale farms to be most affected. The least to be affected are irrigated farms. This also indicates the crucial positive effects of

Table 5
Impacts of selected climate scenarios on net revenues (US$/ha)

	CGCM2	CGCM2	HadCM3	HadCM3	PCM	PCM
	2050	2100	2050	2100	2050	2100
Change in temperature (°C)	3.6	9	3.9	9.6	2.3	5.6
Change in precipitation (%)	−4	−8	−8	−15	−2	−4
Impacts						
Full sample	−12.88 (−4.22)	−40.79 (−25.65)	−16.26 (−5.32)	−93.24 (−30.52)	−5.14 (−1.68)	−29.99 (−9.82)
Irrigated	−15.91 (−3.4)	−113.99 (−24.43)	−20.23 (−4.34)	−134.55 (−28.84)	−5.34 (−1.15)	−41.16 (−8.82)
Dryland	−43.2 (−27)	−55.24 (−34.74)	−44.1 (−27.74)	−59.06 (−37.44)	−41.63 (−26.18)	−46.29 (−29.12)
Large-scale	−43.11 (−12.01)	−220.16 (−61.41)	−49.39 (−13.78)	−248.21 (−69.23)	−20.65 (−5.76)	−92.99 (−25.94)
Small-scale	−47.29 (−18.61)	−204.6 (−80.49)	−52.73 (−20.74)	−227.2 (−89.39)	−25.05 (−9.86)	−93.86 (−36.93)

Note: percentage changes in parenthesis.

irrigation as a cushion for adverse climate effects. Adaptation strategies if properly implemented are expected to reduce the negative impacts of the climate scenarios on crop net revenues, especially with respect to temperatures.

5. Conclusions

This study is an attempt to assess the impact of climate change on crop-farming activities in South Africa, using a revised Ricardian model for the economic assessment of impacts. The Ricardian model examines how long-term farm profitability varies with local climate, such as temperature and precipitation, while controlling for other factors. In the revised model applied in this study, other important sources of water, such as runoff and irrigation, are included in the model. Estimations were undertaken for the full sample, irrigated farms, dryland farms, large-scale farms and small-scale farms to investigate any differences in the impacts of climate change on these different farming systems. To clearly assess the impact of climate variables, we also estimated the marginal impacts of unit changes in temperatures and precipitation on crop-farming activities for the different farming systems, and also for the different agro-ecological zones and the nine provinces in the country. Selected climate scenarios were also used to predict the extent to which projected climate changes will affect net revenues in 2050 and 2100.

The results indicated that there is a significant difference between the impacts of climate on irrigation and dryland farms. The differences between the impacts on large-scale farms and small-scale farms were, however, not very clear-cut, because they are overshadowed by the impacts of whether a farm is irrigated or not. That is, whether a farm is irrigated or not seems to be more relevant in climate analysis than the scale of the farm.

Estimated results also indicated that climate variables of temperature and precipitation are very relevant for agricultural activities in South Africa and more so for dryland farming. Irrigated farms are cushioned against adverse climate effects by having a substitute for rainwater. Climate impacts were also found to have, to a large extent, a non-linear relationship with net revenue. That is, increases in climate variables will be beneficial to crop farming but beyond a certain limit the impacts will be negative.

The type of soils in particular locations will also affect crops and net revenues and therefore the extent to which climate affects the crop-faming sector. Of the 10 major soil types identified in the country, four major ones were tested in the models. Two major soil types, *acrisols* and *arenosols*, were found to have a positive effect on crops and therefore may help control adverse climate effects.

In addition to irrigation, other sources of water will also affect crops. We tested the influence of hydrology variable runoff to assess this. The outcome indicated that runoff affects crops positively, given that it positively influences the texture and therefore the productivity of the soils and this would also reduce the adverse climate effects in a given area. However, excessive runoff will erode such expected benefits.

Estimated marginal impacts of the climate variables on crop net revenues also indicated different results for temperature and precipitation and also for the four main farming systems. Unexpectedly, an annual increase of 1 °C in temperature will have a positive impact on annual crop net revenues for all farms except dryland ones. A net increase of US$ 80 per hectare is expected for the whole of South Africa: US$ 191 for irrigated farms, U$S588 for large-scale farms and US$ 61 for small-scale farms, but a fall of US$ 50 for dryland farms. However, what these annual estimates hide is the seasonal differences in the impacts. Such an increase in temperature will affect crop farm net revenues negatively in the summer farming season but positively in the winter season. These differences are important to help find ways to limit the negative effects and take advantage of the positive ones. Adaptation-related variables are expected to help increase the positive impacts while reducing the negative impacts of increased temperature. What relevant adaptation measures are appropriate in this direction needs to be investigated.

