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Mapping South African Farming Sector Vulnerability to Climate Change and Variability: A Subnational Assessment

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ABSTRACT

This paper analyzes the vulnerability of South African farmers to climate change and variability by developing a vulnerability index and comparing vulnerability indicators across the nine provinces of the country. Nineteen environmental and socio-economic indicators are identified to reflect the three components of vulnerability: exposure, sensitivity, and adaptive capacity. The results of the study show that the regions most vulnerable to exposure to extreme events and climate change and variability, do not always overlap with the most vulnerable populations. Furthermore, vulnerability to climate change and variability is intrinsically linked with social and economic development. The Western Cape and Gauteng provinces, with the high level of infrastructure development, high literacy rates, and low share of agricultural GDP, are lower on the vulnerability index; whereas, the most vulnerable regions Limpopo, Kwazulu Natal and Eastern Cape, are those with high number of small-scale farmers, high dependency on rainfed agriculture, high land degradation, and highly populated rural areas where the majority of the population relies on agriculture for their livelihoods. These large differences in the extent of vulnerability between provinces suggest that policy makers should develop region-specific policies and address climate change at the local level.

Keywords: climate change and variability, agriculture, vulnerability, adaptive capacity, exposure, sensitivity

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1. INTRODUCTION

In Southern Africa, the manifestations of climate change are predicted to be greatest in the northern regions. Temperature increases in the range of 1 ^{0}C to 3^{0}C are expected by the mid 21st century, with the highest increases expected for the most arid parts of Southern Africa. Of greater consequence for South Africa, as a semi-arid country, is the prediction of broad rainfall reductions (in the range 5 to 10 percent) for the summer rainfall region of the country. This rainfall reduction is predicted to be accompanied an increasing incidence of both droughts and floods, with prolonged dry spells followed by intense storms. A marginal increase in early rainfall is predicted for the winter rainfall region of the country (DEAT 2004).These predictions raise concerns that climate change could have a significant adverse impact on crop production in the country, which would have important implications for the wellbeing of South African farmers, particularly for poorer, emerging farmers in the country. Agriculture plays a prominent role in the stability of rural communities; as in many countries, the poor in South Africa are disproportionately found in rural areas, and most rural households depend on agriculture for food and income. Numerous initiatives have sought to analyze the impact of global climate change on agriculture in South Africa. These studies focus on the implications of future climate change scenarios for crop yields and production, and largely emphasize the physical impacts of climate change on crop yields (Schulze et al. 1993; Du Toit et al. 2002; Kiker 2002; Kiker et al. 2002) and the economic impacts derived from yields losses (Erasmus et al. 2000; Poonyth et al. 2002). Other studies develop a more comprehensive analysis of the economic impacts by including adaptation options (Deressa 2003; Gbetibouo and Hassan 2005; Benhin 2006). Based on predictions regarding the physiological responses of affected plants, these studies predict that climate change will adversely impact the agricultural sector, induce (or require) major shifts in farming practices and patterns in different regions of the country, and have significant effects on crop yields (e.g., some of the marginal western areas are predicted to become unsuitable for the production of maize, the main staple crop). While it is increasingly accepted that the vulnerability of agricultural populations to climatic conditions cannot be solely understood through the quantification of biophysical impacts, no previous climate change study in South Africa has explored

the social aspects of vulnerability to climate change with an in depth examination of the underlying socio-economic and institutional factors that determine how farmers respond to and cope with climate hazards. The degree to which climatic events affect an agricultural system depends on a wide variety of factors, including (among other things) the types of crops or livestock produced, the scale of the operation, the farm's orientation towards commercial or subsistence purposes, the quality of the natural resource base, and specific human variables of the farm's managers (e.g., education, risk tolerance, age, etc.). Vulnerability is also mediated by institutional factors, including the rules, norms and policies that govern land tenure, the availability of markets, financial capital, insurance and support programs, and the degree of technology development and distribution. With a developed commercial farming sector functioning alongside a large subsistence farming sector and a wide variety of crops geographically distributed across the country due to variations in climate patterns, the agricultural sector of South Africa displays a diverse range of social, economic, political and environmental conditions. As this suggests that vulnerability is not evenly distributed across the regions and social groups in South Africa, it becomes more challenging to develop a methodology for vulnerability assessment that accurately captures the spatial dimension of vulnerability in the country. We therefore need to identify the agricultural areas, production systems, and populations that are most vulnerable to climate change.

The aim of this paper is to examine the vulnerability of South Africa's farming sector to climate change by developing a nationwide province-level vulnerability profile that will identify the most vulnerable farming areas in South Africa. The remainder of this paper is organized as follows. The next section outlines the conceptual framework for this research. Section 3 describes the study area. Section 4 presents the casual model and the selection of indicators. Section 5 the data used in the study. Section 6 the methods used to calculated the vulnerability index. Section 7 presents the results of the study. Section 8 concludes, discusses policy implications, and outlines some directions for further research.

2. THE CONCEPTUAL FRAMEWORK OF VULNERABILITY

Chambers (1989) defines vulnerability as exposure to contingencies and stress, and the difficulty of coping with these exposures. Adger (1996) also identifies two components of vulnerability: the effects that an event may have on humans (referred to as capacity or social vulnerability), and the risk that such an event may occur (referred to as exposure). Thus, vulnerability refers to both internal and external dimensions. The internal dimension relates to defencelessness and insecurity, as well as the capacity to anticipate, cope with, resist, and recover from the impacts of a hazard. The external dimension involves exposure to risks and shocks. Furthermore, Bohle (2001) developed a conceptual framework of vulnerability named the "double structure of vulnerability," which comprises exposure and coping. Here, the external perspective refers mainly to the structural dimensions of vulnerability and risk, while the internal dimension of vulnerability focuses on coping and actions taken to overcome or at least mitigate the negative effects of economic and ecological change. The Intergovernmental Panel on Climate Change (IPCC) Second Assessment Report (SAR) and Moser (1998) change the focus of vulnerability from emphasizing internal/coping and external/exposure, and examine two similar but different factors: sensitivity and adaptive capacity (or resilience). The SAR defines vulnerability as the extent to which climate change may damage or harm a system; vulnerability therefore depends not only on the system's sensitivity, but also on its ability to adapt to new climatic conditions (Watson et al. 1996). According to Moser (1998), any definition of vulnerability requires the identification of two components: sensitivity and resilience. Sensitivity refers to the responsiveness of a system to climatic influences, and the degree to which this responsiveness might be affected by climate changes. The IPCC Third Assessment Report (TAR) reconciles both sides by adding a third component to vulnerability, defining it as: "The degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate variation to which a system is exposed, its sensitivity, and its adaptive capacity" (McCarthy et al. 2001). According to this definition, vulnerability includes an external dimension that is represented by the exposure of a system to climate variations, as well as a more complex internal dimension comprising its sensitivity and adaptive capacity to these stressors (Füssel and Klein

