TECHNIQUES FOR ASSESSING IMPACTS OF PROJECTED CLIMATE CHANGE ON AGROHYDROLOGICAL RESPONSES IN THE LIMPOPO CATCHMENT

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ABSTRACT

Climate detection studies point to changes in global surface temperature and rainfall patterns over the past 100 years, resulting from anthropogenic influences. Studies on the analysis of rainfall patterns [1950 – 1999] in southern Africa's summer rainfall areas show an increase in the duration of late summer dry spells, and this change is in line with expected effects of global warming. Observations of surface temperature increases are consistent with climate projections from General Circulation Models (GCMs), as well as with overall changes in climate over the past century. As such, the alterations in climate conditions have a potential to significantly impact agro-ecosystems. The changes in these climatic patterns are projected to result in a cascade of changes in crop responses, and their associated crop yield-*limiting* factors through altering water available for agriculture, as well as yield-*reduction* factors by increasing pest/disease/weed prevalence, both of which may lead to agricultural production being affected severely. The objective of this study is to explore effects of scenarios of climate change on agrohydrological responses in the Limpopo Catchment, with an emphasis on the development and application of statistical modelling and analysis techniques.

The algorithms of temperature based life cycle stages of the *Chilo partellus* Spotted Stem Borer, those for agricultural water use and production indicators, and for net above-ground primary production (an option in the *ACRU* model) as a surrogate for the estimation of agricultural production. At the time that these analyses were conducted, the downscaled daily time step climate projections of the ECHAM5/MPI-OM GCM, considered to indicate projections that are midway between the extremes from other GCMs for southern Africa, were the only scenarios available at a high spatial resolution which had been configured for South Africa. Further, the statistical analysis techniques conducted in the dissertation include quantitative uncertainty analyses on the temperature and precipitation projections from multiple GCMs (the output of which subsequently became available), as well as validation analyses of various algorithms by comparing results obtained from the GCM's present climate scenarios with those from historically obtained climates from the same time period.

The uncertainty analyses suggest that there is an acceptable consistency in the GCMs' climate projections in the Limpopo Catchment, with an overall high confidence in the changes in mean annual temperature and precipitation projections when using the outputs of the multiple GCMs analysed. However, the means of monthly projections indicated varied confidence levels in the

GCMs' output, more so for precipitation than for temperature projections. Findings from the Validation analyses of the ECHAM5/MPI-OM GCM's present climate scenario estimations of agricultural production and the agricultural yield-*reduction* (*Chilo partellus*) factor against those from observed baseline climate conditions for the same time period indicated a positive linear relationship and a high spatial correlation. This suggests that the ECHAM5/MPI-OM GCM's present climate scenario is relatively robust when compared with output from observed climate conditions.

ECHAM5/MPI-OM GCM projections show that agricultural production in future might increase by over half in the southern and eastern parts of the Limpopo Catchment compared to that under present climate conditions. Findings from the projections of the yield-*limiting* factor representing water available for agriculture over the Catchment suggest increases in the agricultural water *productivity* indicator under future climate conditions, with pronounced increases likely in the eastern and southern periphery. On the other hand, the agricultural water *use* indicator maintained high crop water use over most of the Catchment under all climate scenarios, both present and future. These positive effects might be due to this particular GCM projecting wetter future climate conditions than other GCMs do. Similar increases were projected for the yield-*reduction* factor, *viz*. the development of *Chilo partellus* over the growing season. These results suggest an increase in the *C. partellus* development, and thus prevalence, over the growing season in the Catchment, and this correlates spatially with the projected rise in agricultural production. The projected positive effects on agricultural production are thus likely to be reduced by the prevalence in agricultural yield-*reduction* factors and restricted by agricultural yield-*limiting* factors.

The techniques used in this study, particularly the temperature based development models for the agricultural yield-*reduction* factor and the agricultural water *use*/water *productivity* indicators, could be used in future climate impact assessments with availability of outputs from more and updated GCMs, and in adaptation studies. This information can be instrumental in local and national policy guidance and planning.

Keywords: Climate projections (scenarios), agricultural production, agricultural yield-*reduction* (*Chilo partellus*) and -*limiting* factors, uncertainty analysis, validation analysis

DECLARATION

I declare that this dissertation titled "Techniques for Assessing Impacts of Projected Climate Change on Agrohydrological Responses in the Limpopo Catchment" is the result of my own research, except where indicated and cited in the references. The dissertation has not been accepted for any degree, nor has it simultaneously been submitted in candidature of any other degree.

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07.2009 **NATIONAL LAND CARE CONFERENCE (Co-author)**

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Authors: AE Nesamvuni, RG Lekalakala and BM Petja

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09.2009 **14TH SANCIAHS SYMPOSIUM**

BEEH University of KwaZulu-Natal, Pietermaritzburg, RSA

Title: PROJECTION OF WATER USE AND PRODUCTION IN THE LIMPOPO CATCHMENTS USING PERFORMANCE INDICATORS: PRELIMINARY RESULTS

Authors: RG Lekalakala and RE Schulze

(Based on Chapter 8 in this document)

09.2009 **CONFERENCE ON SUSTAINABLE LAND MANAGEMENT IN DRYLANDS OF SOUTHERN AFRICA**

Ministry of Environment, Windhoek, Namibia

Title: PROJECTED HYDROLOGICAL RESPONSES TO LAND DEGRADATION AND SUGGESTED PLAUSIBLE ADAPTATION STRATEGIES

Authors: RG Lekalakala and RE Schulze

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Title: SPATIAL-TEMPORAL ANALYSIS OF PROJECTED IMPACTS USING THE ECHAM5/MPI-OM GCM CLIMATE SCENARIOS ON THE SHALLOW GROUNDWATER RECHARGE RATES IN LIMPOPO CATCHMENT OF SOUTH AFRICA

Authors: RG Lekalakala, RE Schulze and RP Kunz

10.2008 **INTERNATIONAL CONFERENCE ON CLIMATE CHANGE**

Limpopo Department of Economic Development, Environment and Tourism, Polokwane, RSA

Title: A SPATIAL ANALYSIS OF THE PROJECTED EFFECTS OF CLIMATE CHANGE ON EMERGING AGRICULTURAL PRODUCTION, INCLUDING THE BIOTIC AND ABIOTC FACTORS AFFECTING AGRICULTURAL YIELDS IN THE LIMPOPO CATCHMENT