All the agro-ecological zones and the nine administrative provinces except the desert zone of the Northern Cape Province will also experience annual positive impacts from a 1 °C increase in temperature. Again, the differences in the seasonal impacts are very important, with the summer farming season experiencing a negative impact while the positive impact is experienced in the winter.

Marginal impacts of increased or decreased precipitation on net revenues are, however, not that straightforward. With a 1 mm/month annual increase in precipitation, an increase in net revenue of US$ 2 is expected for the whole country, US$ 29 for irrigated farms, US$ 20 for dryland farms (which is also very significant) and US$ 25 for large-scale farms, but a fall of US$ 28 for small-scale farms (though this is not very significant). Similar decreases or increases are expected with a decrease in precipitation. Again, seasonal differences in the impacts are important. Rainfall in the early part of the summer farming season would be beneficial, while later rainfall would be harmful. Early winter rainfall will also be beneficial for the winter farming season. These differences will influence whether the annual impact of precipitation will be beneficial or not. This means that changes in the volume of rainfall and the timing of the rainfall significantly affect net revenues. Farmers not aware of these possible shifts will be negatively affected, so information provided by extension and other agriculture-related organisations may be helpful.

At the agro-ecological zone and provincial levels, some farmers would experience positive impacts from increased precipitation while others will experience negative impacts. This is a reflection of the unclear impact of change in precipitation on crop activities in the country. It is also a reflection of the high degree of variability of the rainfall experienced in recent past. Again, the seasonal differences are important, with late summer and winter rainfall being more harmful to crops than rain early in the season. Again adaptation-related variables may change the extent of these relationships.

Three climate scenarios which were plausible for South Africa indicate that by 2100, temperatures will increase by 2.3 and 9.6 °C while precipitation will fall by −2% and −8%. Using these estimates, the study predicts that crop net revenues will fall as much as 90% by 2100, with small-scale farms being the most affected. Again, there is the possibility that adaptation could reduce these negative effects.

These results have several policy implications for the way climate change could be managed so as to reduce the damage to the crop-farming sector. Policy makers may need to accept the fact that climate impact on agriculture, especially in the summer, is real and that farmers are doing their best to adapt to it. It is expected that there will be winners and losers. Policies should therefore be directed at taking advantage of the gains and reducing losses by identifying and assessing the efficiency of current coping mechanisms and finding ways to support them.

Assessment of the relative importance of irrigation and farm type indicated that whether a farm is irrigated or not is more important in climate impact assessment than the scale factor. Scale does matter, but what is crucial for controlling any negative impact on crop net revenue in the country is the access to sources of water other than rain, such as irrigation. Policy makers should therefore see this as an important policy instrument in controlling the adverse effects of climate, for both temperature increases and decreasing precipitation. But given that water is already scarce in the country and that 50% of the water resources are already being used for agriculture, as the demand increases with climate change, further pressures will be put on the resources. This means that the country's water resources must be efficiently managed. But increasing water scarcity will mean more research needs to be done into new crop varieties and new animal breeds that are heat tolerant and less affected by water stress. In addition, other adaptation measures such as improved farming technologies have to be investigated to find further appropriate responses to the expected impact of climate change on crop-farming activities in South Africa.

The study also indicates that when assessing the effect of climate change in a country with diverse climate and cropping patterns, it is not only the overall effect (which does tell a story) that is relevant but also and more importantly the effects in the different seasons, different farming systems and different agro-ecological and provincial levels. In this way, we can assess where the losses are and who the winners are and reduce the losses while taking advantage of the gains. If this is done, it is possible that the overall expected negative effects can be reduced. For example, it has been shown that even though increased temperatures may harm dryland farms in the summer, they tend to benefit them in winter farming season, which may override the damage done in summer. Relevant policies and adaptation options should be directed at making this possible, so that climate change damage can be reduced and benefits enhanced.