2006). The IPCC Fourth Assessment Report (AR4), which reports recent advances in our understanding of climate change, contains a vulnerability definition consistent with that of the TAR (IPCC 2007). Under this framework, a highly vulnerable system would be one that is very sensitive to modest changes in climate, where the sensitivity includes the potential for substantial harmful effects, and for which the ability to adapt is severely constrained. Others authors also characterize vulnerability using these three dimensions. In what they call the "space of vulnerability," Watts and Bohle (1993) describe the external side of vulnerability as the risk of exposure to hazards, while the internal side comprises capacity (the risk of having inadequate capacity to mobilize resources to deal with hazards) and potentiality (the risk of severe consequences). Downing et al. (2001) distinguish three domains of vulnerability: present criticality, adaptive capacity, and climate change hazard. Luers et al. (2003) propose a method for quantifying vulnerability (given the system, outcome variable, and stressor of concern) based on its three components: exposure, sensitivity, and adaptive capacity. Turner et al. (2003) recognize that vulnerability is determined not by exposure to hazards (perturbations and stresses) alone, but also depends on the sensitivity and resilience of the system that is experiencing such hazards. These authors develop an integrated conceptual framework of vulnerability built on these three major dimensions of vulnerability, namely exposure, sensitivity and adaptation/resilience. Thus, vulnerability is understood as a function of three components: exposure, sensitivity and adaptive capacity, which are influenced by a range of biophysical and socio-economic factors (TERI 2003).

3. STUDY AREA

There are approximately 100 million hectares of agricultural land in South Africa, of which 14 million receive sufficient rainfall for viable arable farming. The remainder of the land is used for extensive grazing (72 million hectares), nature conservation (11 million hectares), and forestry (1 million hectares). Dry land cultivation is practiced on 11.2 million hectares and irrigated agriculture occupies slightly more than 1.2 million ha that produce 25 to 30 percent of the country's agricultural output (AAS 2007). Agriculture contributed about 3.5 percent of the country's growth domestic product (GDP) in 2002. Kwazulu Natal province made the largest contribution to agricultural value added (VAD) (28.3 percent) followed by the Western Cape (22.6

percent). Three categories of products contributed to the agricultural GDP, namely: (1) field crops; (2) horticultural products; and (3) livestock. Over the past two decades, the average contribution to gross VAD of the agricultural sector was about 37 percent, 20 percent, and 43 percent from field crops, horticulture and livestock, respectively (AAS, 2007). South Africa may be subdivided into a number of farming regions according to climate, natural vegetation, types of soil, and the type of farming practiced. The principal cropping regions are the summer highveld plateaus of Gauteng and Free State, as well as the highveld and midlands of Kwazulu Natal and winter rainfall region of the Western Cape. The Joint Agriculture and Weather Facility of the National Oceanic and Atmospheric Administration (NOAA) of the United States determined four climatic zones for South Africa based on crop areas and climate profiles: the steppe (arid), desert, sub-tropical wet and sub-tropical winter rain zones (Appendix 1). Due to the history of apartheid policies, agriculture in South Africa is highly dualistic; a commercial sector located in the "former white South Africa" is run predominately by white farmers, while a subsistence sector is located in the former homeland areas and run by black farmers. The institutional infrastructure of agriculture differs in quality, availability and accessibility between commercial and subsistence farms (Coetzee and Van Zyl 1992). The commercial sector is the dominant form of agricultural production in South Africa. It is large-scale, commercially oriented, capital-intensive, export-led, and it accounts for 90 percent of total VAD in agriculture and covers 87 percent of the agricultural land. The average size of commercial farms in South Africa is estimated to be about 1,200 hectares under private ownership, and there are about 46,000 commercial farm units in the country. In contrast the subsistence sector is an impoverished sector, dominated by low-input, labour intensive production. Despite the land reform initiatives put in place since 1995, the estimated 3.4– 4.8 million smallholders are predominantly settled in the former homelands and produce on the remaining 13 percent of the agricultural land (17 million hectares) (Feynes and Meyer 2003) for semi-subsistence purposes. Land holdings in the former homelands are generally very small (Groenewald and Nieuwoudt 2003) and are under a communal land tenure system. Only 3.7 percent (47,486 hectares) of the total irrigated land in South Africa is under smallholder agriculture. While there is high potential for veld grazing in these areas, stocking currently exceeds the carrying capacity of the land in most areas, and overgrazing has severely affected the quality of arable land in many areas. Poverty in rural areas is

associated with agricultural policies, which have persistently marginalized small-scale black farmers by curtailing their access to resources such as land, credit and technical know-how (Coetzee and Van Zyl 1992).

4. THE CAUSAL MODEL: THE CHOICE OF INDICATORS

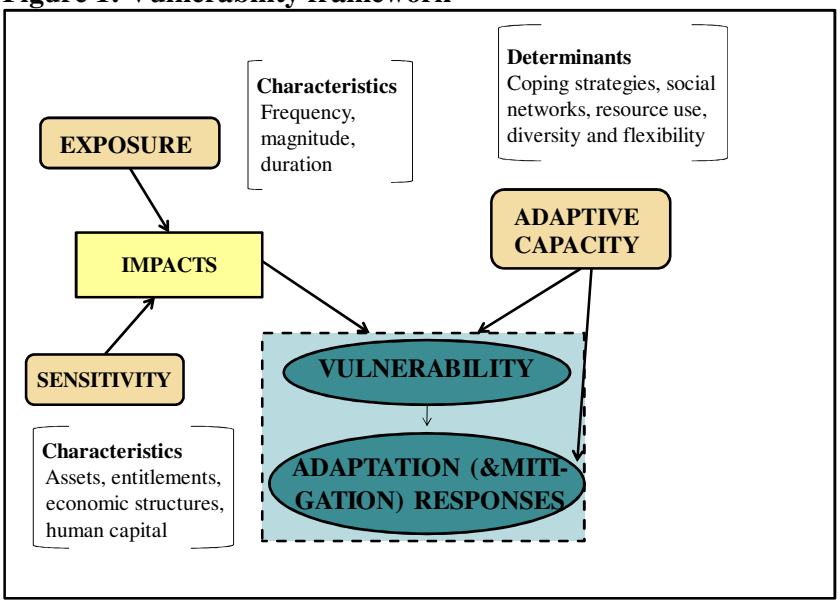
To assess the South African farming sector vulnerability to climate change and variability, we use the indicator approach. The indicator approach uses a specific set or combination of indicators (proxy indicators) and measures vulnerability by computing indices, averages or weighted averages for those selected variables or indicators. This approach can be applied at any scale (e.g., household, county/district, national, system). The indicator approach is the most common method adopted for quantifying vulnerability in the global change community. It is used to develop a better understanding of the socio-economic and biophysical factors contributing to vulnerability (Hebb and Mortsch 2007). For this study, we base our definition of vulnerability on the Intergovernmental Panel on Climate Change's definition, where a region's vulnerability to climate change and variability is described by three elements: exposure, sensitivity, and adaptive capacity (IPCC 2001), as follows:

- Exposure can be interpreted as the direct danger (i.e., the stressor), and the nature and extent of changes to a region's climate variables (e.g., temperature, precipitation, extreme weather events).
- Sensitivity describes the human–environmental conditions that can worsen the hazard, ameliorate the hazard, or trigger an impact.
- Adaptive capacity represents the potential to implement adaptation measures that help avert potential impacts (see also Figure 1).