Authors: RG Lekalakala and RE Schulze

09.2007 **SCIENCE AND AGRICULTURE FACULTY RESEARCH DAY**

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Title: AN ANALYSIS OF THE IMPACTS OF CLIMATE CHANGE ON EMERGING AGRICULTURE IN LIMPOPO: PRELIMINARY INVESTIGATIONS

Authors: RG Lekalakala, M. Warburton and RE Schulze

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SECTION ONE: INTRODUCTION

1. INTRODUCTION

1.1 Background: Detection of Climate Change, Worldwide and in South Africa

Over the past few decades, significant changes in climate have been detected throughout the world, and these have exceeded what would have been expected from natural climate variability. According to Hardy (2003), climate change is an additional change to that of natural climatic variability and is related directly or indirectly to human activities. These activities alter the global atmospheric composition over time. Observed global surface temperatures over a 100 year period [from 1861 to 2000] have shown an increase of about 0.15 ^{o}C per decade (IPCC, 2001). Similarly, the detection analyses of surface air temperature records by Warburton *et al.* (2005) for a 51 year record [1950 to 2000] over South Africa, Lesotho and Swaziland, showed increases across a range of surface air temperature parameters, such as winter, summer and annual means of daily minimum and maximum temperatures as well as heat units, and also changes in frost dates.

Furthermore, an examination by the Intergovernmental Panel on Climate Change (IPCC, 2007), using rainfall records from 1900 to 2005, indicated a reduction in precipitation over some parts of southern Africa and an enhancement in other parts. Analyses by Hewitson *et al.* (2005) of precipitation trends over southern Africa for the period from 1950 - 1999 showed an increase in the duration of late summer dry spells in nearly the entire summer rainfall region. They also stated that the changes in rainfall patterns were in line with the expected effects of global warming (Hewitson *et al.*, 2005). The IPCC (2007) also observed a significant decline in precipitation patterns in southern Africa, but over the period 1900 to 2005. In addition to this, global analyses on trends in precipitation from the IPCC (2007) and a study by Warburton (2005) on detection analyses of changes in precipitation over the South Africa for the 1950 to 2000 time period, suggest that variations in annual precipitation may range from small increases or decreases to large increments or reductions.

Most climate projection studies indicate that the changes in climate are expected to accelerate further in the future (Christensen *et al.*, 2007; IPCC, 2007; Zaehle *et al.*, 2010). The third IPCC Assessment Report (IPCC, 2001) indicated a 0.6 ^{o}C [range 0.4 to 0.8 ^{o}C] increase in observed air and sea surface temperatures from 1901 to 2000. However, analyses summarised in the updated fourth IPCC Assessment Report (IPCC, 2007) show a higher increase in temperature, *viz*. 0.74 ^{o}C [range 0.56 to 0.92 ^{o}C], from 1906 to 2005. In the agriculture sector, results of changes in climate have also been detected, for example, by lengthened growing seasons and earlier flowering dates of fruit trees (IPCC, 2001).

A large portion of the population and economy in South Africa is reliant on agriculture. The FAO (1999) reported that food production for livelihoods was likely to be more insecure when climate changes and could result in more frequent crop failure. To ensure sustainability of food production, greater and more in-depth understanding is therefore required on the vulnerability of agriculture to any impacts of climate change and the strategies that are applicable to cope with, and/or adapt to, the effects of climate change.

1.2 Climate Change Related Drivers and their Effects on the Agrohydrological System

The major climate change related drivers which are important in the agricultural and water sectors are enhanced atmospheric carbon dioxide (CO_2) concentrations, increases in temperature and changes in precipitation (McCarl *et al*., 2001; CEEPA, 2002). They affect major agrohydrological responses by changing the evaporative demand, the rates of photosynthesis, the partitioning of precipitation into the various components of runoff and elements of water quality. These responses to climate change related drivers would therefore affect the landscape on which the natural land cover and soil properties have already been altered due to other anthropogenic activities. Key agricultural issues in climate change are spatial changes (i.e. shifts, gains or losses) in climatically suitable areas for specific crops, and hence of resultant hydrological responses from these areas (Schulze, 2001; Schulze, 2005a).

In this study, the interactive effects of climate change factors (such as temperature and rainfall) are assessed on selected components of the agricultural sector in the Limpopo Catchment within South Africa. The assessment of the effects of climate change is conducted using baseline climate conditions as a reference climate, together with projected future climate change scenarios.

The climate change related drivers highlighted in Kundzewicz *et al*. (2007) to be the most prevailing determinants of water availability are temperature and precipitation, including an area's evaporative demand, which is largely a function of prevailing temperatures. There against, the changes in agricultural crop growth and yields projected for elevated CO_2 concentrations, higher temperatures and changes in precipitation conditions were found to be variable not only from place to place, but also from crop to crop (Easterling *et al*., 2007). Other agriculturally related variables which will be altered directly or indirectly by the above-mentioned three climate change related drivers include transpiration, extreme events and impacts on weeds, pests and pathogens.

Rotter and Van de Geijn (1999) showed that increases in temperature regimes were likely to affect certain processes operating within plants (e.g. photosynthesis, water use efficiency and growth), thus affecting plant yields. Their investigation further indicated that increases in atmospheric CO_2 concentrations would possibly have an indirect effect on temperature (i.e. warming), and a direct effect on a plant's processes related to photosynthesis and water use efficiency (WUE).

In the tropics and subtropics, in which the Limpopo Catchment is located, most crops are generally assumed to already have reached their highest temperature tolerance levels, and studies indicate that crop yields there would be reduced as a result of increases in temperature (McCarl *et al*., 2001; CEEPA, 2002; Peng *et al*., 2004). Additional evidence points to pest incidences increasing in response to a rise in temperature, and this might result in reductions in crop production (IPCC, 2007). A more comprehensive discussion on impacts of climate change related drivers on agriculture production is presented in the literature review.

