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Understanding Farmers' Perceptions and Adaptations to Climate Change and Variability

The Case of the Limpopo Basin, South Africa

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ABSTRACT

Climate change is expected to have serious environmental, economic, and social impacts on South Africa. In particular, rural farmers, whose livelihoods depend on the use of natural resources, are likely to bear the brunt of adverse impacts. The extent to which these impacts are felt depends in large part on the extent of adaptation in response to climate change. This research uses a “bottom-up” approach, which seeks to gain insights from the farmers themselves based on a farm household survey. Farm-level data were collected from 794 households in the Limpopo River Basin of South Africa for the farming season 2004–2005. The study examines how farmer perceptions correspond with climate data recorded at meteorological stations in the Limpopo River Basin and analyzes farmers’ adaptation responses to climate change and variability. A Heckman probit model and a multinomial logit (MNL) model are used to examine the determinants of adaptation to climate change and variability. The statistical analysis of the climate data shows that temperature has increased over the years. Rainfall is characterized by large interannual variability, with the previous three years being very dry. Indeed, the analysis shows that farmers’ perceptions of climate change are in line with the climatic data records. However, only approximately half of the farmers have adjusted their farming practices to account for the impacts of climate change. Lack of access to credit was cited by respondents as the main factor inhibiting adaptation. The results of the multinomial logit and Heckman probit models highlighted that household size, farming experience, wealth, access to credit, access to water, tenure rights, off-farm activities, and access to extension are the main factors that enhance adaptive capacity. Thus, the government should design policies aimed at improving these factors.

Keywords: climate change and variability, perception, adaptation, agriculture

ABBREVIATIONS AND ACRONYMS

WMA	water management areas
CEEPA	Center for Environmental Economics and Policy in Africa
SAWS	South African Weather Service
MNL	multinomial logit
MNP	multinomial probit
GHK	Geweke-Hajivassiliou-Keane
IISHK	irrelevant alternatives

1. INTRODUCTION

Adaptation is widely recognized as a vital component of any policy response to climate change. Studies show that without adaptation, climate change is generally detrimental to the agriculture sector; but with adaptation, vulnerability can largely be reduced (Easterling et al. 1993; Rosenzweig and Parry 1994; Smith 1996; Mendelsohn 1998; Reilly and Schimmelpfennig 1999; Smit and Skinner, 2002). The degree to which an agricultural system is affected by climate change depends on its adaptive capacity. Indeed, adaptive capacity is the ability of a system to adjust to climate change (including climate variability and extremes) to moderate potential damage, to take advantage of opportunities, or to cope with the consequences (IPCC 2001). Thus, the adaptive capacity of a system or society describes its ability to modify its characteristics or behavior so as to cope better with changes in external conditions.

Adaptation to climate change requires that farmers first notice that the climate has changed, and then identify useful adaptations and implement them (Maddison 2006). Many agricultural adaptation options have been suggested in the literature. They encompass a wide range of scales (local, regional, global), actors (farmers, firms, government), and types: (a) micro-level options, such as crop diversification and altering the timing of operations; (b) market responses, such as income diversification and credit schemes; (c) institutional changes, mainly government responses, such as removal-preserve subsidies and improvement in agricultural markets; and (d) technological developments—the development and promotion of new crop varieties and advances in water management techniques (Smith and Lenhart 1996; Mendelsohn 2001; Smit and Skinner 2002; Kurukulasuriya and Rosenthal 2003). Most of these represent possible or potential adaptation measures rather than ones actually adopted. Indeed, there is no evidence that these adaptation options are feasible, realistic, or even likely to occur. Furthermore, they would only be possible with complete and accurate knowledge of future climatic conditions, which is why these were aptly named “clairvoyant farmer” scenarios (Risbey et al. 1999, cited by Belliveau et al. 2006). Thus, climate change impact studies often assume certain adaptations and little explicit examination of how, when, why, and under what conditions adaptation actually occurs in economic and social systems.

The present research, as part of a more recent strand of adaptation research, seeks to investigate actual adaptations at the farm level, as well as the factors that appear to be driving them (e.g. Smit et al. 1996; Brklacich et al. 1997; Belliveau et al. 2006; Maddison 2006).

Based on the case of farmers in the Limpopo River Basin in South Africa, this paper intends to capture the extent of farmers’ awareness and perceptions of climate variability and change and the types of adjustments they have made in their farming practices in response to these changes. The analyses in this study are based on a farm household survey of a total of 794 farmers conducted between August and November 2005 in the Limpopo River Basin of South Africa.

The remainder of the paper is structured as follows. The next section gives brief theoretical insights on research of adaptation to climate change. In Section 3, we present the study area, and in Section 4 the data used in the study are discussed. Section 5 presents the assessment of farmers’ perceptions of climate change and variability. Section 6 presents the analytical and empirical adaptation model. Finally, Section 7 concludes and outlines the policy implications of the study.

The primary hypothesis is that farmers adapt to perceived climate change and variability. The analysis is conducted in two stages. First, it is determined whether the climate has changed, whether the farmers perceive climate change and variability, and what characteristics differentiate farmers who perceived changes from those who did not. Second, the determinants of adaptation are examined. Not all of the farmers who perceived climate change will respond by taking adaptation measures. Here it is argued that farmers who perceived climate changes and responded share some common characteristics. Therefore, there is a need to understand the reasons underlying their response (or failure to respond for those who did not adapt). Furthermore, adaptation to climate change requires farmers to choose from among a set of adaptation options (practices and technologies) available in their region. By identifying the important determinants of choosing any of the adaptation options, this paper provides important policy information on how to promote various adaptations to climate change in rural South Africa.

2. ADAPTATION TO CLIMATE CHANGE: A THEORETICAL PERSPECTIVE[1]

2.1. Research Methods

Research on climate change–agriculture interactions has evolved from a “top-down” approach to a “bottom-up” approach. The top-down mode starts with climate change scenarios, and estimates impacts through scenario analysis, based on which possible adaptation practices are identified. The bottom-up approach, on the other hand, takes on a vulnerability perspective where adaptation strategies are considered more as a process involving the socioeconomic and policy environments, producers’ perceptions, and elements of decision-making (Bryant et al. 2000; Wall and Smit 2005; Belliveau et al. 2006).

In the top-down, scenario-based approach, adaptations are assumed and are invariably treated as primarily technical adjustments (for example, changing to different crops, adopting efficient irrigation systems, or altering production systems) to the impacts identified. Most of these adaptations represent possible or potential adaptation measures, rather than measures that have actually been adopted. Indeed, there is no evidence that these adaptation options are feasible, realistic, or even likely to occur. Furthermore, they would only be possible with complete and accurate knowledge of future climatic conditions, which is why they have been aptly named “clairvoyant farmer” scenarios (Risbey et al. 1999, cited by Belliveau et al. 2006). This approach can be found in spatial analysis, climate impact modeling, and Ricardian studies. Most studies on climate impacts using the top-down approach carried out in South Africa (Schulze et al. 1993; Erasmus et al. 2000; du Toit et al. 2001; Kiker 2002; Kiker et al. 2002; Poonyth et al. 2002; Deressa 2003; Gbetibouo and Hassan 2005) predicted adverse impacts on the agricultural sector with significant adverse effects on crop yields and marginal crop areas in the western part of the country, which would become unsuitable for the production of maize, the main staple crop.

Vulnerability studies have shifted the focus of research from the estimation of impacts to the understanding of farm-level adaptation and decision making. This research explores actual adaptation behavior based on the analysis of farmer decisions in the face of variable conditions through survey data analysis, in-depth interviews, and focus group discussions with farmers and other farms experts (Smit et al. 1996; Brklacich et al. 1997; Chiotti et al. 1997; Maddison 2006; Belliveau et al. 2006). According to Bryant et al. (2000), these studies have raised new research questions regarding how farmers perceive climatic change and variability; have identified those climatic properties that are of most importance to farmers in their decision making; and have suggested the types of adaptive responses that can be anticipated.

2.2. Agricultural Adaptation to Climate Change

Agricultural change does not involve a simple linear relationship between changes in a farmer’s decision-making environment and farm-level change.

One important issue in agricultural adaptation to climate change is the manner in which farmers update their expectations of the climate in response to unusual weather patterns. Referring to Kolstad et al. (1999), Maddison (2006) discusses what he calls “the transitional cost” of adapting to climate change. The transitional cost is the difference between the maximum value of net revenues per acre following perfect adaptation and the net revenues actually experienced by farmers given that their expectations of (and therefore response to) climate change lag behind actual climate change. A farmer may perceive several hot summers but rationally attribute them to random variation in a stationary climate. One could argue that farmers engage in simple Bayesian updating of their prior beliefs according to the standard formula. If so, the process of updating is likely to be slow, and therefore one should not expect decades of information to be thrown out overnight. However, there is evidence that farmers did not update their priors in this way. Indeed, farmers place more weight on recent information than is efficient.[2]

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[1] This section draws heavily on Bryant et al. (2000), Belliveau et al. (2006), and Maddison (2006).

[2] For reference see Smit et al. (1997).

Another important issue related to adaptation in agriculture pointed out by Bryant et al. (2000) is how perceptions of climate change are translated into agricultural decisions. If farmers learn gradually about the change in climate, Maddison (2006) argues that they will also learn gradually about the best techniques and adaptation options available. According to him, farmers learn about the best adaptation options through three ways: (1) learning by doing, (2) learning by copying, and (3) learning from instruction. There is recognition that farmers' responses vary when faced with the same stimuli. Such varied responses, even within the same geographic area, are partly related to the variety of agricultural systems involved and the different market systems in which farmers operate (Bryant et al. 2000). A more important factor of varied farmers' responses is the differences between farmers in terms of personal managerial and entrepreneurial capacities and family circumstances. Also, farmers can be influenced by their peers' perceptions and by values present in their communities as well as their professional associations. A review of literature on adoption of new technologies identified farm size, tenure status, education, access to extension services, market access and credit availability, agroclimatic conditions, topographical features, and the availability of water as the major determinants of the speed of adoption (Maddison 2006).

This paper adopts the bottom-up approach that seeks to investigate actual adaptations at the farm level, as well as the factors that appear to be driving them. Based on the case of farmers in the Limpopo River Basin in South Africa, this paper intends to capture the extent of farmers' awareness and perceptions of climate variability and change, and the types of adjustments they have made in their farming practices in response to these changes.

3. THE STUDY AREA: LIMPOPO RIVER BASIN IN SOUTH AFRICA

The Limpopo River is one of the major river systems in Southern Africa. Originating in South Africa's Witwatersrand region, the Limpopo River is about 1,700 kilometers long, drains an area of about 415,500 square kilometers, and is shared by Botswana, Mozambique, South Africa, and Zimbabwe. South Africa occupies about 46 percent of the total area of the basin (Table 1).

Table 1. Limpopo Basin areas

Country	Total area of the country (km2)	Area of the country within the basin (km2)	Percentage of total area of basin (%)	Percentage of total area of country (%)	Irrigation potential (hectares)	Area under irrigation (hectares)	Average annual rainfall in the basin area (mm)		
							min	max	mean
Botswana	**581,730**	**80,118**	**19.9**	**13.8**	**5,000**	**1,381**	**290**	**555**	**425**
Zimbabwe	**390,760**	**51,467**	**12.38**	**13.2**	**10,900**	**200**	**300**	**635**	**465**
Mozambique	**801,590**	**84,981**	**21.1**	**10.6**	**148,000**	**40,000**	**355**	**865**	**535**
South Africa	**11,221,040**	**185,298**	**46.31**	**15.2**	**131,500**	**198,000**	**290**	**1,040**	**590**
Total	**12,995,120**	**401,864**	**100.0**	**--**	**295,400**	**241,381**	**290**	**1,040**	**530**

Source: Food and Agriculture Organization of the United Nations, www.fao.org/documents/show_cdr.asp?url_file=/docrep/W4347E/w4347e0p.htm

In South Africa, the Limpopo River Basin extends over four administrative provinces (Limpopo, Mpumalanga, Gauteng, and North West) and five water management areas (WMAs).[3] These are the (1) Limpopo, (2) Luvuvhu/Letaba, (3) Crocodile (west) and Marico, (4) Olifants, and (5) Inkomati (Figure 1).