Exposure and sensitivity are intrinsically linked and together affect potential impact. To assess farming vulnerability to climate change, we look at exposure to climate change, sensitivities to those changes, and societal coping and adaptive capabilities (which might include mitigation options). Our vulnerability indicator approach is integrated, in that the selected indicators represent both the biophysical conditions of the farming regions and the socio-economic conditions of the farmers. The selection of indicators was done through an extensive review of previous reports; in particular, we draw from Aandahl and O'Brien (2001), Moss et al. (2001), Cutter et al. (2000 and 2003), TERI (2003), O'Brien et al. (2004b), Lucas and Hilderink (2004),

Brenkert and Malone (2005), Brooks et al. (2005), Patnaik and Narayanan (2005), and Thornton et al. (2006). Further, we were guided by a list of indicators that were developed in a workshop setting[3] and then pragmatically assessed in relation to data availability.

Figure 1: Vulnerability framework



4.1 Exposure

Exposure relates to the degree of climate stress upon a particular unit of analysis; it may be represented by either long-term changes in climate conditions or changes in climate variability, including the magnitude and frequency of extreme events (O'Brien et al. 2004). In this study, exposure is represented by two elements: (i) *Frequency of climate extremes*: In South Africa, one of the key constraints to agriculture is a high climate variability that has historically included numerous droughts and floods (e.g., the 2000 floods and the 2002/2003 drought). In regions with a higher frequency of droughts or floods, crop production is more risky.

[3] A national stakeholder's forum was held on November 21, 2007, at the University of Pretoria. This meeting was organized by the Center for Environmental Economics and Policy in Africa (CEEPA) in collaboration with the International Food Policy Research Institute (IFPRI) to discuss the nature of South Africa's vulnerability and assess stakeholders' perceptions of vulnerability to climate change and options for adaptation. This forum was supported by the "Food and Water Security under Global Change: Developing Adaptive Capacity with a Focus on Rural Africa" project, which forms part of the CGIAR Challenge Program on Water and Food.

(ii) Predicted change in temperature and rainfall by 2050: This metric gives the predicted level of climate change that regions will experience. The larger the changes, the more difficulty the regions are expected to have in adjusting to these changes. More importantly, if increased temperature and decreased rainfall are predicted we would expect to see negative impacts on farm production in already hot and water-scarce regions.

4.2 Sensitivity

Sensitivity, in its general sense, is defined by Gallopín (2003) as the degree to which a system is modified or affected by an internal or external disturbance or set of disturbances. This measure, which herein reflects the responsiveness of a system to climatic influences, is shaped by both socio-economic and ecological conditions and determines the degree to which a group will be affected by environmental stress (SEI, 2004). It is impossible to directly predict crop yields under potential future climates on a decadal timescale (Challinor et al. 2007). This may only be done through crop simulation models, which are complicated because they deal with the complex physiological relationships between crop and climate. Moreover, crop models are ecology- and management-sensitive. Because each crop requires extensive experiments for successful modelling, such models have only been developed thus far for major crops. Also, due to the cost implications of the necessary experiments and the location specificity of the models, the developed models can only be applied to a few locations. For aggregate analyses, inferences must be made from relatively few sites and crops, and then applied to large areas and diverse production systems.

In South Africa, only the CERES-maize model has been widely applied (Schulze et al. 1993; Du Toit et al. 2002). In the present study framework, sensitivity describes the human–environmental conditions that can either worsen the hazard or trigger an impact. We examine five factors that may influence the sensitivity of a farming region: (i) *Irrigation rate*: If we compare two agricultural regions that grow the same crops and have similar climates, their exposure to climate variability might be similar, but their sensitivity could be very different. For example, an irrigated system would have low sensitivity to short-term precipitation variability, whereas a rainfed system would have greater sensitivity to the same exposure. (ii) *Land degradation index*:

Land degradation reduces the productive capacity of land. Contributors to land degradation include natural disasters and human activities (e.g., agricultural mismanagement, overgrazing, fuelwood consumption, industry and urbanization). This indicator represents the "combined degradation index," which considers soil degradation (erosion, salinization and acidification) and veld or vegetation degradation (loss of cover and changes in species composition, bush encroachment, alien plant invasions, and deforestation). Areas with higher land degradation indices will experience greater negative impacts of climate variability and change. (iii) *Crop diversification index*: Farmers themselves commonly identify diversification as an effective strategy for managing business risks; particularly climatic risks (Bathia 1965).An agricultural region with more diversified crops will be less sensitive to climatic variations. (iv) *Percent small-scale*: Small-scale farmers, generally subsistence farmers, are more sensitive to climate change and variability because they have less capital-intensive technologies and management practices. Thus, a region with a large number of small-scale farmers will be more climate-sensitive than a region with fewer small-scale farmers. (v) *Rural population density*: A region with high population density is more sensitive to climate because more people are exposed and therefore the region will need greater humanitarian assistance.