1.3 Rationale for Studying Effects of Climate Change on Agriculture

Agriculture is one of the most important sectors contributing to the economy, to food security and to the livelihoods of many people in South Africa (FAO, 2004). Much of the agricultural production in the Limpopo Catchment of South Africa derived from subsistence farming, is dependent mainly on rainfall rather than on irrigation (FAO, 2004; Van Averbeke and Khosa, 2007). Climatic conditions thus play a crucial role in agriculture as a result of plants being reliant on climate for their development and yield. Thus, climate variability will result in variability of crop production (Rosenzweig and Hillel, 1998; Young and Long, 2000; Rosenzweig *et al.*, 2000; Kurukulasuriya and Rosenthal, 2003). Furthermore, several other factors are controlled by climate, such as pest and disease infestations, as well as the water which is available for irrigation (Rosenzweig *et al*, 2000; Aggarwal *et al*., 2006; Easterling *et al*., 2007). On a global scale the IPCC (2007) paints a picture of a future where temperature regimes are higher than at present throughout the entire growing season(s) and fluctuations in rainfall also generally increases from one season to the next.

Changes in climate are projected in the IPCC (2007) report suggests that the changes might impact crop production in the Limpopo Catchment, mainly through changes in temperature and rainfall patterns. Conventional thinking is that the impacts could increase the vulnerability of agricultural production and hence affect, *inter alia*, food security. Other factors which could contribute to negative effects of climate change are the less advanced technologies used to protect the Limpopo region from floods and/ or droughts. Moreover, in addition to variability in climate, the use of marginal areas less suitable for agriculture due to poor soils, or steep terrain, as well as the lack of skilled labour, exacerbate any further impacts of climate change on agricultural production.

1.4 Rationale for Conduct the Research in the Limpopo Catchment in South Africa

The Limpopo Catchment in South Africa forms part of the Greater Limpopo River Catchment, which is made of sets of subcatchments in Botswana, Zimbabwe and Mozambique in addition to the Limpopo Catchment within South Africa, the latter being the major economic ‘hub’ of the Southern African Development Community (SADC) region.

The Limpopo Catchment covers parts of four of South Africa’s nine Provinces. These are Limpopo, which is almost completely within the Catchment, and smaller parts of Gauteng, Mpumalanga and North West Provinces. Because of the inclusion of parts of Gauteng the Catchment is highly populated, housing approximately 45 % of the Country’s total population (FAO, 2004). Large tracts of the Limpopo Catchment are, however, predominantly rural and poor. The largely semi-arid climatic conditions, with generally scarce water resources, coupled with occasional extreme drought and flood events, add to the high levels of poverty and food insecurity. The high poverty levels can further be related to a number of factors, one being the legacy of the Apartheid regime during which Black Africans were often confined to the drier and agriculturally less suitable parts of South Africa, with little to no access to physical resources and with low adaptive capacity (Lévite *et al.*, 2003). In addition, the lack of financial resources renders the subsistence farmers in the Catchment more vulnerable to climate variability and change compared to commercial farmers (Bharwani *et al*., 2005).

This study on developing techniques to better understand interactions of effects of the climate change related drivers on the agrohydrology is undertaken at high spatial and temporal resolutions. A study of this nature contributes to a nation's knowledge and helps to form the scientific background for agriculture and water policy making, in this case for the Province, the country and the wider SADC.

1.5 Research Objectives and Layout of the Document

The core research objective of this study was to demonstrate statistical modeling and analysis techniques on the understanding and assessment of the sensitivity, thresholds of change and effects of potential interactions of climate change on agrohydrological responses, including agricultural yield-*reduction* factors (e.g. agricultural crop pests) and yield-*limiting* factors (e.g. agricultural water use and productivity) over the Limpopo Catchment. The reasoning behind this objective is that as more improved, more certain (in terms of the projected climate), higher spatial resolution and finer temporally continuous climate change scenarios are now becoming available (IPCC, 2001; IPCC, 2007; Bhat *et al*., 2011; Schulze, 2010), compared to those available in past studies (e.g. Perks, 2001), the climate change scenarios may be utilised in simulations to better assess the implications of climate change and to better implement pro-actively any adaptation measure(s) for the future.

The emphasis in this study is therefore on ***development and application of techniques for analysis and interpretation of results***, rather than on the results *per se*. It should nevertheless be appreciated that the use of GCM climate scenarios for projecting future climates is the product of a powerful computational tool that takes into consideration many complex processes in the land-ocean-atmosphere system (IPCC, 2007). Furthermore, Kundezewicz *et al*. (2007), as well as other studies (Mearns *et al*., 2001; Hewitson *et al*., 2005; IPCC, 2007), point out a common pattern arising from all future climate scenarios from various GCMs, which is that the GCMs with the same projected emissions scenarios all indicate an increase in future temperature, but varying spatial and temporal changes in rainfall attributes.

The techniques developed and presented in this study could therefore be used in future studies using outputs of a series of GCMs for evaluating impacts of projected future climates on agricultural production, and yield reducing and limiting factors.

The broad objective outlined above was achieved by the following five sub-objectives, which have been addressed in the chapters as indicated below:

Sub-objective 1: *Review literature on the drivers of climate change which influence agricultural production, including a review on agricultural yield-reduction and -limiting factors* (**Chapter 3**). Furthermore, in **Chapter 4** a brief review on the types of uncertainties related to GCM outputs is given, as is an assessment as to levels of agreement in the temperature and precipitation outputs from GCMs.

Sub-objective 2: *Assess the sensitivity and thresholds of change in the spatial distribution of potential agricultural production, using baseline climate conditions (i.e. from observed climate data) as a point of departure and an analyses of the projected climate scenarios from the ECHAM5/MPI-OM GCM.* This sub-objective is addressed in **Chapter 6**.

Sub-objective 3: *Determine the likely distribution of the **Chilo partellus** Spotted Stem borer, over the Limpopo Catchment for both baseline climate conditions and for projected ECHAM5/MPI-OM GCM climate scenarios* (**Chapter 7**). ***Chilo partellus*** is an agricultural yield reduction factor over the Limpopo Catchment.

Further to the above sub-objectives, a synoptic perspective is presented of agricultural yield-*reduction* factors required to assess the potential impacts they pose on agricultural production. This information can be used pro-actively in managing biological invasions and in developing appropriate long-term strategies on a large-scale.

In addition, in **Chapters 6** and **7**, the ECHAM5/MPI-OM GCM simulations under present climate conditions were used in verification studies of agricultural production, as well as for distributions of *C. partellus*.