The climate in the basin ranges from temperate and semiarid in the south of the Limpopo WMA and the east of the Crocodile (west) and Marico WMA to arid in the extreme north of the Limpopo WMA. Mean annual precipitation ranges from 200 millimeters per year in the Limpopo WMA to more than 2,300 millimeters annually in the Luvuvhu/Letaba WMA, with temperatures ranging from 8 degrees Celsius to more than 30 degrees Celsius in the northern parts of the Limpopo WMA. Among the five WMAs, Inkomati has the highest mean annual runoff with 3,539 million cubic meters, followed by Olifants (2,040 million), Luvuvhu/Letaba (1,185 million), Limpopo (986 million) and Crocodile (west) and Marico (855 million).

South Africa and the Limpopo Basin feature both large commercial agricultural farms as well as small-scale agriculture.

The diverse climate in the basin influences the vegetation and agricultural activities in the five WMAs and the four provinces. Farming activities range from dry farming to intensive irrigation and livestock production. For example, farming in the Limpopo WMA mainly focuses on livestock and irrigation, while the Olifants WMA is favorable for dry-land farming and livestock as well as extensive irrigation. Intensive irrigation is prevalent in the Crocodile (west) and Marico, where the irrigation sector is the second largest water consumer in the WMA, using an estimated 33 percent of the total water use. In the Limpopo WMA, crops grown include cotton, grain sorghum, and tobacco, as well as considerable

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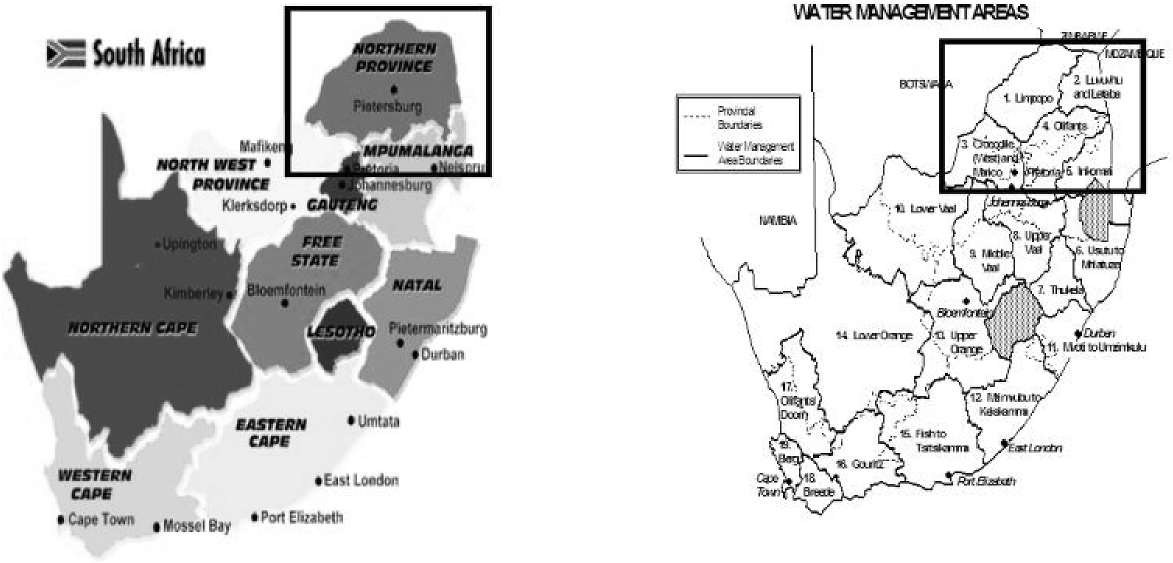
[3] To facilitate the management of the scarce water resources, the country has been divided into 19 catchment-based water management areas (WMAs). All except one WMA are interlinked with other areas through inter-catchment transfers. The interlinking of catchments gives effect to one of the main principles of the country's National Water Policy Acts, which designates water as a national resource (DWAF 2004).

subsistence production. In the Luvuvhu/Letaba WMA, citrus and a variety of fruits plus commercial forestry are prevalent. The Olifant WMA features trout and game farming.

Figure 1. Provinces and WMAs in the Limpopo River Basin area



Source: http://www.exittoafrica.com/media/images/maps/m-sa_provinces.gif and http://www.dwaf.gov.za/Documents/Notices/Water%20Management%20areas%20engl.doc

4. THE DATA

4.1. Survey Data

The survey collected a large range of data. However, this study used principally the section of the survey on perceptions of climate change, adaptations made by farmers, and barriers to adaptation. Open-ended questions were used to ask farmers whether they had noticed long-term changes in mean temperature, mean rainfall, the number of malaria cases, and vegetation cover over the past 20 years. Questions about adaptation and the constraints to adaptation were also posed. The exact formulation of the questions is included in Appendix A.

The empirical analyses of this paper used data obtained from an ongoing project entitled Food and Water Security under Global Change: Developing Adaptive Capacity with a Focus on Rural Africa, funded by the Advisory Service on Agricultural Research for Development of the German Government. Under the project, a survey was carried out by the Center for Environmental Economics and Policy in Africa (CEEPA), University of Pretoria, in collaboration with the International Food Policy Research Institute (IFPRI) to analyze the potential impact of climate variability and climate change on household vulnerability and farm production. The survey period was between August and November 2005 covering the April/May 2004 to April/May 2005 agricultural season. In total, 794 surveys were completed in 19 districts of 4 provinces of South Africa. Farmers were carefully selected with the assistance of producers associations and the National Department of Agriculture.

4.2. Meteorological Data

Monthly precipitation and temperature data was obtained from the South African Weather Service (SAWS). The data covers the period from January 1960 to October 2003. To capture the provincial temperature, a mean of all stations in each province was calculated. For the whole Limpopo River Basin the same analysis was conducted.

5. ASSESSING FARMERS' PERCEPTIONS TO CLIMATE CHANGE AND VARIABILITY

5.1. Comparison between Perceptions of Changes in Climate and Meteorological Stations' Recorded Data

To assess farmers' perceptions of climate change and variability, we first look at how climate data recorded at meteorological stations evolved (trends and variability) and how farmers perceived these changes. Tests were undertaken for linear trend in annual means and seasonal means of temperature, and total annual and seasonal rainfall both at the Limpopo River Basin level and at the provincial level. Descriptive statistics based on summary counts of the questionnaire structure are used to provide insights into producers' perceptions of climate change and variability. In the literature several studies have undergone the same type of analysis.

For example, Vedwan and Rhoades (2001) examine how apple farmers in the western Himalayas of India perceive climatic change. This is done by comparing the locally idealized traditional weather cycle with climate change as perceived by the farmers of the region using snowfall and rainfall data to measure the accuracy of perceptions. Hageback et al. (2005) assess small-scale farmers' perceptions of climate change in the Danagou watershed in China by comparing the local precipitation and temperature data trend with the responses given by farmers to the question "Do you feel any changes in the weather now compared to 20 years?" They conclude that farmers' perceptions of climatic variability correspond with the climatic data records. Another study by Maddison (2006), using data for over 9,500 farmers from eleven African countries, compared the probability that the climate has changed, as revealed by an analysis of the statistical record, with the proportion of individuals who believe that such a change has in fact occurred to assess farmers' perceptions of climatic change.

5.1.1. Temperature Changes

About 95 percent of the farmers interviewed perceived long-term changes in temperature. Most of them (91 percent or 686 farmers) perceive the temperature in the Limpopo Basin to be increasing. Only 1.5 percent noticed the contrary, a decrease in temperature. Across the four provinces of the basin, the same pattern is noticed with the exception of Gauteng, where 16 percent, which represents 7 farmers interviewed, have not noticed any changes in the temperature (Figure 2 and Table 2).

Figure 2. Farmers' perceptions of changes in temperature in the Limpopo River Basin

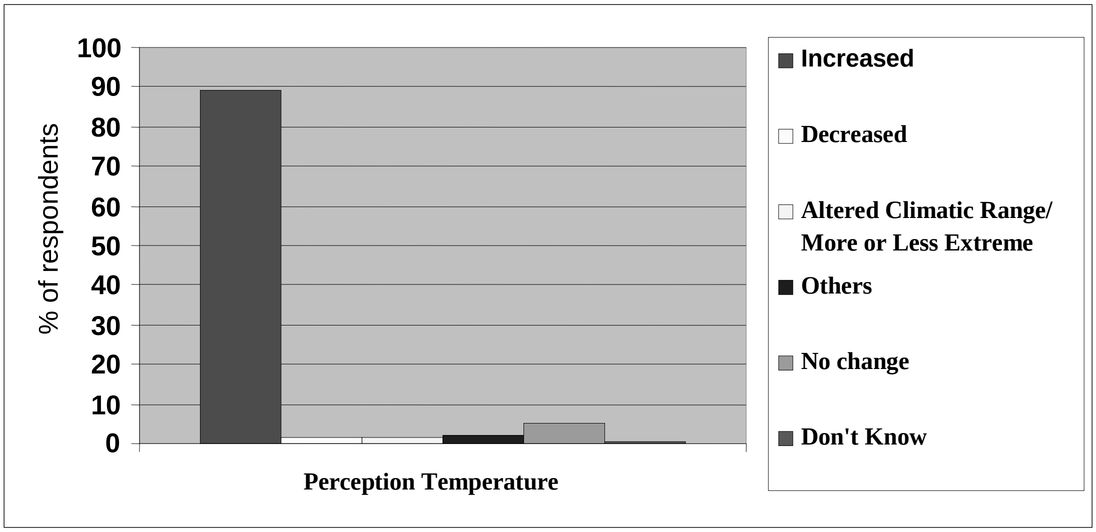


Table 2. Perception of changes in temperature at provincial level (%)

	Increased	Decreased	More or less Extreme	Others	No change	Don't know
Total Basin	89.32	1.56	1.56	2.21	5.08	0.26
Limpopo	90.67	1.2	1.67	1.44	4.78	0.24
Gauteng	66.67	4.44	4.44	8.89	15.56	0
North West	89.52	2.86	0	4.76	2.89	0
Mpumalanga	91.52	1	1.5	1	4.5	0.5

The statistical record of temperature data from the Limpopo River Basin between 1960 and 2003 shows an increasing trend, with the increase mostly in the summer. In 43 years, the temperature has risen around 1 degree Celsius. An analysis at the provincial level shows the same general trend of increasing temperature (Figure 3). However, in the North West province the trend is not significant. Mpumalanga province had a higher increase in temperature of around 1.83 degrees Celsius. In Limpopo, Gauteng, and Mpumalanga provinces, the increased trend is occurring mostly during the winter season (Table 3).

Thus, farmers' perceptions appear to be in accordance with the statistical record in the region.