4.3 Adaptive capacity

Adaptive capacity is a significant factor in characterizing vulnerability. In the climate change literature, adaptive capacity is similar or closely related to a host of other commonly used concepts such as adaptability, coping ability, management capacity, stability, robustness, flexibility, and resilience (Smit and Wandel 2006). According to Brooks (2003), the adaptive capacity of a system or society reflects its ability to modify its characteristics or behavior in order to better cope with existing or anticipated external stresses and changes in external conditions. The IPCC (2001) describes adaptive capacity as the potential or ability of a system, region, or community to adjust to the effects or impacts of climate change (including climate variability and extremes). The capacity to adapt is context-specific and varies from country to country, from community to community, among social groups and individuals, and over time (IPCC 2001; Smit and Wandel 2006). Adaptive capacity is considered to be "a function of wealth, technology, education, information, skills,

infrastructure, access to resources, and stability and management capabilities" (McCarthy et al. 2001). Analyzing vulnerability involves identifying not only the threat, but also the "resilience," or the responsiveness of the system and its ability to exploit opportunities and resist or recover from the negative effects of a changing environment. The means of resistance are the assets and entitlements that the individuals, households, or communities can mobilize and manage in the face of hardship. There are close linkages between vulnerability and livelihoods, and building resilience is a question of expanding and sustaining these assets (Moser 1998). Vulnerability is therefore closely linked to asset ownership. The more assets people have, the less vulnerable they are; conversely, the greater the erosion of people's assets, the greater their insecurity. Here, adaptive capacity is described as being dependent upon four[4] livelihoods assets: (1) **Social capital** is represented by farm organizations (the number of farmers in organized agriculture). This indicator is a proxy for private social networks. First, social networks act as conduits for financial transfers that may relax the farmer's credit constraints. Second, they act as conduits for information about new technology. Third, social networks can facilitate cooperation to overcome collective action dilemmas, where the adoption of technologies involves externalities (Deressa et al. 2008). It is hypothesized that social capital positively influences adaptation to change. (2). **Human capital** is represented by *literacy rate* and *HIV prevalence*. (3). According to Leichenko et al. (2002),

increased overall literacy levels reduce vulnerability by increasing people's capabilities and access to information, thereby enhancing their ability to cope with adversities. HIV prevalence is used as indicator under the assumption that areas with higher rates of HIV/AIDS are more vulnerable. Drimie (2002) states unequivocally that HIV/AIDS is "…the major development issue facing Sub-Saharan Africa." The epidemic deepens poverty, reverses human development achievements, worsens gender inequalities, erodes the ability of governments to maintain essential services, reduces labour productivity and supply, and puts a brake on economic growth. (3) **Financial capital** is represented by (i) *farm income*; (ii) *farm holding size*; (iii) *farm assets*; (iv) *percentage of people below the poverty line*; (v) *share of agricultural GDP*; and (vi) *access to credit*. These indicators provide a general picture of the

[4] We also include a fifth asset, that of natural capital; however, this is classified under the sensitivity component of vulnerability which describes the human–environmental conditions that can either worsen the hazard or trigger an impact. The indicator of natural capital is the "land degradation index."

financial situation of the province. Regions with higher farm income, larger farms, greater farm value assets, and more access to credit are wealthier and are therefore better able to prepare for and respond to adversity. In contrast, regions with a higher dependence on agriculture (higher share of agriculture in total GDP) are assumed to be less economically diversified and thus more susceptible to climatic events and changes. (4). **Physical capital** is related to infrastructure and access to markets. The quality of infrastructure is an important measure of the relative adaptive capacity of a region. Regions with better infrastructure are presumed to be better able to adapt to climatic stresses. Improved infrastructure may reduce transactions costs, and strengthen the links between labour and product markets. Markets may be important for a variety of reasons, including their abilities to spread risk and increase incomes. According Zhang et al. (2007), markets are a means of linking people both spatially and over time. That is, they allow shocks (and risks) to be spread over wider areas. In particular, markets should make households less vulnerable to (localized) covariate shocks. Furthermore, pre-existing coping strategies (e.g. the sale of productive assets) will be more effective, thereby avoiding the potentially irreversible effects of these actions. Moreover, improved infrastructure should encourage the formation of nonfarm enterprises as a source of diversification in the short run and, eventually, a transition out of agriculture. Infrastructure may also facilitate migration and remittances, which are important ex ante and ex post mechanisms for reducing vulnerability. Here, we construct an infrastructure index to represent the physical capital of the agricultural regions.

The utilized indicators and their inter-linkages, which are geared towards reflecting overall vulnerability, are graphically presented in Appendix 2.

5 DATA

Data on the selected indicators for the nine provinces of the country are taken from various secondary sources. Socio-economic data covering the four livelihood assets (social, financial, human and physical) come from the South African Statistical Agency (Census, 2001 and Agricultural Census, 2004). Data on agriculture (irrigation rate, land size, etc.) come from the Agricultural Census of 2004. Data on drought and flood frequencies come from the International Disaster Data Base for 1906 to 2006 (Emergency Events Database (EM-DAT) 2006). Predicted changes in temperature

and rainfall come from the Climate Systems Analysis Group at the University of Cape Town (Appendix 3).

6 CALCULATING THE VULNERABILITY INDICES

From our conceptual framework, we see that the vulnerability of a given system largely depends on its exposure and sensitivity, which combined provides the potential impact and the potential for effectively coping with the impacts and associated risks. Vulnerability may be formulated mathematically as follows:

$$\mathbf{V = f\ (I - AC)}$$
$$(-)\quad (+)$$

where V is vulnerability, I is potential impact, and AC is adaptive capacity. A higher adaptive capacity is associated with a lower vulnerability, while a higher impact is associated with a higher vulnerability. Given the above equation, vulnerability is defined as a function of a range of biophysical and socio-economic factors, commonly aggregated into three components that estimate the adaptive capacity, sensitivity, and exposure to climate variability and change.

Having considered the theoretical determinants of provincial farming sector vulnerability and selected appropriate indicators for its capture, we must now carry out some form of standardization to ensure that all the indicators are comparable (Vincent 2004). Based on the method in the United Nations Development Programme (UNDP)'s Human Development Index (UNDP 2002), all of the variables in the vulnerability indices are normalized to a range of 0 to 100. The values of each variable are normalized to the range of values in the data set by applying the following general formula:

$$\text{Index value} = \frac{(\text{Actual value} - \text{minimum value}) * 100}{(\text{Maximum value} - \text{minimum value})} \qquad (1)$$

To ensure that high index values indicate high vulnerability in all cases, we reverse the index values by using [100 – index value] for indicators hypothesized to decrease vulnerability. After standardizing the data, we next attach weights to the vulnerability indicators. A review of the literature indicates that three methods are used to assign weights to indicators: (1) expert judgment (Brooks et al. 2005; Moss et al. 2001); (2) arbitrary choice of equal weight (Lucas and Hilderink 2004; O'Brien et al. 2004b; Patnaik and Narayanan 2005) and (3) statistical methods such as principal component