In order to highlight the importance of **Sub-objective 3,** it is stressed that the agricultural yield-*reduction* factor which was studied, *viz. C. partellus*, is amongst the major cereal crop pests in southern Africa (Way and Kfir, 1997; Duale and Nwanze, 1999; Kfir *et al.*, 2002). For example, the conventional control method of *C. partellus* by insecticides has not only been found to be an expensive by Kfir (2001) and environmentally-unfriendly exercise, but has also proven to be ineffective owing to the chemicals used being unable to penetrate into the host stalk where the *C. partellus* larvae reside and where their development stage takes place (cf. **Chapter 6**).

Sub-objective 4: *Evaluate the projected impacts of a changed climate related drivers on agricultural water use and productivity, i.e. water being viewed as an agricultural yield limiting factor*. The techniques which were used for spatially evaluating beneficial utilization and productivity of water in the dryland agricultural sector are presented in **Chapter 8**. The techniques were used to map the distribution patterns of dryland agricultural water use and water productivity at high spatial resolution (which had not been done before) for baseline climate conditions and projected GCM climate scenarios over the Limpopo Catchment.

Sub-objective 5: *Draw conclusions on the impact analyses in the Limpopo Catchment and make recommendations relating to future impact assessment studies of this nature.* This was undertaken in light of the sub-objectives outlined above and the application of techniques developed in this research,

The layout of the document is as follows;

Section One: Introduction

Chapter 1: Introduction

Chapter 2: Study Area

Section Two: Literature Review

Chapter 3: Review of the Effects of Climate Change Drivers on Agricultural Production (crop and livestock) as well as the Agricultural Yield-Limiting and -Reducing Factors

Chapter 4: Uncertainty Analysis of Climate Projections

Section Three: Methodology

Chapter 5: Databases and Models

Section Four: Results and Discussion

Chapter 6: Effects of Projected Future Climate Change on Net Above-Ground Primary Production

Chapter 7: Effects of Projected Future Climate Change on the *Chilo partellus* Spotted Stemborer

Chapter 8: Effects of Projected Future Climate Change on Agricultural Water Use and Productivity

Chapter 9: Conclusions

Chapter 10: References

Appendices

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Following this introductory chapter, background information on the study area is presented in **Chapter 2**. This includes information on the population characteristics and history, the physical environment, climate, hydrology and agriculture.

2. STUDY AREA

In this chapter an introduction is presented to the study area, *viz.* the Limpopo Catchment. The background information presented is on the Catchment's location, its population and (briefly) its history, as well as biophysical characteristics.

2.1 Geographical Location

The Limpopo Catchment in South Africa (**Figure 2.1**), hereafter referred to as the Limpopo Catchment, forms part of the Great Limpopo River Basin which also comprises of catchments within the political boundaries of Botswana, Zimbabwe and Mozambique. The Limpopo Catchment contributes to the runoff of the Limpopo River, mainly from the Marico and Crocodile Rivers. The Limpopo River is joined to the Notwane River from Botswana, forming a boundary between Botswana and South Africa, and eventually flows through Mozambique into the Indian Ocean.

The Limpopo Catchment incorporates most of the Limpopo Province (in the north), and portions of the North West (in the southwest), Mpumalanga (in the southeast) and Gauteng (in the south) Provinces, with the latter being the economically most productive region in Africa (FAO, 2006). The Catchment thus links South Africa to other sub-Saharan Africa countries, both economically and hydrologically. The Catchment's economic importance is based on its major economical activities such as mining, industry and agriculture (Earle *et al*., 2006; Krishna *et al*., 2006).

Hydrologically, the Limpopo Catchment is comprised of the Limpopo (Drainage Area A) and Olifants (Drainage Area B) Primary Catchments (**Figure 2.1**), which form part of the 22 Primary Catchments making up the drainage regions of South Africa (cf. **Section 5.2**). These two Primary Catchments are each comprised of two Water Management Areas (WMAs), with the Limpopo and Luvuvhu/Letaba WMAs being in Drainage Area A, while the Olifants and Crocodile/Marico WMAs are in Drainage Area B (cf. **Figure 2.1** ; FAO, 2004).