Figure 3. Trend of temperature data for the Limpopo River Basin: 1960–2003

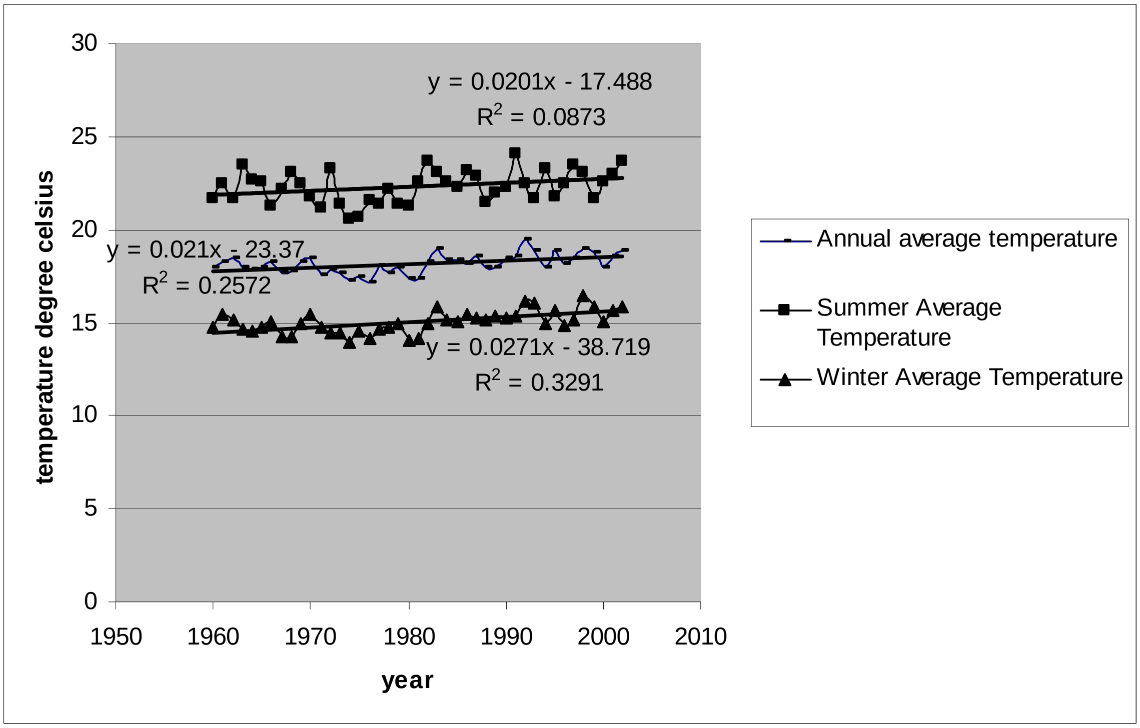


Table 3. Analysis of temperature data from 1960 to 2003

Temperature data for the total Limpopo River Basin

Temperature	Yearly	Summer	Winter
Mean (^{0}C)	18.15	22.31	15.04
Standard deviation (^{0}C)	0.52	0.85	0.59
Minimum temperature (^{0}C)	17.15	20.6	13.93
Maximum temperature (^{0}C)	19.43	24.09	16.41
Trend (^{0}C/year or season)	0.02*	0.02*	0.03*
Correlation	0.51	0.30	0.60
Total change calculated from the trend (^{0}C/43 years)	0.94	2.04	1.15

Temperature data for the Limpopo province

Temperature	Yearly	Summer	Winter
Mean (^{0}C)	20.83	23.93	17.75
Standard deviation (^{0}C)	0.57	0.64	0.68
Minimum temperature (^{0}C)	19.18	22.67	16.58
Maximum temperature (^{0}C)	22.18	25.35	19.15
Trend (^{0}C/year or season)	0.02*	0.01*	0.03*
Correlation	0.47	0.29	0.55
Total change calculated from the trend (^{0}C/43 years)	0.83	0.76	1.02

Temperature data for the North West province

Temperature	Yearly	Summer	Winter
Mean (^{0}C)	18.39	22.31	14.49
Standard deviation (^{0}C)	0.48	0.68	0.47
Minimum temperature (^{0}C)	17.28	20.98	13.64
Maximum temperature (^{0}C)	19.51	23.86	15.45
Trend (^{0}C/year or season)	0.009	0.007	0.01*
Correlation	0.24	0.14	0.32
Total change calculated from the trend (^{0}C/43 years)	0.28	0.85	0.41

Temperature data for the Gauteng province

Temperature	Yearly	Summer	Winter
Mean (^{0}C)	9.91	14.15	5.71
Standard deviation (^{0}C)	0.48	0.46	0.63
Minimum temperature (^{0}C)	8.56	12.11	4.53
Maximum temperature (^{0}C)	10.75	15.09	6.85
Trend (^{0}C/year or season)	0.02*	0.01*	0.03*
Correlation	0.58	0.38	0.58
Total change calculated from the trend (^{0}C/43 years)	1.03	0.31	1.68

Temperature data for the Mpumalanga province

Temperature	Yearly	Summer	Winter
Mean (^{0}C)	17.52	20.59	13.90
Standard deviation (^{0}C)	0.77	0.80	0.91
Minimum temperature (^{0}C)	16.08	18.94	12.22
Maximum temperature (^{0}C)	19.17	22.15	15.66
Trend (^{0}C/year or season)	0.04*	0.03*	0.05*
Correlation	0.63	0.57	0.65
Total change calculated from the trend (^{0}C/43 years)	1.83	1.80	2.26

Notes: *P <0.05 Student's t-test, N=43.
Total change is the difference between the trend line value of the first and last year.

5.1.2. Precipitation Changes

In total, 97 percent of the respondents observed changes in rainfall patterns over the past 20 years, and 81 percent (or 624) noticed a decrease in the amount of rainfall or a shorter rainy season. Almost 5 percent of the informants noticed a change not in the total amount of rainfall but in the timing of the rains, with rains coming either earlier or later than expected. The same pattern is observed across the four provinces with slight differences (Figure 4 and Table 4). A change in the timing of rainfall was mentioned by 7 percent of the farmers in Mpumalanga, 12 percent in North West, and 24 percent in Gauteng. Many respondents observed that the main rainfall season, which is the summer, is coming late and is also shorter.

Figure 4. Farmers' perceptions of changes in precipitation in the Limpopo River Basin

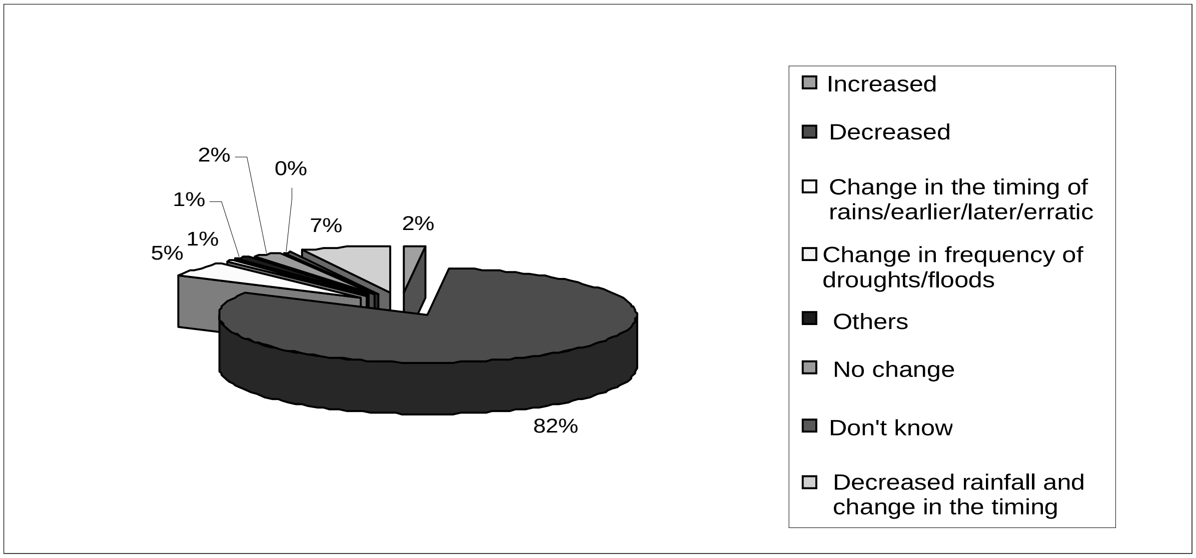


Table 4. Perceptions of changes in rainfall (%)

	Increased	Decreased	Change in timing of rains (earlier/ later/ erratic)	Change in frequency of droughts/ floods	Others	No change	Don't know	Decrease rainfall and change in the timing
Total Basin	1.69	81.25	5.34	0.65	1.43	2.21	0.39	7.03
Limpopo	1.68	91.61	0.72	0.72	0.96	2.4	0.24	1.68
Gauteng	2.22	57.78	24.44	0	2.22	4.44	0	8.89
North West	0.94	62.26	12.26	1.89	3.77	2.83	0.94	15.09
Mpumalanga	2	75	7	0	1	1	0.5	13.5

The recorded data on rainfall from 1960 to 2003 shows that about 85 percent of the rainfall occurs during summer months (October to March). Also, there is no statistically significant trend in the data. The exception is during the winter season, when data show a decreasing trend. The correlation between rainfall and time is also insignificant. Indeed, there is a large variability in the amount of precipitation from year to year. The same pattern is observed in each province (Table 5 and Figure 5).

The high proportion of farmers noticing a decrease in precipitation could be explained by the fact that during the last few years of the study (2001 to 2003), there was a substantial decrease in the amount of rainfall (Figure 5). Thus, farmers' perceptions of a reduction in rainfall over the 20-year period is explained by the fact that, as Maddison (2006) noticed, some farmers place more weight on recent information than is efficient.

Table 5. Analysis of the rainfall data from 1960 to 2003

Rainfall data for the Limpopo River Basin

Rainfall	Yearly	Summer	Winter
Mean (mm)	681.76	579.89	99.36
Percentage of yearly total		85	15
Standard deviation (mm)	123.53	128.97	38.16
Minimum rainfall (mm)	425.858	352.97	30.65
Maximum rainfall (mm)	967.09	906.25	181.94
Trend (mm/year or season)	0.38	0.7	-0.91*
Correlation	0.04	0.07	-0.27
Total change calculated from the trend (mm/43 years)	-242.84	-255.87	-20.97
Total change calculated from the trend (%)	-37.64	-38.77	-18.79

Rainfall data for the Limpopo province

Rainfall	Yearly	Summer	Winter
Mean (mm)	612.39	525.00	85.64
Percentage of yearly total		85.78	14.22
Standard deviation (mm)	143.15	153.44	33.108
Minimum rainfall (mm)	364.64	271.48	26.50
Maximum rainfall (mm)	1000.36	900.54	159.56
Trend (mm/year or season)	1.92	1.61	-0.37
Correlation	0.17	0.13	-0.09
Total change calculated from the trend (mm/43 years)	-304.59	-308.35	-23.22
Total change calculated from the trend (%)	-45.26	-47.23	-22.56

Rainfall data for the North West province

Rainfall	Yearly	Summer	Winter
Mean (mm)	605.83	513.80	89.95
Percentage of yearly total		84. 8	15.2
Standard deviation (mm)	133.61	133.10	52.11
Minimum rainfall (mm)	341.85	320.96	17.30
Maximum rainfall (mm)	922.01	879.78	224.006
Trend (mm/year or season)	-1.09	-0.4	-1.25*
Correlation	-0.10	-0.03	-0.26
Total change calculated from the trend (mm/43 years)	-272.86	-242.69	0.93
Total change calculated from the trend (%)	-39.51	-39.88	1.07

Rainfall data for Gauteng province

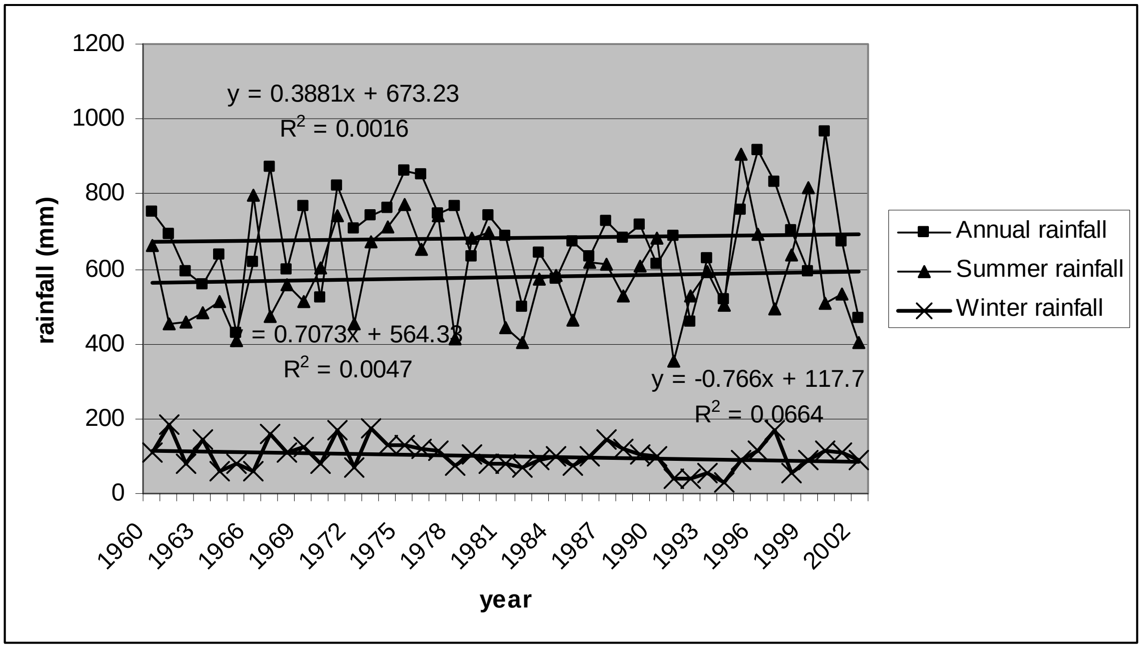
Rainfall	Yearly	Summer	Winter
Mean (mm)	687.71	588.58	97.67
Percentage of yearly total		85.58	14.42
Standard deviation (mm)	133.91	135.72	43.37
Minimum rainfall (mm)	429.36	353.65	18.43
Maximum rainfall (mm)	971.45	965.29	212.59
Trend (mm/year or season)	0.33	0.85	-1.11*
Correlation	0.03	0.08	-0.27
Total change calculated from the trend (mm/43 years)	-190.62	-162.17	-8.37
Total change calculated from the trend (%)	-28.26	-26.73	-8.55