analysis or factor analysis (Cutter et al. 2003; Thornton et al. 2006). We do not assign equal weights because this strategy is too subjective, and the literature shows that indicators do not equally affect vulnerability (Hebb and Mortsch 2007). The development of weights via expert judgment is often constrained by the availability of expert knowledge in smaller communities and difficulties in reaching a consensus on the weights among expert panel members (Lowry et al. 1995). Therefore, we herein use principal component analysis (PCA) to generate weights for the indicators. PCA is a technique for extracting from a set of variables those few orthogonal linear combinations of variables that most successfully capture the common information. Following Filmer and Pritchett (2001), we define the first principal component of a set of variables as the linear index of all the variables that captures the largest amount of information common to all the variables. Let suppose we have a set of *N*-variables (a^*_{1j} to a^*_{Nj}) that represents the *N*-variables (indicators) of each province *j*. PCA starts by specifying each variable normalized by its mean and standard deviation. For instance, $a_{1j} = (a^*_{1j} - a^*_1)/s^*_1$, where a^*_1 is the mean of a^*_{1j} across regions and s^*_1 is its standard deviation. The selected variables are expressed as linear combinations of a set of underlying components for each region *j:*

$$
\begin{aligned}
&a_{1j} = \gamma_{11} A_{1j} + \gamma_{12} A_{2j} + \ldots + \gamma_{1N} A_{Nj} \\
&\ldots \qquad\qquad\qquad\qquad j = 1 \ldots J \\
&a_{Nj} = \gamma_{N1} A_{1j} + \gamma_{N2} A_{2j} + \ldots + \gamma_{NN} A_{Nj} \,, \qquad\qquad (1)
\end{aligned}
$$

where the *A*'s are the components and the γ's are the coefficients on each component for each variable (and do not vary across regions). Because only the left side of each line is observed, the solution to the problem is indeterminate. PCA overcomes this indeterminacy by finding the linear combination of the variables with maximum variance (usually the first principal component W_{1j}), then finding a second linear combination of the variables orthogonal to the first and with maximal remaining variance, and so on. Technically, the procedure solves the equations $(\mathbf{R} - \lambda_n \mathbf{I})\mathbf{v}_n = 0$ for λ_n and $\mathbf{v}_n$, where $\mathbf{R}$ is the matrix of correlations between the scaled variables (the *a*'s) and $\mathbf{v}_n$ is the vector of coefficients on the *n*th component for each variable. Solving the equation yields the characteristic roots of $\mathbf{R}$, λ_n (also known as eigenvalues), and their associated eigenvectors, $\mathbf{v}_n$. The final set of estimates is

produced by scaling the $\mathbf{v}_n$s so that the sum of their squares sums to the total variance, another restriction imposed to achieve determinacy of the problem.

The scoring factors from the model are recovered by inverting the system implied by equation (1). This yields a set of estimates for each of the *A*-principal components:

$$A_{1j} = f_{11}\, a_{1j} + f_{12}\, a_{2j} + \ldots + f_{1N}\, a_{Nj}$$

$$\ldots \qquad\qquad j = 1 \ldots \mathbf{J}$$

$$A_{Nj} = f_{N1}\, a_{1j} + f_{N2}\, a_{2j} + \ldots + f_{NN}\, a_{Nj}\,, \qquad \mathbf{(2)}$$

where the *f*'s are the factor scores. Therefore, the first principal component, expressed in terms of the variables is an index for each province based on the following expression:

$$\mathbf{A}_{1j} = f_{11}\,(a^*_{1j} - a^*_1)/(\mathbf{s}^*_1) + \ldots + f_{1N}\,(a^*_{Nj} - a^*_N)/(\mathbf{s}^*_N) \qquad \mathbf{(3)}$$

7. RESULTS AND DISCUSSION

7.1 Descriptive Statistics

Our preliminary analyses show that provinces in South Africa demonstrate a vast diversity in terms of environmental and socio-economic conditions. The coastal provinces of Kwazulu Natal, the Eastern Cape and the Western Cape show the highest frequency of extreme events (droughts/floods) over the last century. The highest incremental increase in temperature by 2050 is found in the desert region of the Northern Cape and the steppe arid regions of Free State and Mpumalanga, whereas changes in rainfall are predicted to be greatest in the Gauteng and North West provinces. Concerning the sensitivity indicators, 65 percent of the crop area in the Northern Cape (the desert region) is irrigated. The regions showing the highest levels of soil and veld degradation are the Eastern Cape, Kwazulu Natal and Limpopo. The Western Cape and Limpopo are the most diversified regions; in these areas, 5 or 6 different types of crops occupy around 70 percent of the crop land. The most populated rural areas are the Eastern Cape, Kwazulu Natal, Mpumalanga and North West, where small farmers comprise more than 70 percent of the farming population. The most developed provinces are Gauteng and the Western Cape, which have

infrastructure index scores of 2.95 and 2.92, respectively. They also have the highest literacy rates and lower unemployment rates. In contrast, the Eastern Cape and Limpopo have the highest share of agricultural GDP, the lowest average value of farm assets, the lowest literacy rate, and the highest unemployment rate.

7.2 The calculated vulnerability index

To quantitatively assess the overall vulnerability index, we run a PCA with the 19 indicators, using data analysis and statistical software (STATA). Nineteen components are extracted in the first stage of the PCA but only the first five are significant (based on the Kaiser criterion of an eigenvalue greater than 14). These five components explain 91 percent of the total variation in the data set. The first principal component explains most of the variation (33 percent), the second principal component explains 23 percent, the third explains 16 percent, the fourth explains 12 percent, and the fifth explains only 6 percent. The first component is then used to construct the vulnerability index. Each variable is normalized to take a value between 0 and 100. The weights (or scores) assigned to the indicators on component 1 are shown in Table 2, along with their associated statistics. Following Filmer and Pritchett (2001), the assigned weights are then used to construct an overall vulnerability index by applying the following formula:

$$v_j = \sum_{i=1}^{k} \left[b_i \left(a_{ji} - x_i \right) \right] / s_i \qquad (4)$$

The eigenvalue is a measure of standardized variance, with a mean of 0 and standard deviation of 1. Each standardized variable (here, each of the 19 indicators) contributes at least the variance of 1 to the principal component extraction. The Kaiser criterion states that unless a principal component extracts at least as much as one of the original variables (i.e. has a standardized variance equal to or greater than 1), it should be dropped from further analysis (Filmer and Pritchett 2001).where v is the vulnerability index, b is the weight from PCA 1, a is the indicator value, x is the mean indicator value, and s is the standard deviation of the indicators.

Figure 2 depicts the results of the vulnerability index for each province in South Africa. The results show that Western Cape and Gauteng, the most developed provinces, have low vulnerability indices, ranging from -4 to -2.5. Provinces with

medium vulnerabilities (ranging from -1.2 to +1) are Free State, the Northern Cape, Mpumalanga and North West. The three most vulnerable provinces are the Eastern Cape, Kwazulu Natal and Limpopo. The low vulnerabilities of the Western Cape and Gauteng are associated with high levels of infrastructure development, high literacy rates, and low shares of agricultural GDP. The most vulnerable regions are those with more small-scale farmers, high dependencies on rainfed agriculture, high land degradation, and populated rural areas where most people rely on agriculture for their livelihoods.