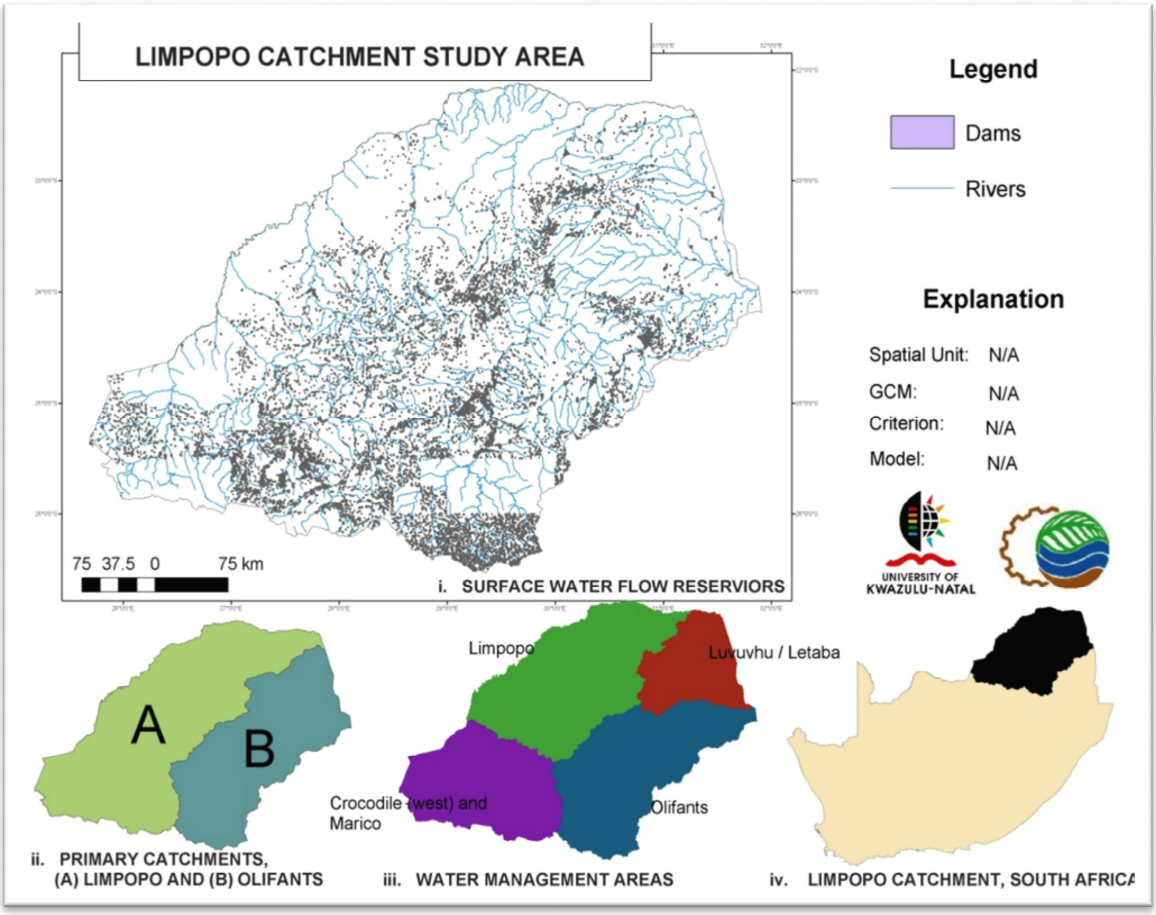

Figure 2.1 (i) Major rivers, tributaries and dams, (ii) Primary Catchments and (iii) Water Management Areas making up (iv) the Limpopo Catchment in South Africa (FAO, 2006; Source data: BEEH, 2008)

In **Table 2.1** the areas of the WMAs, as well as the names of major rivers, are given. The Minister of the Department of Water Affairs (formerly Department of Water Affairs and Forestry) is to establish nine Water Management Areas (WMAs) to serve as water resource management entities in line with the National Water Resource Strategy (NWRS, 2004). A Water Management Area will have a Catchment Management Agency (CMA, as outlined in the National Water Act 36 of 1998) with a mandate to carry out duties of protection, use, development, conservation, management and control of the water resources.

Table 2.1 Water Management Area characteristics (FAO, 2004)

Water Management Area (WMA)	WMA ID	Area (km^2)	Major Rivers
Limpopo	1	60 890	Limpopo, Matlabas, Mokolo, Lephalala, Mogalakwena, Sand and Nzhelele
Luvuvhu and Letaba	2	25 880	Mutale, Luvuvhu and Letaba
Crocodile (West) and Marico	3	43 571	Crocodile (West) and Marico
Olifants	4	54 957	Eland, Wilge, Steelport and Olifants

2.2 Population Characteristics and the Catchment's History in the Context of South Africa

The Limpopo Catchment covers an area of 185 298 km^2 (FAO, 2004), making up 15% of the total area of South Africa. It forms a major portion of the Great Limpopo River Basin, occupying 45% of its total area (FAO, 2004). The United Nation Development Program Report of 2003 reported the population in the Limpopo Catchment to be 10.7 million people (i.e. population density of 57.7 people per km^2).

The high population, many of whom reside in rural areas, is partially a result of the former homelands system under past migration policies of the pre-1994 National Party government, which largely restricted Black African populations from migrating to urban areas (FAO, 2006). Lévite *et al.* (2003) state that this area, particular the Olifants WMA within the Limpopo Catchment, still reflects the influence of the past 'apartheid' government, during which people were geographically divided based on race. Many Black African's during this era were confined to the homeland areas (**Figure 2.2**), which were frequently located in agriculturally marginal and/or hydrologically relative dry parts of catchments (Lévite *et al.*, 2003), with limited access to financial and marketing resources and with low potential to realise high agricultural production (Earle *et al.*, 2006). The homelands within the Limpopo Catchment were the former Bophuthatswana, Gazankulu, KwaNdebele, Lebowa and Venda.

The Limpopo Catchment displays high language and ethnic diversity, with six of the national official languages recognised, in addition to other languages not officially recognised. These official languages are Afrikaans and English, spoken mostly by the White African population (of mainly Dutch and English origin), while those spoken mainly in the Black African communities include Sesotho (Sepedi), Setswana, Xitsonga, Tshivenda and IsiNdebele (Earle *et al*., 2006). The spatial distributions of the Tswana (in Bophuthatswana, who speak Setswana), Sotho (in Lebowa, who speak Sesotho), Venda (in Venda, who speak Tshivenda), Tsonga (in Gazankulu, who speak Xitsonga) and Ndebele (in KwaNdebele, who speak IsiNdebele) dominant ethnic groups, correlate closely to the former homelands depicted in **Figure 2.2** with corresponding names.

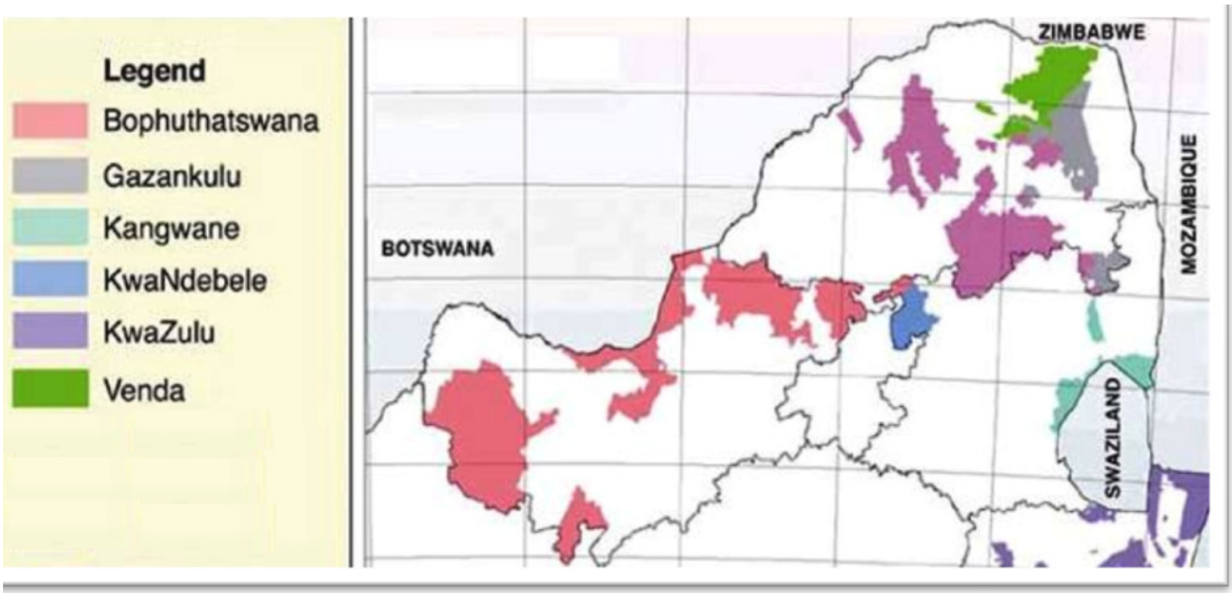

Figure 2.2 The former homelands in the north of South Africa (FAO, 2006)

2.3 The Physical Environment

2.3.1 Altitude

Altitude has influence on the climate and the responses of agrohydrological processes (Schulze, 1997; Mohamoud, 2004). The effect of altitude on the landscape varies over an area from macro- to meso-scale. *Inter alia*, it can act as a physical barrier, forcing moist air masses to rise, resulting in orographic rainfall with consequent increases in total rainfalls, the numbers of rainfall days and rainfall per rainday often being experienced on windward facing slopes (Schulze, 1997).