Table 5. Continued

Rainfall data for Mpumalanga province			
Rainfall	Yearly	Summer	Winter
Mean (mm)	821.11	692.16	124.19
Percentage of yearly total		84.29	15.71
Standard deviation (mm)	140.03	137.95	44.46
Minimum rainfall (mm)	554.93	442.57	41.20
Maximum rainfall (mm)	1197.05	1077.90	255.27
Trend (mm/year or season)	0.37	0.7	-1.25*
Correlation	0.03	0.07	-0.22
Total change calculated from the trend (0C/43 years)	-361.70	-310.26	-53.25
Total change calculated from the trend (%)	-37.56	-40.22	-33.70

Notes: *P <0.05 Student's t-test, N=43.
Total change is the difference between the trend line value of the first and last years.

Figure 5. Limpopo River Basin rainfall trend (1960-2003)



5.2. Spatial Clustering of Climate Change Perceptions

As shown in the above section, a large number of farmers believe the climate has become hotter and drier. As suggested by Maddison (2006), this perception might be a case of prominence bias in questionnaires dealing with climate change. It's likely that some respondents provided answers during the interview that the enumerators were more interested in hearing. Thus, validation of the respondent's assessment of climate change with his/her neighbors' responses would provide more confidence that the responses were objective and not subjective.

We employed Moran's I[4]test for spatial autocorrelation with an inverse distance weights matrix on the portion of farmers who perceive particular types of climate change within a given area. The results (see Table 6) suggested that neighboring farmers agree that temperature is increasing and rainfall is

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[4] For further details on Moran I test see Cliff, A. D., Ord, J. K. 1981. Spatial processes, Pion.
Ho: spatial independence.

decreasing with a change in the timing. These results are evidence that farmers are capable of perceiving changes in climate. Thus, neighboring farmers tell a consistent story.

Table 6. Moran's I Test for spatial correlation of climate change perception

Perception of temperature	Moran I statistics	Perception of rainfall	Moran I statistics
Increased temperature	0.044**	**Increased rainfall**	-0.013
Decreased temperature	0.002	**Decreased rainfall**	0.125**
More or less extreme	0.001	**Change in the timing**	0.051**
No change	-0.003	**Change in frequency of droughts/floods**	-0.007
		No change	0.003

Note: ** significant at 1% level * significant at 5% level

5.3. What Types of Farmers Perceive Climate Change?

To answer the questions regarding which types of farmers perceive climate change, farmers' perceptions of climate change have been classified according to their years of experience and their level of education. In Appendix B, we distinguish the responses of farmers having less than 10 years, between 10 and 30 years, and 30 or more years of experience. For the level of education, we distinguish four classes: (1) no formal education, (2) standard education, (3) secondary education, and (4) tertiary education. Using the Kruskal-Wallis test, a nonparametric test, we assess if the perceptions of climate according experience level and education level differed significantly.

The results show that a slightly higher proportion of farmers with more than 30 years of experience claimed that temperature is increasing and rainfall is decreasing, and noted change in the frequency of droughts and floods. Farmers with more than 30 years of experience are also less likely to claim no change in temperature and no change in rainfall. However, the Kruskal-Wallis test indicated that the views between experienced and inexperienced farmers are statistically not significant. The results also indicated that there is statistically no difference between the views of the educated and less-educated farmers.

The above results do not indicate whether the results are sensitive to other factors; therefore, we analyze which types of farmers are likely to notice climate change (temperature and/or rainfall changes) by running a probit model. Rather than present results for each category of climate change perception, we limit the analysis to explaining the twin perception of change in both temperature and precipitation. Because these two perceptions are likely to be correlated, we run a seemingly unrelated biprobit model. The independent variables are education, farming experience, farm size, whether or not a crop farm, soil characteristics, irrigation, access to extension services, access to climate information, and region dummy for Gauteng. These results are adjusted for clustering at the district level on the assumption that the responses from farmers in the same district are likely to be related anyway.

The results displayed in Table 7 below show the following:

1. Education seems to decrease the probability that the farmer will perceive long-term changes in rainfall. Thus, educated farmers are more likely to see that rainfall does not have a significant trend over the long run.
2. With experience, farmers are more likely to perceive change in temperature.
3. Farmers who have access to water for irrigation purposes are unlikely to perceive any change in the climate whether in temperature or rainfall. Indeed, having access to water increases the resilience of farmers to climate variability.
4. Access to extension, on the other hand, increases the probability of perceiving change in temperature.

5. The results also confirm that being in Gauteng (the biggest province where agriculture is a small part of the economy) decreases the probability of perceiving climate change.
6. Farmers with highly fertile soil are less likely to perceive change in temperature but more likely to perceive change in rainfall.

Table 7. Results of the seemingly unrelated biprobit model of farmers' perception of change in the climate, Limpopo River Basin

	Perceive change in temperature	**Perceive change in rainfall**
Education	-0.0049	-0.0371***
Farming experience	0.0136*	0.0048
Farm size	0.2900	-0.3474
Crop farm	0.0822	-0.0219
Infertile soil	-0.3838	0.0994
Highly fertile soil	-0.3231**	0.6542**
Access to water for irrigation	-0.5917**	-0.7279**
Access to extension services	0.3361**	0.2271
Access to climate information	-0.0101	0.2044
Gauteng dummy	-0.6374***	.245423
Intercept	1.91923 ***	2.4828***
Log likelihood: -186.0339		
Number of observations: 632		
Athrho: 0.8027***		
Rho: 0.6655		

Notes: The coefficient indicated the impact of a marginal change on the probability, while dF/dx is for discrete change of dummy variable from 0 to 1.

Dummy variable for Gauteng is included because in the descriptive analysis, 16% of farmers from Gauteng did not perceive climate change.

Clustering at district level.

Wald test of rho=0: chi2(1) = 28.5094 Prob > chi2 = 0.0000

*** significant at 1% level; ** significant at 5% level; * significant at 10% level.

6. MODELING FARMERS' ADAPTATION OPTIONS TO CLIMATE CHANGE AND VARIABILITY

This section describes the approach adopted by the study to model adaptation options to climate change and variability by farmers in the Limpopo River Basin as follows: (6.1) the adaptation choices in the study area, (6.2) the analytical framework, (6.3) the factors hypothesized to influence farmers' adaptation options, and (6.4) the empirical models and the results.

Nevertheless, empirical assessment of actual adaptive behavior is advocated, even though such behavior is place- and time-specific and more likely represents a response to interperiodic climatic variability, as well as to multiple nonclimatic risks and opportunities (Belliveau et al. 2006).

Understanding the likely adaptive responses of farmers to anticipated climate change represents serious challenges for researchers. One major challenge is to isolate the climate stimuli response from other stimuli (market, policy, etc.) that farmers face in the real world. Secondly, farmers are more concerned with and respond more to short-term climate variability than climate change. However, the ability of farmers to cope with current climate variability is an important indicator of their capacity to adapt to future climate change. Thirdly, as Belliveau et al. (2006) mention, a more fundamental barrier to improved knowledge of climate change adaptation derives from the simple fact that humans can respond in highly variable ways to similar external stimuli.

6.1. Adaptation Options in the Study Area

This section focuses on the various adjustments that farmers in the survey made in their farming activities if they perceived changes in the climate. Even though a large number of farmers interviewed noticed changes in climate, almost two-thirds did not undertake any remedial actions. More than 53 percent of farmers cited lack of access to credit, poverty, and lack of savings as the main barriers to adaptation. Despite perceiving a decrease in the volume of rainfall, 20 percent of farmers are not irrigating because they do not have access to water. In the Limpopo province, the claim of no access to water is about 32 percent. Insecure property rights and lack of markets are also cited as significant barriers to adjustments. Few farmers (1.9 percent) designated lack of information or knowledge of appropriate adaptation measures as barriers to adaptations (Table 8).

Table 8. Barriers to adaptation in the Limpopo River Basin (% of the respondents)

	Lack of information about long-term climate change	Lack of knowledge concerning appropriate adaptations	Lack of credit or savings / poverty	No access to water	Insecure property rights	Lack of market access poor transport links	Other	No barriers to adaptation
Total Basin	6.03	1.95	53.9	20.75	9.57	6.21	10.99	0.78
Limpopo	4.32	2.65	24.24	32.58	14.27	10.3	7.97	8.31
North West	10.47	0.00	54.65	3.49	3.49	1.16	9.3	22.09
Gauteng	0.00	0.00	32	12	0.00	4	20	10
Mpumalanga	8.56	1.98	48.04	8.56	5.92	1.32	13.10	23.03

Indeed, in the Limpopo River Basin only 30 percent of respondents made adjustments to their farming practices in response to perceived increases in temperature, and 33 percent in response to changes in rainfall patterns. A number of adaptation options are identified. However, the responses to perceived rainfall and perceived temperature changes differ. The main adjustments in farming activities are discussed below.

6.1.1. Farmers' Responses in the Face of Increased Temperature

Eight adaptation measures could be identified in the Limpopo River Basin as farmers' responses to increased temperature (Table 9): planted different crops (6.86 percent), changed crop variety (3 percent), changed planting dates (3.69 percent), increased irrigation (3.96 percent), used crop diversification (1 percent), changed the amount of land under cultivation or grazed (3.43 percent), and invested in livestock by buying feed supplements (3.69 percent); other adaptation measures were cited by 5 percent of farmers.

Table 9. Adaptations options in response to change in temperature (% of respondents)

	Change crop variety	**Irrigate more**	**Feed supple-ments**	**Different crops**	**Crop diversification (mixed/ multi-cropping)**	**Different planting dates**	**Change amount of land under cultivation or grazed**	**Other[5]**	**No adaptation**
Total Basin	3.03	3.96	3.69	6.86	0.53	3.69	3.43	5.01	**69.39**
Limpopo	1.21	3.38	3.62	9.66	0.97	3.62	4.11	4.83	**67.87**
North West	3.92	1.96	5.88	3.92	0.00	0.98	1.96	2.94	**78.43**
Gauteng	2.27	6.82	4.55	0.00	0.00	6.82	2.27	6.82	**70.45**
Mpumalanga	6.57	5.56	2.53	4.04	0.00	4.55	3.03	6.06	**67.68**

6.1.2. Farmers' Responses in the Face of Reduced Rainfall and Disrupted Rainfall Patterns

Among those who did adjust to changes in rainfall patterns (Table 10), 88 farmers (11.56 percent) engaged in irrigation, 3.81 percent for a new water scheme, and 7.75 percent for increased in irrigation). Farmers also used different crops (4.7 percent), shifted their planting dates to match the delay in rainfall (3 percent), changed the amount of land under cultivation or grazed (2.76 percent), and invested in livestock by buying feed supplements (2.23 percent).

The adaptations induced by perceptions of changing rainfall patterns seem to differ from those induced by perceptions of changing temperature. While adopting a new crop variety is the main strategy used to adapt to increasing temperature, building water-harvesting schemes is a popular adaptation strategy to those experiencing the effects of decreased precipitation.