Table 2: Factor scores from PCA and associated statistics

Indicators	Eigenvalue	Proportion	Cumulative	Mean	Standard Deviation	Scoring factor: PCA1
Change in temperature	6.22896	0.3278	0.3278	63.93909	38.38529	0.0355
Change in rainfall	4.43806	0.2336	0.5614	35.89761	32.63587	-0.1334
Frequency droughts/floods	3.13086	0.1648	0.7262	36.66667	29.15476	0.1278
Irrigated land	2.42104	0.1274	0.8536	71.93974	32.55948	-0.11
Soil degradation	1.10933	0.0584	0.912	48.20182	36.07274	0.3391
Veld degradation	0.850657	0.0448	0.9568	53.86779	32.31948	0.2691
Crop diversification	0.509999	0.0268	0.9836	47.31183	39.70495	0.0261
Small Scale	0.311103	0.0164	1	52.26757	44.27848	0.3701
Rural population density	0	0	1	45.09044	33.90975	0.3672
Access to credit	0	0	1	64.8487	28.92462	0.2273
Farm Organisation	0	0	1	52.59259	43.26205	0.1253
Literacy rate	0	0	1	65.8835	37.37238	0.3424
HIV prevalence	0	0	1	58.50067	34.24387	0.1037
Net farm income	0	0	1	59.05648	35.34395	0.1951
Unemployment rate	0	0	1	70.37037	30.36557	0.3115
Farm holding size	0	0	1	77.22207	32.42789	0.2079
Share agricultural GDP	0	0	1	65.53288	30.51335	0.062
Farm assets	0	0	1	79.81361	31.07182	0.0028
Infrastructure Index	0	0	1	51.57343	32.93298	0.3393

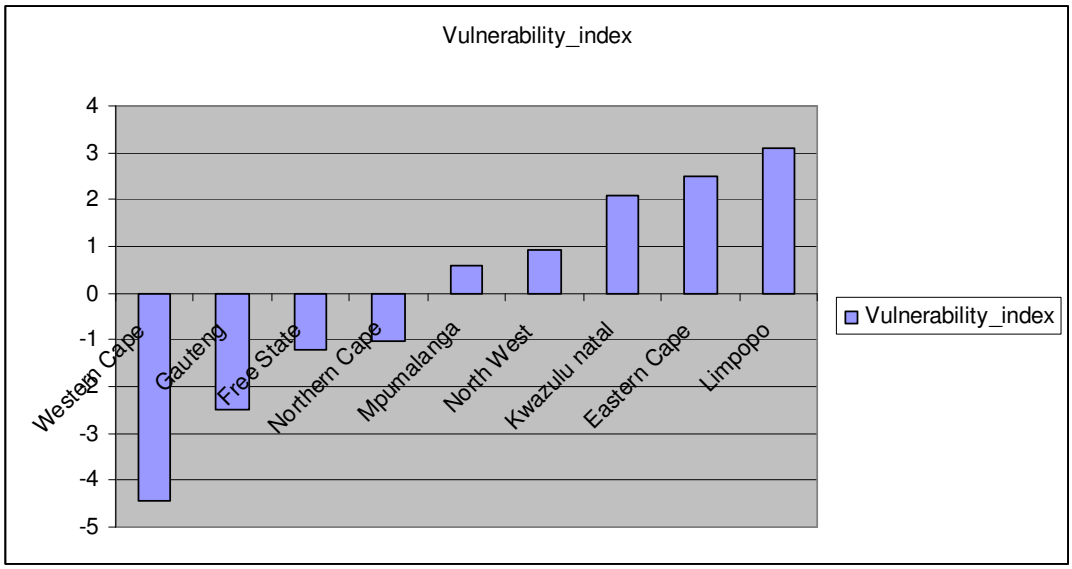


Figure 2: Overall vulnerability index of the farming sector across South Africa provinces

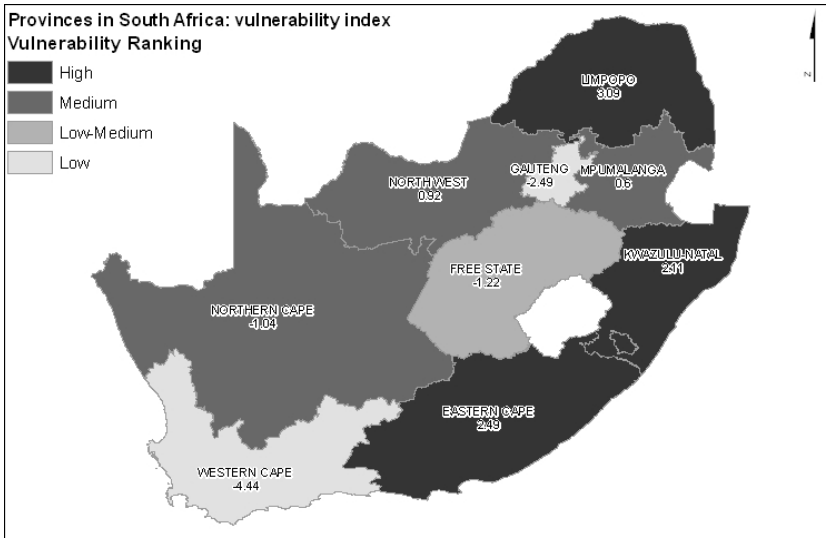


Figure 3: Map of overall vulnerability index of the farming sector across South Africa provinces

8. CONCLUSION

We herein report the quantitative operationalization of climate change vulnerability across the nine provinces of South Africa. Vulnerability has three components: exposure, sensitivity, and adaptive capacity. We examine the use of 19 environmental and socio-economic indicators to reflect these three components of vulnerability. Our framework combines exposure with sensitivity to give the potential impact, which is then compared with the adaptive capacity to yield an overall measure of vulnerability. Principal component analysis is used to generate weights for the different indicators, and an overall vulnerability index is calculated. The methodology used herein has both limitations and strengths. The macro-profiles are limited in that mapping vulnerability at the provincial level may lead to a false sense of precision. There is enormous heterogeneity within provinces and districts with regard to household-level resource access, poverty level, and ability to cope with climate change and variability. Examination of vulnerability can certainly be guided by macro-level analyses, but ultimately future work should be done at higher resolutions, such as the district and villages levels. Currently, to our knowledge there is only limited data available for the district level, necessitating a macro approach at this time. The advantages of this approach are the transparency of the indicator framework that allows us to trace vulnerable regions back to their underlying determinants. Another key strength of our approach is that it provides a means for evaluating the relative distribution of vulnerability at a sub-national level. Our results show that the regions deemed to be most vulnerable to exposure to extreme events and climate change/variability do not always overlap with the most vulnerable populations. Rather, our study confirms the findings of Cutter et al. (2000) on the vulnerability of Georgetown, that the overall vulnerability of the South African farming sector is characterized by a combination of medium-level risk exposure coupled with medium to high levels of social vulnerability. Our findings indicate that farmers in the Western Cape will be confronted with high exposure to extreme events and climate change/variability. They will therefore incur great economic losses. However, the adaptive capacity of this province is high due to its greater wealth, high infrastructure development, and good access to resources. In contrast, for Limpopo, Kwazulu Natal and the Eastern Cape, it will take only moderate climate changes to disrupt the livelihoods and wellbeing of the rural inhabitants, who are largely subsistence farmers. Thus, climate change will