Thunderstorm activity (with enhanced resultant erosion) and associated lightning incidence (ground fires) also increase with altitude (Schulze, 1997).

Lower temperatures generally occur at higher altitudes, with temperature lapse rates varying from one region to the next, between seasons and with temperature parameter (Schulze, 1997). The link which exists between the rise in altitude and decrease in atmospheric pressure can be a direct factor in the transmissivity of solar radiation and in evaporation rates. At the micro-scale, changes in altitude have varying impacts on temperature at different slope gradients and aspects (Schulze, 1997). The distributions in mean annual temperature and precipitation (MAT and MAP, respectively) are strongly related to changes in altitude over the Limpopo Catchment (cf. **Figure 2.3**), with temperatures being lower at higher altitudes (cf. **Figure 2.7**) and MAP increasing (cf. **Figure 2.5**).

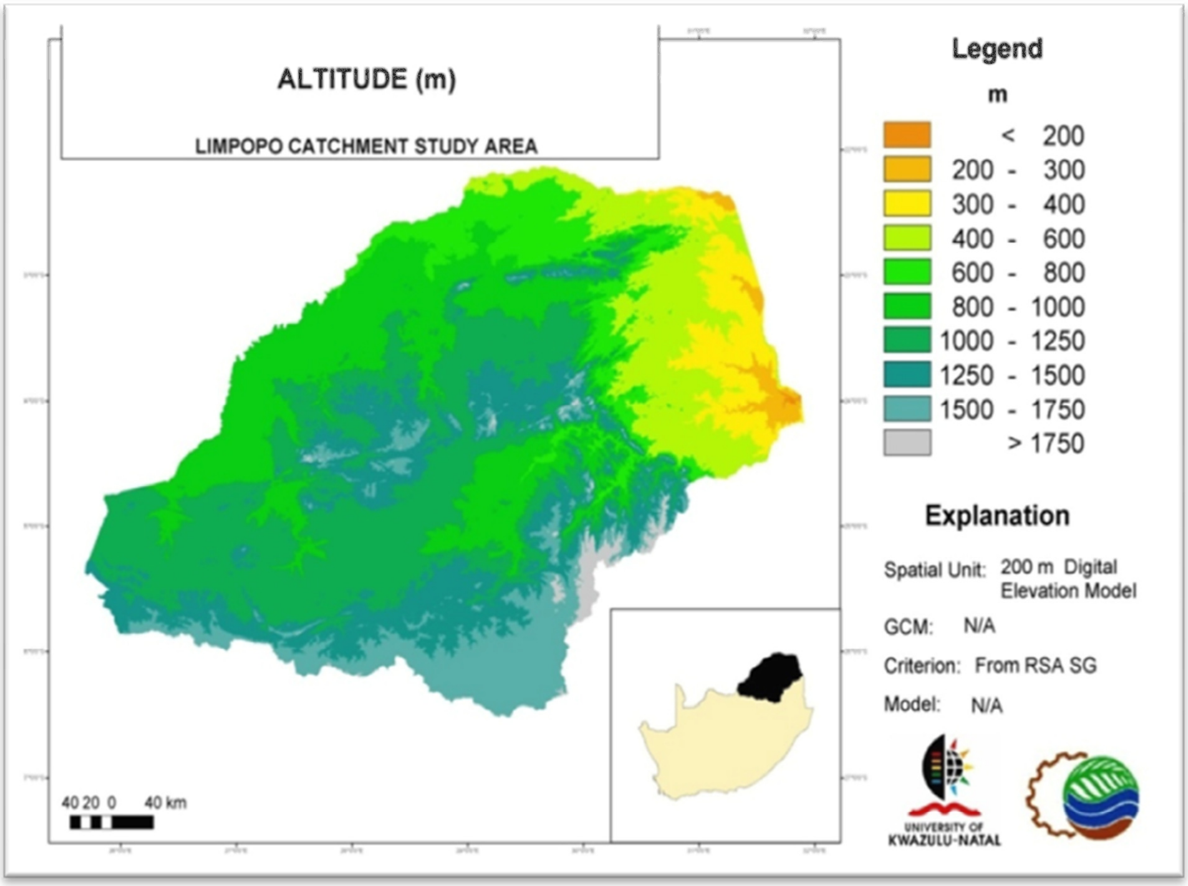

Figure 2.3 Altitude of the Limpopo Catchment (Source: Schulze and Horan, 2008)

2.3.2 Terrain morphology

Altitude does not fully explain either the characteristics of the landscape or the quantitative analysis of landforms (which can be described by indicators of local relief). Moreover, altitude *per se* is unable to evaluate the influence of the landscape on processes and activities, such as hydrological responses and the potential agriculture (Schulze, 1997). For this reason the terrain morphology is described below. The terrain morphology over the study area, shown in **Figure 2.4**, was extracted from a southern Africa map by Kruger (1983). He classed the terrain over southern Africa into six broad divisions (A to F), based on relief (cf. **Table A.1** in **Appendix A**). Of these broad divisions, all of which are represented in the Limpopo Catchment, five were further subdivided by Kruger (1983) to become 30 terrain morphology classes in total, of which 17 are found in the Limpopo Catchment.