Table 10. Adaptations in Response to Changes in Rainfall (% of respondents)

	Change crop variety	**Build a water-harvesting scheme**	**Irrigate more**	**Buy feed supplements**	**Different crops**	**Different planting dates**	**Change amount of land under cultivation or grazed**	**Other**	**No adaptation**
Total Basin	0.66	3.81	7.75	2.23	4.99	4.73	2.76	5.12	**67.94**
Limpopo	0.72	3.61	4.82	2.41	6.75	3.13	4.34	4.34	**69.88**
North West	0.00	1.94	13.99	3.88	2.91	3.88	0.00	4.85	**68.06**
Gauteng	0.00	4.55	4.55	2.27	2.27	9.09	0.00	4.55	**72.73**
Mpumalanga	1.01	5.03	11.56	1.01	3.02	7.54	1.51	7.04	**62.31**

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[5] Other adaptation measures: (1) implement soil conservation techniques; (2) put trees for shading; (3) change from crops to livestock; (4) reduce number of livestock; (5) migrate to urban area; and others.

6.2. Analytical Framework

The decision of whether or not to use any adaptation option could fall under the general framework of utility and profit maximization.

Consider a rational farmer who seeks to maximize the present value of expected benefits of production over a specified time horizon, and must choose among a set of *J* adaptation options.

The farmer *i* decides to use *j* adaptation option if the perceived benefit from option *j* is greater than the utility from other options (say, *k*) depicted as

$$U_{ij}\left(\beta_j' X_i + \varepsilon_j\right) > U_{ik}\left(\beta_k' X_i + \varepsilon_k\right), k \neq j\,, \tag{1}$$

where U_{ij} and U_{ik} are the perceived utility by farmer *i* of adaptation options *j* and *k,* respectively; X_i is a vector of explanatory variables that influence the choice of the adaptation option; βj and βk are parameters to be estimated; and εj and εk are the error terms.

Under the revealed preference assumption that the farmer practices an adaptation option that generates net benefits and does not practice an adaptation option otherwise, we can relate the observable discrete choice of practice to the unobservable (latent) continuous net benefit variable as $Y_{ij} = 1$ if $U_{ij} > 0$ and $Y_{ij} = 0$ if $U_{ij} < 0$. In this formulation, Y is a dichotomous dependent variable taking the value of 1 when the farmer chooses an adaptation option in question and 0 otherwise.

The probability that farmer *i* will choose adaptation option *j* among the set of adaptation options could be defined as follows:

$$\begin{aligned} P(Y = 1/X) &= P\left(U_{ij} > U_{ik} / X\right) \\ &= P\left(\beta_j' X_i + \varepsilon_j - \beta_k' X_i - \varepsilon_k > 0 / X\right) \\ &= P\left(\left(\beta_j' - \beta_k'\right) X_i + \varepsilon_j - \varepsilon_k > 0 / X\right) \\ &= P(\beta^* X_i + \varepsilon^* > 0 / X) = F(\beta^* X_i)\,, \end{aligned} \tag{2}$$

where ε* is a random disturbance term, β* is a vector of unknown parameters that can be interpreted as the net influence of the vector of explanatory variables influencing adaptation, and F (β*Xi) is the cumulative distribution of ε* evaluated at β*Xi. Depending on the assumed distribution that the random term follows, several qualitative choice models such a linear probability, logit, or probit model could be estimated (Greene 2003). The logit and probit models are the most common models used in the literature. Indeed, they have desirable statistical properties as the probabilities are bound between 0 and 1 (Greene 2003).

Given that we investigate several adaptation choices, the appropriate econometric model would, thus, be either a multinomial logit (MNL) or multinomial probit (MNP) regression model. Both models estimate the effect of explanatory variables on a dependent variable involving multiple choices with unordered response categories.

In this study, therefore, an MNL specification is adopted to model climate change adaptation behavior of farmers involving discrete dependent variables with multiple choices. Thus, the probability that household i with characteristics X chooses adaptation option j is specified as follows:

The main attractive feature of the MNP model is that it allows a rather general covariance structure for the alternative-specific errors. However, because observed choices only reveal information regarding utility differences, and because scale cannot be determined, not all parameters in an arbitrary MNP specification may be identified (Bunch 1991). With recent advances in computational methods, some researchers have developed techniques for the estimation of the MNP. A more recent method is the Geweke-Hajivassiliou-Keane (GHK) smooth recursive conditioning stimulator used to calculate multivariate normal probabilities of maximum likelihood estimation to evaluate trivariate and higher dimensional normal distributions, based on the works of Cappellari and Jenkins (2003, 2005, 2006).

However, there is still a relative dearth of successful empirical applications of MNP in the published literature (Bunch 1991; Tizale 2007).

$$P_{ij} = prob(Y=1) = \frac{e^{x'\beta}}{1+\sum_{j=1}^{j} e^{x'\beta}} \text{, } \mathbf{j=1....j,} \tag{3}$$

where β is a vector of parameters that satisfy ln $(P_{ij}/P_{ik}) = X'(\beta j - \beta k)$ (Greene 2003).

Unbiased and consistent parameters estimates of the MNL model in Equation 3 require the assumption of independence of irrelevant alternatives (IIA) to hold. Specifically, the IIA assumption requires that the likelihood of a household's using a certain adaptation measure needs to be independent of other alternative adaptive measures used by the same household. Thus, the IIA assumption involves the independence and homoscedastic disturbance terms of the adaptation model in Equation 1. The validity of the IIA assumption could be tested using Hausman's specification, which is based on the fact that if a choice set is irrelevant, eliminating a choice or choice sets from the model altogether will not change parameter estimates systematically.

Differentiating Equation 3 with respect to each explanatory variable provides marginal effects of the explanatory variables given as

$$\frac{\partial P_j}{\partial x_k} = P_j\left(\beta_{jk} - \sum_{j=1}^{j-1} P_j \beta_{jk}\right). \tag{4}$$

Using the MNL model for our analysis gives rise to a sample selectivity problem because only those who perceive climate change will adapt. Indeed, adaptation to climate change begins with two processes: first, perceiving change, and then, deciding on a particular adaptation choice. Therefore, the correct modeling of the adaptation behavioral to climate change implies the use of a sample selectivity model or a two-period framework (t=0, observation of the climate change; and t=1, adaptation choice is made). However, the two-period choice model is a complicated model to estimate (Dagsvik 2000). Also, a review of applied literature[6] on selectivity bias correction methods did not reveal a two-stage model that uses a multivariate choice model as the outcome equation. Therefore, both the Heckman sample selectivity probit model and the MNL model are used to study the determinants of adaptation to climate change.

- **Heckman sample selectivity probit model**

Following Maddison (2006), Heckman's sample selectivity probit model is based on the following two latent variables:

$$Y_1 = b'X + U_1 \tag{5}$$

$$Y_2 = g'Z + U_2, \tag{6}$$

where X is a k-vector of regressors; Z is an m-vector of regressors, possibly including 1's for the intercepts; and the error terms U_1 and U_2 are jointly normally distributed, independently of X and Z, with zero expectations. Although we are primarily interested in the first model, the latent variable Y_1 is only observed if $Y_2 > 0$. Thus, the actual dependent variable is:

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[6] We found in the literature that following the seminal insight of Heckman (1979), two traditional approaches suggested by Lee (1983) and Dubin and McFadden (1984) are applied when the selection model is a multinomial logit, and in the outcome equation the dependent variable is a continuous variable. We also found that Dagsvik (2000) has developed a theoretical model where the two stages are MNL model; however, a successful application of this model still has to be verified.

$$Y = Y_1 \text{ if } Y_2 > 0,\ Y \text{ is a missing value if } Y_2 <= 0. \qquad (7)$$

The latent variable Y_2 itself is not observable, only its sign. We only know that $Y_2 > 0$ if Y is observable, and Y2 <= 0 if not. Consequently, we may without loss of generality normalize U2 such that its variance is equal to 1. If we ignore the sample selection problem and regress Y on X using the observed Y's only, then the ordinary least squares (OLS) estimator of b will be biased, because

$$E[Y_1|Y_2 > 0, X,Z] = \mathrm{b}'X + \mathrm{rs}f(\mathrm{g}'\mathrm{Z})/F(\mathrm{g}'\mathrm{Z}), \qquad (8)$$

where F is the cumulative distribution function of the standard normal distribution, f is the corresponding density, s^2 is the variance of U_1, and r is the correlation between U_1 and U_2. Hence,

$$E[Y_1|Y_2 > 0, X] = \mathrm{b}'X + \mathrm{rs}E[f(\mathrm{g}'\mathrm{Z})/F(\mathrm{g}'\mathrm{Z})|X]. \qquad (9)$$

The latter term causes sample selection bias if r is nonzero. In order to avoid the sample selection problem, and to get asymptotically efficient estimators, the model parameters are estimated by maximum likelihood.

6.3. Choice of Variables and Hypotheses to be Tested

Based on the above information about adaptation choices, the choice sets considered in the adaptation model include 10 variables:

1. Change crop variety
2. Intensification irrigation
3. Water-harvesting scheme
4. Plant different crops
5. Crop diversification/mixing
6. Change planting date
7. Change amount of land
8. Livestock feed supplements
9. Other
10. No adaptation

Much of what we know about the research question (farm and farmers’ characteristics related to adaptive capacity and propensity) in the adaptation process derives from the vast body of research on the dynamics of agricultural development and the diffusion of agricultural practices. Based on the review of literature on adoption of new technologies and adaptation studies, a range of household and farm characteristics, institutional factors, and other factors that describe local conditions are hypothesized to influence farmers’ adaptation choice in the Limpopo River Basin.

- Household characteristics

Generally the household characteristics considered to have differential impacts on adoption or adaptation decisions are age, education level and gender of the head of the household, family size, years of faming experience, and wealth.

According to Adesina and Forson (1995) cited by Teklewold et al. (2006), there is no agreement in the adoption literature on the effect of age. The effect of age is generally location- or technology-specific. The expected result of age is an empirical question. We may found that age negatively influence the decision to adopt new technologies. It may be that older farmers are more risk-averse and less likely to be flexible than younger farmers and thus have a lesser likelihood of adopting new technologies. In another case, we may found that age positively influence the decision to adopt. It could also be that older farmers have more experience in farming and are better able to assess the characteristics of modern technology than younger farmers, and hence a higher probability of adopting the practice.

Higher level of education is often hypothesized to increase the probability of adopting new technologies (Daberkow and McBride 2003; Adesina and Forson 1995). Indeed, education is expected to increase one's ability to receive, decode, and understand information relevant to making innovative decisions (Wozniak 1984).

Gender of the household head is hypothesized to influence the decision to adopt changes. The way gender influences adaptation is location-specific. A number of studies in Africa have shown that women have lesser access to critical resources (land, cash, and labor), which often undermines their ability to carry out labor-intensive agricultural innovations (De Groote and Coulibaly 1998, Quisumbing et al. 1995). However, a recent study by Nhemachena and Hassan (2007), based on Southern Africa, finds that female-headed households are more likely to take up climate change adaptation methods. According to the authors, the possible reason for this observation is that in most rural smallholder farming communities in the region, men are more often based in towns, and much of the agricultural work is done by women. Therefore, women have more farming experience and information on various management practices and how to change them, based on available information on climatic conditions and other factors such as markets and food needs of the households.

Wealth is believed to reflect past achievements of households and their ability to bear risks. Thus, households with higher income and greater assets are in better position to adopt new farming technologies (Shiferaw and Holden, 1998).

Farming experience increases the probability of uptake of all adaptation options because experienced farmers have better knowledge and information on changes in climatic conditions and crop and livestock management practices (Nhemachena and Hassan 2007).

The influence of household size on the decision to adapt is ambiguous. Household size as a proxy to labor availability may influence the adoption of a new technology positively as its availability reduces the labor constraints (Teklewold et al. 2006). However, according Tizale (2007), there is a possibility that households with many family members may be forced to divert part of the labor force to off-farm activities in an attempt to earn income to ease the consumption pressure imposed by a large family size.