increase the burden of those who are already poor and vulnerable. General policy recommendations can be drawn from the above results. First, given large spatial differences across province-level vulnerability, policy makers should tailor policies to local conditions. In addition, climate change should be placed within the broader developmental context. An effective way to address the impacts of climate change would be to integrate adaptation measures into sustainable development strategies, thereby reducing the pressure on natural resources, improving environmental risk management, and increasing the social wellbeing of the poor. In regions found to be highly vulnerable, such as Limpopo, Kwazulu Natal, and the Eastern Cape, policy makers should enact measures to: support the effective management of environmental resources (e.g., soil, vegetation and water resources); promote increased market participation, especially within the large subsistence farming sector; stimulate both agricultural intensification and diversification of livelihoods away from risky agriculture; and enact social programs and spending on health, education and welfare, which can help maintain and augment both physical and intangible human capital. Finally, policy makers should invest in the development of infrastructure in rural areas, while in high exposure regions, especially the coastal zones, priority should be given to the development of more accurate systems for early warning of extreme climatic events (e.g.,drought or floods), as well as appropriate relief programs and agricultural insurance.

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APPENDIX

Appendix 1: South African agro-climatic zones and main crops

Figure A.1: The Agro-climatic zones in South Africa

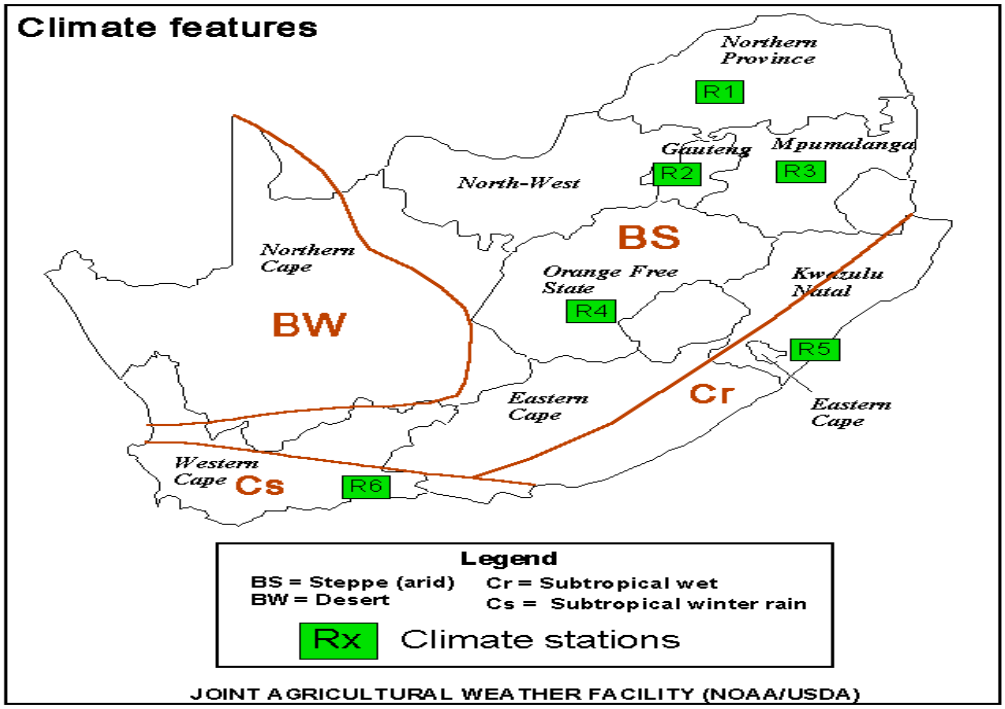
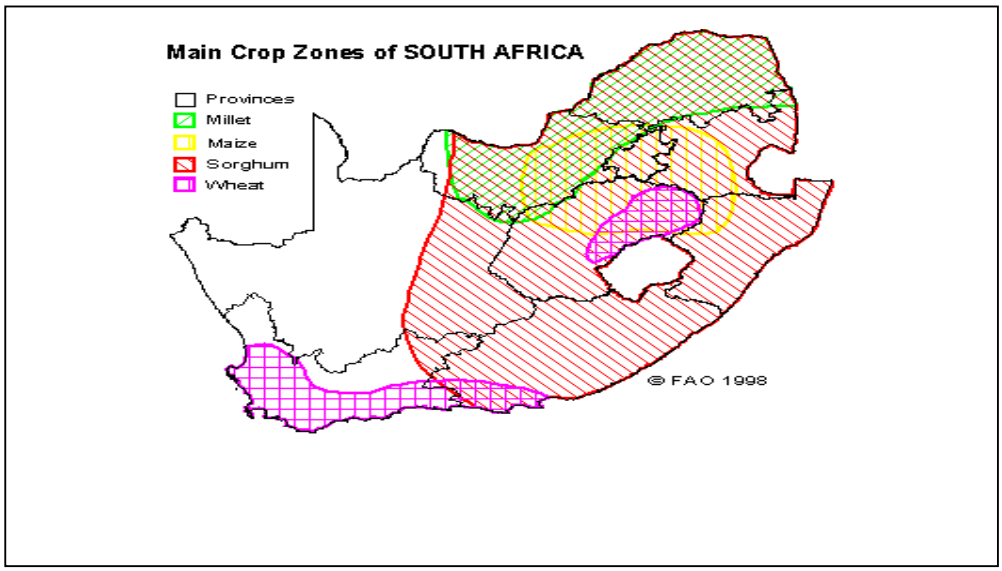
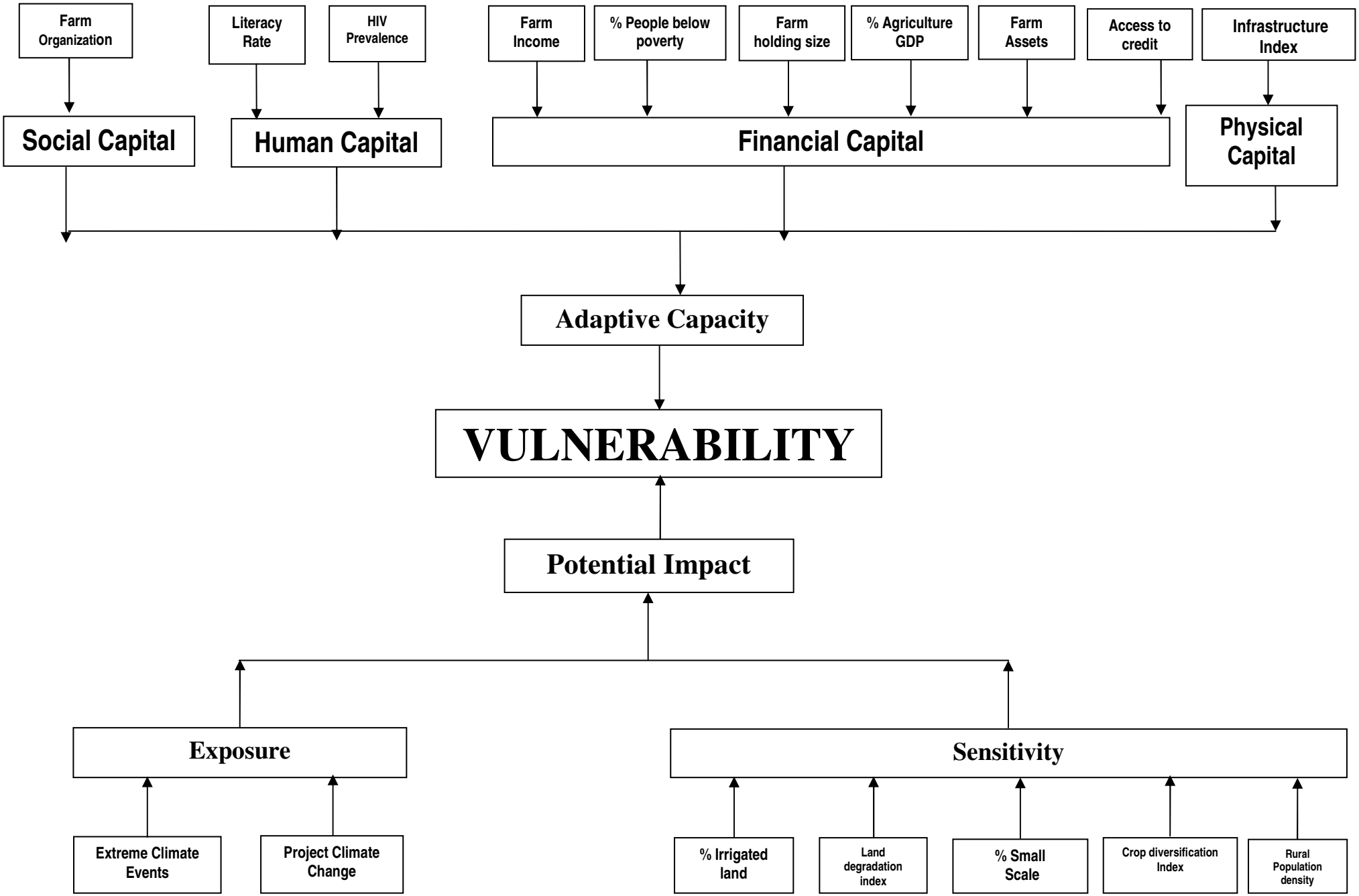