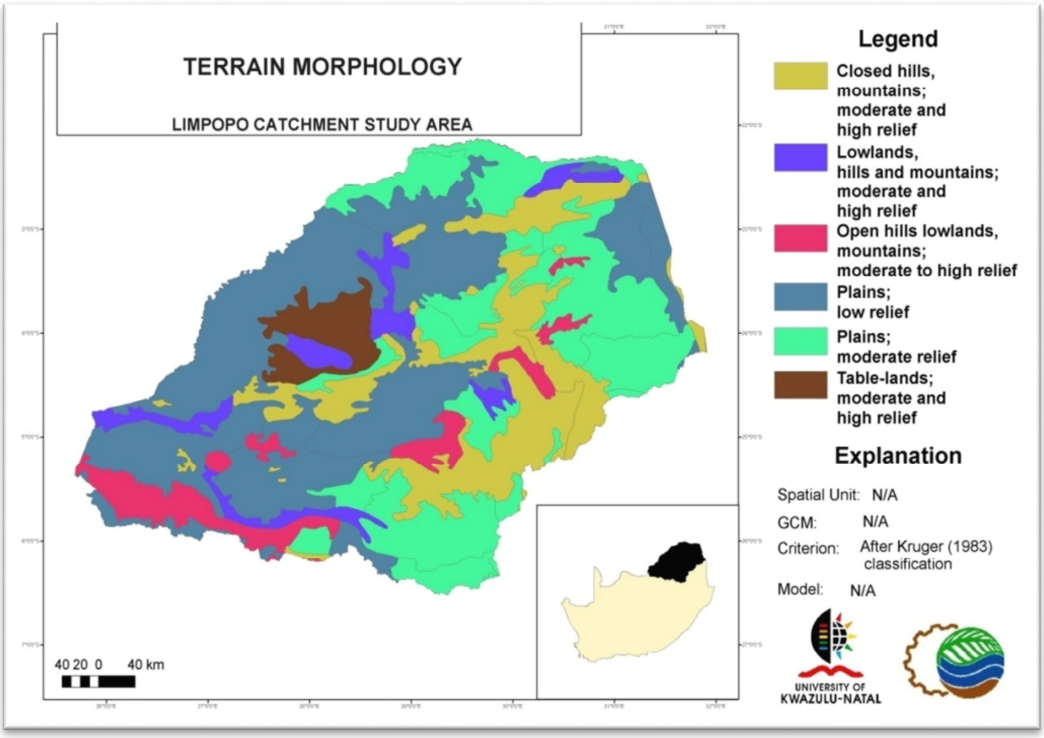

Figure 2.4 Broad divisions of terrain morphology in the Limpopo Catchment (After Kruger, 1983; Source: Schulze, 1997)

The Limpopo Catchment's terrain morphology attributes are summarised in **Table A.1** in **Appendix A**. The slope forms in the Catchment are commonly concave to straight, implying that the slopes are steep at higher elevations and flatten towards lower elevations, and are also roughly even down the slope. A concave slope is related to accumulations of soil water at its foot, due to lateral subsurface flows. Regions with such slopes (i.e. plains of low to moderate relief in **Figure 2.4**) generally result in good crop growth, but are prone to flood damage. In the Limpopo Catchment they are found along the far northern border (cf. **Figure 2.4**). Relief, referred to above, is the difference in elevation between the top and bottom of the slope (Small and Anderson, 1998). The high relief areas (> 900 m) are generally associated with shallow soils that are prone to elevated rates of erosion and rapid flood peaks. The drainage density as defined by Kruger (1983) is the length of stream (km) per unit area (km^2). The Limpopo Catchment's drainage density is generally low to medium, and hence prone to slower flows after rainfall events and less formation of gullies. The Catchment's stream frequency (i.e. stream per km^2) is generally low to medium (from 0 to 6) and this has similar hydrological implications to those of the drainage density. The percentage of area with slopes < 5 % covers more than 80 % of the Catchment and hence indicates that this area has potential for agricultural production. These terrain morphology attributes are used to interpret results from **Chapters 6**, **7** and **8**.

2.4 Climate

The baseline climate data used in generating the maps presented in this Chapter were obtained from the School of Bioresources Engineering and Environmental Hydrology (BEEH), unless the source is otherwise stated.

2.4.1 Precipitation

The quantity of water available for hydrological and agricultural purposes within a region in the long term is characterised by its Mean Annual Precipitation (MAP). Rainwater in an area such as the Limpopo Catchment, in which largely rainfed agriculture is practised, forms a portion of the limiting factor for sustained productivity, i.e. if factors such as soil, topography, photoperiod and temperature are not limiting (cf. **Chapter 8**; Schulze, 1997). Using the Markham (1970) technique, Schulze and Maharaj (2008) identified this study area to be an early to mid-summer rainfall region, i.e. with peak rainfalls in December and January, respectively. Furthermore, the rainfall season was found to be short according to the rainfall concentration index of Markham's (1970).

Figure 2.5 shows an overall northward decrease in MAP over the Limpopo Catchment, generally corresponding with changes in altitude (cf. **Figure 2.3**), amongst other factors (such as wind speed and direction; Johansson and Chen, 2003). Between the eastern catchment border and mountainous areas there are complex rainfall patterns due to uneven topography. The rainfall is markedly higher in the high altitude regions, mainly in the eastern interior and along the southern periphery. The range in rainfall is between 800 and 1 400 mm (light to dark blue colour) in high relief areas, compared with most of the Catchment which receives less than 600 mm of rainfall yearly. The Catchment as a whole receives an average annual rainfall of ~ 600 mm.