- Farm characteristics

Institutional factors often considered in the literature to influence adoption of new technologies are access to information via extension services (climate information and production technologies), access to credit, off-farm employment, and land tenure.

Agricultural extension enhances the efficiency of making adoption decisions. In the world of less-than-perfect information, the introduction of new technologies creates a demand for information useful in deciding on adopting new technologies (Wozniak 1984). Of the many sources of information available to farmers, agricultural extension is the most important for analyzing the adoption decision. Based on the innovation-diffusion literature (Adesina and Forson 1995), it is hypothesized that access to extension services is positively related to adoption of new technologies by exposing farmers to new information and technical skills. Also, in the specific case of climate change adaptation, access to climate information may increase the likelihood of uptake of adaptation techniques.

Another variable that has received attention is access to credit, which commonly has a positive effect on adaptation behavior (Caviglia-Harris 2002; Saín and Barreto 1996; Napier 1991; and Hansen et al. 1987). Any fixed investment requires the use of owned or borrowed capital. Hence, the adoption of a technology requires a large initial investment, which may be hampered by lack of borrowing capacity (El Osta and Morehart 1999).

The occupation of the farmer is an indication of the total amount of time available for farming activities. Off-farm employment may present a constraint to adoption of technology because it competes for on-farm managerial time (McNamara et al. 1991).

Similarly, land tenure can contribute to adaptation, because landowners tend to adopt new technologies more frequently than tenants, an argument that has justified numerous efforts to reduce tenure insecurity (Lutz et al. 1994; Shultz et al. 1997). Land ownership is widely believed to encourage the adoption of technologies linked to land such as irrigation equipment or drainage structures. Land ownership is likely to influence adoption if the innovation requires investments tied to land.

- Others factors

Local climatic conditions and agro-ecological conditions are expected to influence the decision to adapt. We therefore included district level climate variables (temperature and rainfall). Further to take into account spatial autocorrelation and neighborhood effects, we included latitude and longitude references for each household. Finally we included dummy variables for provinces to take into account any specific institutional arrangements having bearing on the ability of their farmers to adapt to climate change.

Table 11 provides the variables hypothesized to determine adaptation behavior, a brief description of each variable, its value, and expected sign in relation to adoption of new technologies.

The farm characteristics hypothesized to influence adaptation in this study are farm size (large-scale or small-scale) and soil fertility.

Farm size. Adoption of an innovation will tend to take place earlier on larger farms than on smaller farms. Daberkow and McBride 2003 show that given the uncertainty and the fixed transaction and information costs associated with innovation, there may be a critical lower limit on farm size that prevents smaller farms from adapting. As these costs increase, the critical size also increases. It follows that innovations with large fixed transaction and/or information costs are less likely to be adopted by smaller farms.

Soil fertility. Farmers' perceptions that their lands are infertile may be a first step in the adaptation process. They may therefore be more likely to adopt any adaptation techniques that will help improve their productivity.

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Local climatic conditions and agro-ecological conditions are expected to influence the decision to adapt. We therefore included district level climate variables (temperature and rainfall). Further to take into account spatial autocorrelation and neighborhood effects, we included latitude and longitude references for each household. Finally we included dummy variables for provinces to take into account any specific institutional arrangements having bearing on the ability of their farmers to adapt to climate change.

Table 11 provides the variables hypothesized to determine adaptation behavior, a brief description of each variable, its value, and expected sign in relation to adoption of new technologies.

Table 11. Variables hypothesized to affect adaptation decisions by farmers in the Limpopo River Basin

Variable	Description	Value	Expected sign
	Household characteristics		
Age	Age of the head of the farm household	Years	Cannot be signed a priori (+ or -)
Education	Number of years of formal schooling attained by the head of the household	Years	Positive
Gender	Gender of the head of the farm household	1= male, 0= female	Cannot be signed a priori (+ or -)
Household size	Number of family members of a household	Number	Cannot be signed a priori (+ or -)
Farming experience	Number of years of farming experience for the household head	Years	Positive
Wealth	An index[7] was constructed using household ownership of seven households' assets: a television, radio, flushing toilet, cell phone, brick house, refrigerator, and car.	number	Positive
	Farm characteristics		
Farm size	Determine if the farm is large-scale or small-scale	1= large scale 0= small scale	Positive
Soil fertility	Farmer's own perception of the fertility level of his land. Three dummies: infertile, fertile, and highly fertile.	0 or 1	Positive

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[7] Following Filmer and Pritchett 2001, principal component analysis (PCA) was used to assign weights to each asset. The overall wealth index is calculated by applying the following formula:

$$w_j = \sum_{i=1}^{k} \left[b_i \left(a_{ji} - x_i \right) \right] / s_i$$

where w is the wealth index, b is the weights from PCA 1, a is the asset value, x is the mean asset value, and s is the standard deviation of the assets.

Table 11. Continued

Variable	Description	Value	Expected sign
Institutional factors			
Extension	If household has access to extension services	1=yes, 0= no	Positive
Climate information	If household gets information about weather, climate from any source (extension officers, TV, radio, etc.)	1=yes, 0= no	Positive
Credit	If household has access to credit from any sources	1=yes, 0= no	Positive
Off-farm employment	Income from off-farm activities during the survey year		Cannot be signed a priori (+ or -)
Tenure	If land use is owned or rented/share-cropped, etc.	1= owned 0= otherwise	Positive
Others factors			
Temperature	Average temperature between 1960 and 2003	degree Celsius	Positive
Rainfall	Average rainfall between 1960 and 2003	Mm	Negative
Latitude		degree centigrade	
Longitude		degree centigrade	
Limpopo	If household farm in Limpopo province	1=yes, 0= no	Cannot be signed a priori (+ or -)
North west	If household farm in North West province	1=yes, 0= no	Cannot be signed a priori (+ or -)
Gauteng	If household farm in Gauteng province	1=yes, 0= no	Cannot be signed a priori (+ or -)
Mpumalanga	If household farm in Mpumalanga province	1=yes, 0= no	Cannot be signed a priori (+ or -)

6.4. The Empirical Models and Results

In this section, two models for adaptation choices to climate change in the Limpopo River Basin are estimated by using the statistical software Stata version 9.0: the Heckman probit and the MNL model. The analysis is based on cross-sectional data collected in the Limpopo River Basin. Before initial runs of the model, the data were checked for the presence of any multicollinearity in the data set. Among the variables hypothesized to influence adaptation, age of the head of household was found to be correlated inversely with education ($\rho = -0.39$) and positively with farming experience ($\rho = 0.30$) and extension and climate information ($\rho = 0.25$). Although these correlations coefficients do not suggest incidence of strong collinearity, age was dropped from the model (see Appendix Table B.4). Appendix Table B.5 provides the summary statistics of the independent variables included in the analysis.

6.4.1. Modeling Adaptation with the Heckman Probit Model

This section presents the results of the Heckman probit adaptation model. The model determines the likelihood of perceiving any change in the climate as well as the likelihood of farmers' adapting to these changes. The dependent variable for the selection equation is binary indicating whether or not a farmer perceives climate change; the dependent variable for the outcome equation is also binary indicating whether or not a farmer responded to the perceived changes by adapting farming practices. The explanatory variables are those discussed in the previous section, and "access to water for irrigation" is also included in the selection equation. The likelihood function for the Heckman probit model was significant (Wald $\chi 2 = 36.26$ with $P<0.001$), showing a strong explanatory power.

As shown in Table 12, access to water for irrigation, access to irrigation services, and living in Gauteng influence the likelihood of perceiving climate change. On the other hand, farming experience, farm size, soil fertility, access to extension, access to credit, land tenure status, and region influence the probability of adapting to climate change.

Table 12. Results of the Heckman probit model of adaptations behavior in the Limpopo River Basin

Variables	Estimated coefficients outcome equation: adaptation model	Estimated coefficients selection equation: perception model
Access to water for irrigation		-0.621***
Education	-0.011	-0.012
Gender	0.134	-0.088
Farming experience	0.01***	0.006
Wealth	0.114	0.051
Farm size	0.649***	-0.036
High fertility of soil	-0.142*	-0.005
Extension	0.179*	0.364***
Access to climate info	-0.1	-0.115
Credit	0.232*	-0.0650
Off-farm employment	0.127	0.0472
Land tenure	0.268***	0.0359
Mpumalanga	-0.006	-0.031
Gauteng	-0.603***	-0.527**
North West	-0.445***	-0.029
Intercept	-0.6615***	1.83***
Wald test (zero slopes)	36.26***	
Wald test (independent equations)	0.47	
Total observations	577	
Censored observations	43	

Note: *** significant at 1% level ** significant at 5% level * significant at 10% level

As expected, experienced farmers are more likely to adapt. Likewise, farm size positively and significantly leads to an increase in the likelihood of adapting to climate change. Farmers' perception of having highly fertile soil decreases the probability of taking up adaptation in response to changes in the climate. Access to extension services increases the likelihood of perceiving changes in climate as well as the likelihood of adaptation. This suggests that extension services help farmers to take climate changes and weather patterns into account and help advise them on how to tackle climatic variability and change. The results also show important regional variation. Farmers in Limpopo province are more likely to adapt compared with farmers in the other provinces. Indeed, in Limpopo, the population is largely rural (82 percent), and the main rural economic activity is agriculture.

6.4.2. Modeling Adaptation with the Multinomial Logit Model

This section presents the empirical results of the MNL adaptation model. The MNL, as specified in section 6.3 with 10 adaptation options, failed to produce satisfactory results in terms of the significance level of the parameters estimates and also in terms of the validity of the independence of irrelevant alternatives (IIA) assumption. The model was thus restructured by grouping three closely related choices together in the same category. The replacement of plant-type cultivars with new varieties, the adoption of new crops, and multicropping and mixed farming systems of crops and livestock were grouped in the same category, labeled "portfolio diversification." Indeed, these three choices are closely related because they are considered for the same purpose of risk-spreading. Also, we aggregate intensification irrigation and water-harvesting scheme into the same category, irrigation, because both are related to the use of water for the purpose of increasing productivity and withstanding rainwater shortages.

Accordingly, the choice set in the restructured MNL model included the following adaptation options:

1. Portfolio diversification
2. Irrigation
3. Change planting date
4. Change amount of land
5. Livestock feed supplements
6. Other
7. No adaptation

The MNL adaptation model with these restructuring choices was run and tested for the IIA assumption using the Hausman specification test. The test failed to reject the null hypothesis of independence of the included "change amount of land under cultivation," suggesting there is no evidence against the correct specification for the adaptation model, $\chi2 = -0.375$ with P value of 0.9311. Therefore, the application of the MNL specification to the data set for modeling climate change adaptation behavior of farmers is justified.

Appendix Table B.6 and Table 13 present the estimated coefficients and the marginal effects, respectively. The likelihood ratio statistics as indicated by $\chi2 = 291.07$ are highly significant at 1 percent, suggesting strong explanatory power of the model. It is important to note that the estimated coefficients should be compared with the base category of not adopting any of the adaptation choices.

There is a 70 percent probability of farmers not adapting in face of climate change and variability. Following are the household characteristics included in the model:

Household size. A large household will be more willing to choose the "Other" category as an adaptation option. The "Other" category includes adaptations such as soil conservation techniques, chemical treatments that are labor-intensive especially in small-scale farming, which involves household labor.

Farming experience. Experienced farmers have an increased likelihood of using portfolio diversification, changing planting dates, and changing the amount of land under production. These results confirm the findings of Nhemachena and Hassan (2007) in a similar study of adaptation in the Southern Africa region. Experienced farmers have high skills in farming techniques and management and are able to spread risk when facing climate variability by exploiting strategic complementarities between activities such as crop-livestock integration.

Wealth. Wealthier households are more willing to adapt by changing their planting dates. Surprisingly, the results suggested that education level and gender did not have a significant impact on the probability of choosing any adaptation technique.

The farm characteristics included in the model are as follows:

- Farm size. The coefficient on farm size is significant and positively correlated with the probability of choosing irrigation as an adaptation measure. Indeed, large-scale farmers are more likely to adapt because they have more capital and resources. Therefore, they can easily invest in irrigation technologies, which demand high investment costs.
- Soil fertility. The perception of having highly fertile soil increases the probability that farmers will change their amount of land under cultivation.