The study also indicated the importance of irrigation and to some extent scale factor in climate impact analysis. But the scale effect may have been unclear because of the influence of irrigation. A possible extension of this study would be to compare and contrast the effects for large- and small-scale irrigated farms and large- and small-scale dryland farms, to clearly assess the scale effect of climate change in South Africa. It would also be interesting to undertake such analysis at the agro-ecological and provincial levels. Moreover, a more explicit spatial analysis in addition to an explicit assessment of the role of adaptation, such as crop choice, fertilizer use, access to market and extension services is required to help in the formulation of further targeted policies, especially at the provincial level

Acknowledgements

This study was part of an 11 African-wide study "Regional climate, water and agriculture: Impacts on adaptation of agro-ecological systems in Africa". The author acknowledges with many thanks funding from the following organisations and institutions: Global Environment Facility (GEF), World Bank, World Bank Institute (WBI), National Oceanic Atmospheric Agency, Office of Global Programs (NOAA-OGP), Finnish Trust Fund, and the Centre for Environmental Economics and Policy in Africa (CEEPA) of the University of Pretoria. Helpful comments from three reviewers are very much appreciated. The author is responsible for any remaining errors.

Appendix A. Climate variables only

Variable	Dependent variable: crop farming net revenue				
	Col. 1	Col. 2	Col. 3	Col. 4	Col. 5
	Full sample	Irrigated	Dryland	Large-scale	Small-scale
Summer temperature squared	27.48***	30.345*	27.53***	28.58*	44.91***
Fall temperature	−1020.7	228.729		566.21	2450.26
Fall temperature squared	−26.76	−63.826	−47.28***	−38.61	−182.5
Winter temperature	2346.96***	2186.54	1531.43***	5459.5	−785.34
Winter temperature squared	−26.35	−17.288	−6.338	−211.19	162.93
Spring temperature	551.94	794.96	−375.49	2408.73	2814.24
Spring temperature squared	−43.53	−57.092	−16.76	−124.25	−132.07
Summer precipitation	145.26	239.104	−161.58*	261.524	268.33
Summer precipitation squared	−0.59	−0.507	1.841***	0.446	1.983
Fall precipitation	1198.96	1014.11	1211.19***	631.1	

Fall precipitation squared	−11.95*	−10.407	−10.109***	−2.185	−8.011
Winter precipitation	114.66	182.268	87.718	123.816	594.59
Winter precipitation squared	−1.50**	−1.048	0.816**	0.744	2.767**
Spring precipitation	−831.68*	−862.82		−349.354	
Spring precipitation squared	6.45**	5.34	−2.914***	−0.406	−8.137**
Constant	−21774	−32343	−31884	−52807	−68252
Pseudo-*R*	0.1328	0.1533	0.253	0.194	0.1516
No. of observations	191	91	100	94	97

*Significant at 10%.
**Significant at 5%.
***Significant at 1%.

Appendix B. Climate and soil variables only

Variable	Dependent variable: crop farming net revenue				
	Col. 1	Col. 2	Col. 3	Col. 4	Col. 5
	Full sample	Irrigated	Dryland	Large-scale	Small-scale
Summer temperature squared	14.58*	39.381	13.199	42.781	37.76**
Fall temperature squared	−47.77**	−146.09	−35.59*	−95.362	−94.73**
Winter temperature squared	51.86**	152.21	35.844*	126.994	110.83**
Spring temperature	1431.61	4187.12			2950.35
Spring temperature squared	−51.52	−139.81	−6.603	−30.803	−123.08
Summer precipitation	260.59	954.61	46.026*	−55.921	355.62
Summer precipitation squared	−1.095*	−3.77	−0.169**	−0.381	0.7302
Fall precipitation squared	−1.75	−7.233	−0.284	1.245	−2.661
Winter precipitation	191.32	775.36	58.941	−68.916	526.551
Winter precipitation squared	−0.47*	−1.582	0.085*	−0.411	2.130*
Spring precipitation	−369.96	−1279.8		25.3	
Spring precipitation squared	2.65	8.925	−0.224*	0.835	−5.974*
Soil vertisols	−322.39**	−974.96	−240.54	−11.276	−135.5
Soil acrisols	943.08***	1487.38	1011.20***	631.37	
Soil arenosols	450.24***	1220.76	287.859	−24.76	
Soil xerosols	−80.57	−310.73		−265.27	−63.63
Constant	−11053	−36297	−1532.	979.9	−41324
Pseudo-*R*	0.1363	0.1564	0.253	0.194	0.1516
No. of observations	191	91	100	94	97

*Significant at 10%.
**Significant at 5%.
***Significant at 1%.

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