Figure A.2: The main cropping zones of the field crops



Source: FAO/GIEWS (2001)

Appendix 2: The aggregation of the different indicators towards overall vulnerability



Appendix 3: Vulnerability indicators, variables and data sources

Determinants of vulnerability	Components Indicators	Description of the indicator	Unit of measurement	Hypothesized functional relationship between indicator and vulnerability	Data source
EXPOSURE	**Extreme climate Events: floods/droughts**	**Frequency of droughts or floods**	**Number of occurrence of droughts/floods events from 1960 to 2006**	**The higher the frequency, the higher the vulnerability level**	**EM-DAT: The OFDA/CRED International Disaster Database**
	Change in climate	**Change in temperature**	**Change (delta T) in degrees from base value (2000)**	**The higher the changes from present climate normal, the higher the vulnerability level**	Climate Systems Analysis Group
		Change in precipitation	**Percentage change from base value (2000)**		**University of Cape Town**
SENSITIVITY	**% Irrigated land**	**Percentage of irrigated land**	**percentage**	**The higher the land under irrigation, the lesser the vulnerability level**	**Agricultural Census**
	Land degradation Index	**Combined soil degradation and veld or vegetation degradation**	**Unit less**	**The higher the land degradation index the higher the vulnerability level**	**Meadows and Hoffman (2002)**
	% small scale farming operations	**Percentage**	**percentage**	**The higher the % of small scale farming, the higher the vulnerability level**	**Agricultural Census**
	Rural population density	**Total rural population/area**	**Population/km2**	**The higher rural population density, the higher the vulnerability level**	**Census 2001**
	Crop diversification Index[5]	**Percentage of snow area under x crops/ number of x crops**	**percentage**	**The higher the crop diversification index, the lesser the vulnerability level**	**Agricultural census**
ADAPTIVE CAPACITY	**Farm organization**	**Number of farmers members of organized agriculture**	**number**	**The higher the number of farmers, the lesser the vulnerability level**	**Agricultural Census**
	Literacy rate	**proportion of persons aged 15 years or older who were able to read and write**	**percentage**	**The higher literacy rate, the lesser the vulnerability level**	**Census 2001**
	HIV prevalence	**Percentage of people infected by HIV**	**percentage**	**The higher the HIV prevalence, the higher the vulnerability level**	**Census 2001**
	Access to credit	**Amount of credit received**	**rand**	**The higher access to credit, the lesser the vulnerability level**	**Agricultural Census**
	Farm income	**Net farm income**	**rand**	**The higher farm income, the lesser the vulnerability level**	**Agricultural census**
	Percentage of people below poverty	**Proxy unemployment rate**	**percentage**	**The higher the proportion of people below poverty line, the higher the vulnerability level**	**Census 2001**
	farm holding size	**Average farm size**	**hectares**	**The higher size of land, the lesser the vulnerability level**	**Agricultural census**
	Share Agricultural GDP	**Percentage**	**percentage**	**The higher the share, the higher the vulnerability level**	**Census 2001**
	Farm assets	**Total value of farm assets**	**rand**	**The higher farm assets, the lesser the vulnerability level**	**Agricultural census**
	Infrastructure Index	**Computation of infrastructure index[3]**	**Unit less**	**The higher infrastructure index, the lesser the vulnerability level**	**Agricultural census**

[5] The computations of crop diversification index and infrastructure index are illustrated in the appendix section