Following are the institutional factors:

- Access to extension services. With an increased probability of taking up portfolio diversification, farmers who have access to extension services are more likely to be aware of changing climatic conditions (confirmed by the Heckman probit model, above) and to have knowledge of the various management practices that they can use to adapt to changes in climatic conditions. It appears that extension messages emphasized risk spreading and farm-level risk management. Having access to extension increases the probability of choosing portfolio diversification by 4 percent. The implementation of the land reform has increased the number of new, emerging farmers who did not have the skills and information gathered by experienced farmers; therefore, extension is of great need in South Africa.

- Access to credit. As expected, access to credit increases the likelihood of adaptation. Poverty or lack of financial resources is one of the main constraints to adjustment to climate change. In a study on Tanzania, O'Brien et al. (2000) reports that despite numerous adaptation options that farmers are aware of and willing to apply, the lack of sufficient financial resources to purchase the necessary inputs and other associated equipment (e.g., purchasing seeds, acquiring transportation, hiring temporary workers) is one of the significant constraints to adaptation. In our study, 60 percent of the respondents who did not adapt cited lack of financial resources as the main constraint to adaptation. The results show that access to credit increases the likelihood that farmers will take up portfolio diversification and buy feed supplements for their livestock. Having access to credit indeed increased the likelihood of choosing portfolio diversification by 3 percent.
- Tenure. Having secure property rights increases the probability of farmers to adapt by 9 percent. With proper property rights, farmers may be able change their amount of land under cultivation to adjust to new climatic conditions.
- Off-farm employment. While off-farm employment may present a constraint to adaptation because it competes for on-farm managerial time (McNamara et al. 1991), the empirical results suggest that off-farm activities increase the likelihood of buying feed supplements for the livestock. This suggests that expanding smallholder farmers' access to off-farm sources of income increases the probability that they will invest in farming activities.
- Temperature and rainfall. Households living in regions with high temperatures have an increased likelihood of adapting. These households are more likely to choose the following adaptation options: (1) portfolio diversification, such as by changing their types of crops (e.g., from maize to sorghum, a more heat-tolerant crop); (2) intensification irrigation; and (3) changing their planting dates. A decrease in rainfall is likely to push farmers to delay their planting dates.

Table 13. Results marginal effects of the MNL adaptation model, Limpopo River Basin

	Portfolio diversification	Irrigation	Changed planting dates	Changed amount of land	Livestock feed supplements	Other	No Adaptation
Education	-0.0023	0.0019	-0.0003	0.0003	-0.0003	0.0009	-0.0003
	(0.39)	(0.50)	(0.82)	(0.56)	(0.62)	(0.49)	(0.94)
Gender	-0.0084	0.0388	0.0115	-0.0034	0.0046	-0.0044	-0.0387
	(0.75)	(0.22)	(0.38)	(0.54)	(0.41)	(0.8)	(0.37)
Household size	-0.0021	0.0058	-0.0002	0.0003	-0.0010	**-0.0041**	0.0013
	(0.60)	(0.25)	(0.94)	(0.79)	(0.25)	**(0.09)***	(0.85)
Farming experience	**0.0020**	0.0007	**0.0011**	**0.0005**	-0.0002	-0.0001	**-0.0039**
	(0.01)***	(0.59)	**(0.03)****	**(0.09)***	(0.47)	(0.8)	**(0.03)****
Wealth	-0.0083	0.0128	**0.0231**	0.0030	0.0010	0.0026	**-0.0343**
	(0.29)	(0.23)	**(0.00)*****	(0.22)	(0.49)	(0.62)	**(0.01)*****
Farm size	0.0536	**0.1176**	0.0034	0.0077	-0.0007	0.0030	**-0.1846**
	(0.32)	**(0.09)***	(0.91)	(0.58)	(0.94)	(0.9)	**(0.05)****
Highly fertile soil	0.0342	0.0314	-0.0066	**0.0125**	0.0080	-0.0148	-0.0648
	(0.21)	(0.39)	(0.64)	**(0.10)***	(0.32)	(0.33)	(0.17)
Infertile soil	-0.0375	-0.0168	0.0091	0.0176	-0.0032	0.0471	-0.0162
	(0.29)	(0.73)	(0.70)	(0.30)	(0.64)	(0.20)	(0.81)
Extension	**0.0434**	-0.0075	0.0138	0.0052	0.0016	-0.0027	**-0.0537**
	(0.09)*	(0.80)	(0.30)	(0.35)	(0.73)	(0.84)	**(0.08)***
Climate information	-0.0257	0.0018	-0.0112	0.0031	-0.0011	0.0172	0.0161
	(0.32)	(0.95)	(0.43)	(0.60)	(0.82)	(0.26)	(0.69)
Credit	**0.0355**	0.0289	-0.0014	-0.0093	**0.0149**	0.0172	**-0.0858**
	(0.06)*	(0.42)	(0.93)	(0.19)	**(0.09)***	(0.37)	**(0.08)***
Off-farm employment	0.0302	-0.0046	0.0006	**-0.0077**	**0.0339**	0.0074	-0.0597
	(0.27)	(0.88)	(0.96)	**(0.09)***	**(0.00)*****	(0.63)	(0.18)
Tenure	0.0112	0.0204	0.0102	**0.0124**	-0.0048	**0.0466**	**-0.0960**
	(0.63)	(0.52)	(0.47)	**(0.10)***	(0.27)	**(0.02)****	**(0.03)****
Latitude	**0.0404**	-0.0208	**-0.0082**	0.0074	-0.0034	0.0020	-0.0174
	(0.03)**	(0.12)	**(0.10)***	(0.14)	(0.13)	(0.69)	(0.41)
Longitude	-0.0132	-0.0020	**0.0175**	0.0060	**-0.0039**	-0.0046	0.0002
	(0.39)	(0.91)	**(0.02)****	(0.17)	**(0.05)****	(0.52)	(0.99)
Rainfall	0.0005	0.0004	**-0.0003**	0.0001	0.0000	-0.0001	-0.0006
	(0.12)	(0.16)	**(0.03)****	(0.36)	(0.87)	(0.68)	(0.12)
Temperature	**0.0133**	**0.0136**	**-0.0114**	0.0005	0.0005	**0.0075**	**-0.0240**
	(0.04)**	**(0.09)***	**(0.00)*****	(0.73)	(0.72)	**(0.07)***	**(0.03)****
Probability	0.09	0.12	0.035	0.01	0.01	0.035	0.7

Notes: *** significant at 1%, ** significant at 5%, * significant at 10%

7. CONCLUSIONS AND POLICY IMPLICATIONS

The statistical analysis of temperature data from 1960 to 2003 in the Limpopo River Basin shows a trend of increasing around 1 degree Celsius, with the increase mostly in the summer period. Over the 43 years examined, rainfall is characterized by large interannual variability with a substantial decrease in the amount of rainfall over the final three years of the data. However, there is a noticeable, long-running trend of decreasing rainfall during winter.

Farmers' perceptions of climatic variability are in line with climatic data records. Indeed, farmers in the Limpopo River Basin of South Africa are able to recognize that temperatures have increased and there has been a reduction in the volume of rainfall. Farmers with access to extension services are likely to perceive changes in the climate because extension services provide information about climate and weather. Having access to water for irrigation increases the resilience of farmers to climate variability; therefore, they do not need to pay as much attention to changes in the patterns of rainfall and temperature. With more experience, farmers are more likely to perceive change in temperature.

Although farmers are well aware of climatic changes, few seem to take steps to adjust their farming activities. Only approximately 30 percent of farmers have adjusted their farming practices to account for the impacts of climate change. The main adaptation strategies of farmers in the Limpopo River Basin are switching crops, changing crop varieties, changing planting dates, increasing irrigation, building water-harvesting schemes, changing the amount of land under cultivation, and buying livestock feed supplements.

The Heckman probit and multinomial logit models are applied to examine the determinants of adaptation to climate change and variability. The results highlight that household size, wealth, farm size, farming experience, perception of soil fertility, extension, access to credit, off-farm activities, property rights, high temperature, and low rainfall are the factors that enhance adaptive capacity to climate change.

Government policies should therefore ensure that farmers have access to affordable credit to increase their ability and flexibility to change production strategies in response to the forecasted climate conditions. Because access to water for irrigation increases the resilience of farmers to climate variability, irrigation investment needs should be reconsidered to allow farmers increased water control to counteract adverse impacts from climate variability and change. However, to promote efficient water use, emphasis should be on pricing reforms and clearly defined property rights, as well as on the strengthening of farm-level managerial capacity of efficient irrigation. More importantly, the implementation of the land reform has increased the number of new, emerging farmers who did not have the skills and information gathered by experienced farmers; therefore, increasing farmers' access to extension services is of great need in South Africa. Furthermore, government should improve off-farm income-earning opportunities.

APPENDIX A: QUESTIONNAIRE ON CLIMATE CHANGE AND ADAPTATION OPTIONS

Section 9: Climate change and adaptation options

9.1 Have you noticed any long-term changes in the mean temperature over the last 20 years? (please explain) Please mark ☐ with x if used.

If too difficult: Has the number of hot days stayed the same, increased, or declined over the last 20 years? (please explain) ☐

9.2 Have you noticed any long-term changes in the mean rainfall over the last 20 years? (please explain) ☐

If too difficult: Has the number of rainfall days stayed the same, increased, or declined over the last 20 years? (please explain) ☐

9.3 What adjustments in your farming have you made to these long-term shifts in temperature? Please list below.

9.4 What adjustments in your farming have you made to these long-term shifts in rainfall? Please list below.

9.5 Check the answers for **9.3** and **9.4** and then ask for the ones not yet listed there: What additional measures would you consider in the future?

9.5.1 Why did you not	9.5.2 Reason (key)
1. change crop variety	
2. build a water-harvesting scheme	
3. implement soil conservation techniques	
4. buy insurance	
5. put trees for shading	
6. irrigate more	
7. change from crop to livestock	
8. reduce number of livestock	
9 migrate to urban area	
10.find off-farm job	
11.lease your land	

Key for 9.5.2: 1: lack of money, 2: lack of information, 3: shortage of labor, 5: Other [write into the lines provided above]

9.6 What were the main constraints/difficulties in changing your farming ways?

9.7 Have you seen any changes in the number of malaria cases over the last 20 years? (please explain)

9.8 Have you seen changes in the vegetation cover over the last 5 years? (please explain)

APPENDIX B: SUPPLEMENTARY TABLES

Table B.1. Perceptions of changes in temperature by farmer experience (%)

	Increased	Decreased	More or less extreme	Others	No change	Don't know
Total population	89.32	1.56	1.56	2.21	5.08	0.26
Low experience 0–10 years	89.01	1.76	1.32	2.64	5.05	0.22
Medium experience 10–30 years	87.50	1.39	2.78	1.85	6.02	0.46
High experience 30 years +	94.85	1.03	0	1.03	3.09	0

Notes: Test: Equality of populations: The Kruskal-Wallis Test; chi-squared = 1.105 with 2 d.f.; probability = 0.5755

Table B.2. Perceptions of changes in rainfall by farmer experience (%)

	Increased	Decreased	Change in timing of rains (earlier/ later/erratic)	Change in frequency of droughts/ floods	Others	No change	Don't know	Decrease in rainfall and change in timing
Total population	1.69	81.25	5.34	0.65	1.43	2.21	0.39	7.03
Low experience 0– 0 years	1.10	78.51	6.14	0.66	1.75	2.41	0.44	8.99
Medium experience 10– 0 years	2.79	86.05	4.19	0.47	0.93	1.86	0.47	3.26
High experience 30 years +	2.06	83.51	4.12	1.03	1.03	2.06	0.00	6.19

Notes: Test: Equality of populations: The Kruskal-Wallis Test; chi-squared = 1.105 with 2 d.f.; probability = 0.5755

Table B.3. Perceptions of changes in temperature by farmer education level (%)

	Increased	**Decreased**	**More or less extreme**	**Others**	**No change**	**Don't know**
Total population	89.32	1.56	1.56	2.21	5.08	0.26
No formal education 0 years	88.00	2.00	2.67	2.00	4.67	0.67
Standard education 1–7 years	91.06	1.63	0.00	0.81	6.50	0.00
Secondary education 8–12 years	89.06	1.29	1.80	2.58	4.38	0.26
Tertiary education 13 years +	87.85	1.87	0.93	2.80	6.54	0.00

Notes: Test: Equality of populations: The Kruskal-Wallis Test; chi-squared = 0.253 with 3 d.f.; probability = 0.9687

Table B.4. Correlation matrix of the independent variables of the adaptation model

	Age	Education	Gender	Household size	Experience	Wealth	Farm size	Infertile soil	Fertile soil	Highly fertile soil	Extension	Climate information
Age	1											
Education	**-0.3924**	1										
Gender	0.1329	0.0743	1									
Household size	0.077	**-0.2063**	0.0261	1								
Experience	**0.3055**	0.0077	-0.0125	0.0093	1							
Wealth	-0.0774	-0.0032	-0.0065	-0.0478	-0.0189	1						
Farm size	-0.0243	0.1391	0.11	-0.0035	0.057	0.0381	1					
Infertile soil	-0.0142	-0.0373	0.0212	0.0329	0.0381	0.0763	-0.0129	1				
Fertile soil	-0.0254	-0.062	-0.0666	0.0052	0.0274	-0.0452	-0.0561	**-0.4209**	1			
Highly fertile soil	0.0415	0.0921	0.0582	-0.0088	-0.0346	-0.0135	0.0772	**-0.2099**	**-0.7724**	1		
Extension	-0.001	-0.0165	-0.0493	-0.0233	-0.122	0.0578	-0.0115	-0.0785	0.0114	0.027	1	
Climate information	0.083	-0.0751	0.0141	0.042	0.0502	-0.0045	0.0173	-0.0595	0.0694	-0.0448	**0.2513**	1
Credit	-0.0625	0.117	0.0347	-0.0081	-0.0339	-0.0186	0.1037	0.0005	-0.0052	-0.0162	-0.0104	-0.1004
Off-farm activities	-0.1075	0.1886	0.052	-0.0053	-0.0583	0.0055	-0.0263	0.0685	-0.0339	-0.0081	0.0309	-0.0981
Tenure	0.0208	0.064	0.1399	-0.0455	-0.0977	0.0258	0.1246	-0.0715	-0.0052	0.0765	0.0805	-0.0427
Temperature	-0.0588	0.0269	-0.0592	0.0887	0.0499	0.0713	0.0785	0.0818	-0.1372	0.0946	-0.0466	-0.0307
Rainfall	0.0079	-0.078	-0.0304	-0.0382	-0.1537	-0.025	-0.0172	-0.1241	0.1844	-0.0937	0.1432	-0.0083
Latitude	-0.0755	0.1206	-0.0867	0.0788	0.1868	-0.0102	0.0713	-0.0428	-0.1509	0.1828	-0.0047	0.0771
Longitude	-0.0709	-0.0797	-0.1112	0.146	-0.0421	0.0007	0.0039	-0.0496	0.0609	-0.0245	0.1268	0.0519
Limpopo	-0.024	0.1145	-0.0467	0.0795	0.1645	-0.0135	0.0268	0.0188	-0.1906	0.1791	-0.0518	-0.0277
Gauteng	-0.0946	0.054	0.1038	-0.0421	-0.0909	-0.0586	-0.0475	-0.0202	0.0267	-0.0087	-0.0099	-0.0825
Mpumalanga	0.0498	-0.2081	-0.0337	0.0388	-0.1657	0.0388	-0.0388	0.0234	**0.2366**	**-0.2584**	0.1398	0.0494
North West	0.0396	0.0645	0.0387	-0.1405	0.0392	0.012	0.0461	-0.0446	-0.047	0.08	-0.1006	0.0367

Table B.4. Continued

	Credit	Off-farm activities	Tenure	Temperature	Rainfall	Latitude	Longitude	Limpopo	Gauteng	Mpumalanga	North West
Age											
Education											
Gender											
Household size											
Experience											
Wealth											
Farm size											
Infertile soil											
Fertile soil											
Highly fertile soil											
Extension											
Climate information											
Credit	1										
Off-farm activities	0.0848	1									
Tenure	0.0874	0.05	1								
Temperature	0.0011	-0.02	-0.1987	1							
Rainfall	0.0764	-0.05	0.1206	**-0.3619**	1						
Latitude	-0.0672	0.02	**-0.2303**	**0.3527**	-0.1676	1					
Longitude	0.0015	-0.08	-0.1096	**0.2796**	**0.5386**	**0.4346**	1				
Limpopo	-0.1053	0.03	-0.2738	**0.5573**	**-0.5423**	**0.7027**	0.1218	1			
Gauteng	0.0562	0.07	0.176	**-0.4985**	0.0856	-0.1983	-0.1576	-0.2882	1		
Mpumalanga	0.033	-0.1	0.1598	-0.167	**0.5845**	**-0.5118**	**0.3538**	**-0.6592**	-0.1536	1	
North West	0.0735	0.03	0.0707	-0.251	-0.0228	-0.2328	**-0.5381**	**-0.4188**	-0.0976	**-0.2232**	1

Table B.5. Summary statistics of the variables for the adaptation model

Variables	Observations	Mean	Standard Deviation	Minimum	Maximum
Age	771	55.32	12.87	18	100
Education	775	7.39	5.10	0	33
Household size	784	6.22	2.99	1	24
Farming experience	784	12.51	11.72	1	60
Wealth	781	0.00000653	1.50	-3.96	2.12
Latitude	794	-24.58	1.64	-31.57	-22.33
Longitude	794	29.02	1.66	21.20	31.75
Temperature	794	20.45	2.39	15.04	23.03
Rainfall	794	564.45	94.61	260.092	814.184
	Choices	**Frequency**	**Percent**	**Cumulative**	
Gender	0	216	27.55	27.55	
	1	568	72.45	100	
	Total	784			
Farm size	0	730	91.94	91.94	
	1	64	8.06	100.00	
	Total	794			
Infertile soil	0	521	69.38	69.28	
	1	231	30.72	100	
	Total	752			
Fertile soil	0	309	41.09	41.09	
	1	443	58.91	100	
	Total	752			
Highly fertile soil	0	674	89.63	89.63	
	1	78	10.37	100	
	Total	752			
Access to water for irrigation	0	201	26.80	26.80	
	1	549	73.20	100	
	Total	750	100		
Extension	0	303	40.08	39.66	
	1	453	59.92	100	
	Total	756	100		
Climate info	0	455	63.46	63.46	
	1	262	36.54	100	
	Total	717	100		
Credit	0	616	77.58	77.58	
	1	178	22.42	100	
	Total	794	100		
Off-farm employment	0	516	69.45	69.45	
	1	227	30.55	100	
	Total	743	100		
Tenure	0	419	56.17	56.17	
	1	327	43.83	100	
	Total	746	100		
Limpopo	0	342	43.72	43.72	
	1	432	54.48	100	
	Total	794			
North West	0	684	86.13	86.13	
	1	110	13.87	100	
	Total	794			

Table B.5. Continued

Variables	Observations	Mean	Standard Deviation	Minimum	Maximum
Mpumalanga	0	592	74.55	74.55	
	1	202	25.45	100	
	Total				
Notice temperature change	0	41	5.34	5.34	
	1	727	94.66	100	
	Total	768	100		
Notice rainfall change	0	20	2.60	2.60	
	1	748	97.40	100	
	Total	768	100		
Notice climate change	0	54	7.06	7.06	
	1	711	92.94	100	
	Total	765	100		
Adapt to temperature change	0	494	68.50	68.50	
	1	223	31.10	100	
	Total	717	100		
Adapt to rainfall change	0	497	67.34	67.34	
	1	241	32.66	100	
	Total	738	100		
No Adaptation	0	298	39.16	60.84	
	1	463	60.84	100	
	Total	761	100		

Table B.6. Results of the multinomial logit adaptation model, Limpopo River Basin

	Portfolio diversification	Irrigation	Changed planting dates	Changed the amount of land	Livestock feed supplements	Other
Education	-0.0256 (0.45)	0.015 (0.56)	-0.0072 (0.84)	0.0239 (0.54)	-0.02606 (0.63)	0.0274 (0.51)
Gender	-0.0381 (0.90)	0.390 (0.24)	0.4163 (0.39)	-0.2365 (0.61)	0.5869 (0.41)	-0.0687 (0.89)
Household size	-0.0256 (0.62)	0.045 (0.34)	-0.0065 (0.92)	0.0235 (0.80)	-0.1032 (0.23)	-0.1206 (0.09)*
Farming experience	0.0283 (0.01)***	0.011 (0.36)	0.0362 (0.01)***	0.0478 (0.00)***	-0.0159 (0.55)	0.0015 (0.92)
Wealth	-0.0439 (0.66)	0.152 (0.09)*	0.7200 (0.00)***	0.3255 (0.07)*	0.1524 (0.32)	0.1223 (0.43)
Farm size	0.7903 (0.09)*	0.994 (0.03)**	0.3967 (0.65)	0.8507 (0.26)	0.2231 (0.86)	0.3850 (0.58)
Highly fertile soil	0.4521 (0.10)*	0.335 (0.29)	-0.1061 (0.823)	1.0011 (0.05)**	0.7963 (0.19)	-0.3737 (0.50)
Infertile soil	-0.4928 (0.44)	-0.120 (0.81)	0.2631 (0.658)	1.0477 (0.14)	-0.3601 (0.71)	0.9341 (0.09)*
Extension	0.5876 (0.09)*	0.016 (0.95)	0.4915 (0.27)	0.5658 (0.22)	0.2494 (0.62)	0.0001 (0.99)
Climate information	-0.3225 (0.33)	-0.009 (0.97)	-0.3602 (0.42)	0.2471 (0.61)	-0.1404 (0.80)	0.4426 (0.29)
Credit	0.4903 (0.08)*	0.348 (0.26)	0.0860 (0.87)	-0.9608 (0.13)	1.2228 (0.02)**	0.5648 (0.22)
Off-farm employment	0.4091 (0.19)	0.050 (0.87)	0.1044 (0.80)	-0.7191 (0.31)	2.1167 (0.00)***	0.2936 (0.50)
Tenure	0.2672 (0.36)	0.304 (0.31)	0.4309 (0.28)	1.1490 (0.02)**	-0.3775 (0.49)	1.3012 (0.00)***
Latitude	0.4806 (0.05)**	-0.142 (0.25)	-0.2132 (0.17)	0.7003 (0.09)*	-0.3234 (0.07)*	0.0809 (0.58)

Table B.6. Continued

	Portfolio diversification	Irrigation	Changed planting dates	Changed the amount of land	Livestock feed supplements	Other
Longitude	-0.1496 (0.45)	-0.016 (0.92)	0.5093 (0.03)**	0.5458 (0.23)	-0.4082 (0.09)*	-0.1312 (0.54)
Rainfall	0.0062 (0.12)	0.004 (0.13)	-0.0071 (0.04)**	0.0079 (0.269)	0.0001 (0.97)	-0.0007 (0.86)
Temperature	0.1851 (0.02)**	0.144 (0.08)*	-0.2957 (0.00)***	0.0783 (0.53)	0.0855 (0.60)	0.2502 (0.03)**
Intercept	6.1086 (0.49)	-11.102 (0.05)**	-14.0650 (0.09)*	-10.6187 (0.53)	-2.6090 (0.75)	-2.3139 (0.74)
Base category	No Adaptation					
No. observations	591					
LR chi-square (90)	291.07***					
Log pseudo likelihood	-676.2506					
Pseudo R-Square	0.1320					

Notes: *** significant at 1% probability level, ** significant at 5% probability level, * significant at 10% probability level

Hausman Test for the IIA Assumption

Test: Ho: difference in coefficients not systematic

$\text{chi}^2(17) = (b-B)'[(V\_b-V\_B)^\wedge(-1)](b-B)$
$= -0.375$
$\text{Prob}>\text{chi}^2 = 0.9311$
(V_b-V_B is not positive definite)

Fail to reject the null hypothesis; therefore, the MNL adaptation model holds consistent.

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