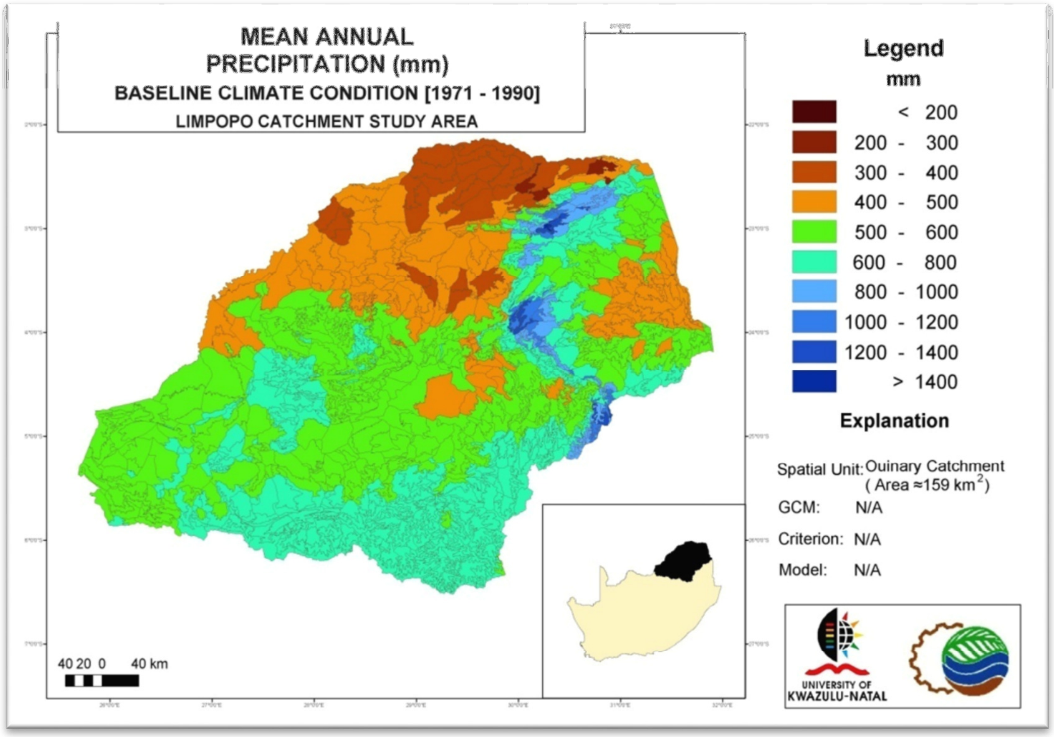

Figure 2.5 Mean annual precipitation of the Limpopo Catchment (Source data: Lynch, 2004; BEEH, 2008)

The coefficient of variation of the annual precipitation was used in this study to compare relative variability between Quinary Catchments, as this statistic considers deviations from the average by taking into account also whether the Quinary experience high or low precipitation (Schulze, 1997). The rainfall variability from year to year is of concern to both the agriculture and water resource sectors in this region. High variability in annual precipitation may make planning (e.g. plant dates; reservoir management) difficult (Palmer and Ainslie, 2002). The inter-annual variability is an index of climatic risk that indicates the potential year-to-year variability in the water resource storage and agricultural production, more particularly so in marginal areas than in dry or wet areas (cf. Schulze, 1997). The reason for this is that regions with dry conditions generally have adapted to climate variability, while for the wet regions lower variability are the norm (Schulze, 1997). In **Figure 2.6**, the Catchment's inter-annual variability is shown to increase northwards from < 20 % to > 40 %.

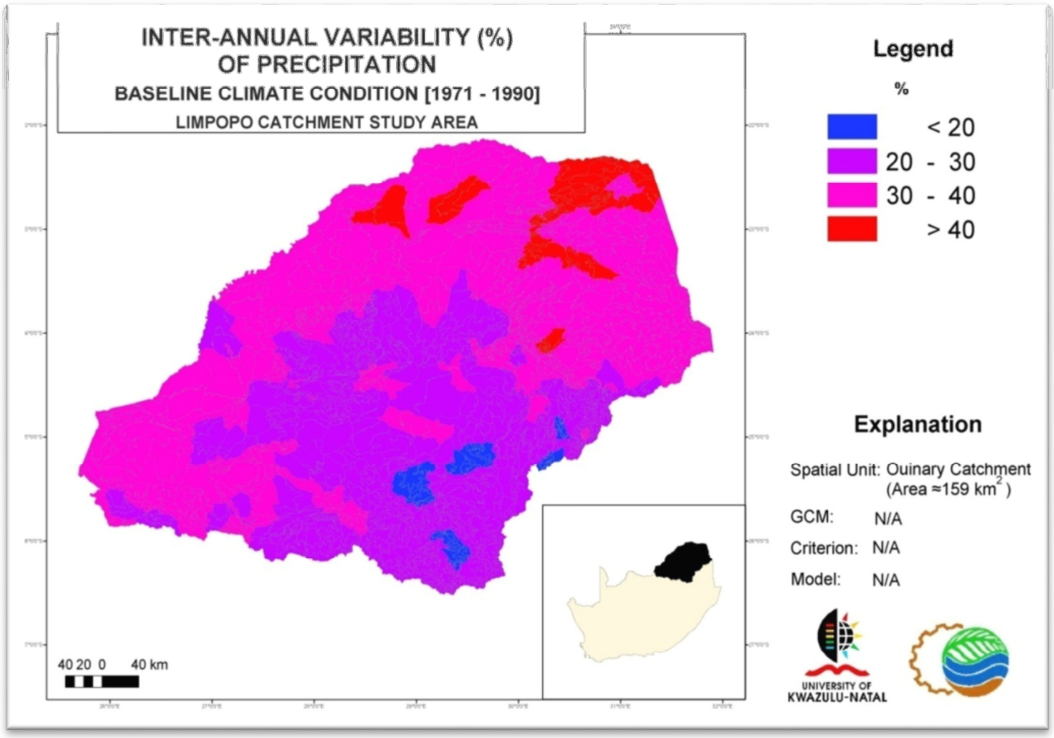

Figure 2.6 Inter-annual variability (%) of precipitation in the Limpopo Catchment (Source data: BEEH, 2008)

The MAP and inter-annual variability of precipitation are important in determining the distribution and selection of agricultural crops, the sustainability of grazing land and the generation of runoff (cf. **Section 2.6.1**; Schulze, 1997). In this regard the Limpopo Catchment experiences relatively harsh conditions, with the agrohydrological system being impacted upon by the low annual rainfall, a generally high concentration of rainfall, variable rainfall and a strong seasonality of rainfall.

2.4.2 Temperature

Temperature directly affects all life forms, processes and activities on earth and Schulze (1997) states that it is a basic climatic parameter frequently used as an indicator of energy status in the environment. Measurements of temperature are used in climatology, hydrology and agriculture applications as inputs for estimating solar radiation, relative humidity, potential evaporation, heat and chill units, frost zones and areas agroclimatically suitable for crop growth (Schulze, 1997). The Mean Annual Temperature (MAT) is a broad statistical index of the energy states of environment. This index is the first guide used for determining the region's optimum for certain agricultural production varieties (Schulze, 1997). From **Figure 2.7** it may be seen that MAT, at > 20 ^{o}C, is highest mainly along the northern and eastern borders of the Catchment. These high temperature areas correspond with areas of low altitude at < 600 m (cf. **Figure 2.3**), while at higher altitudes (> 1250 m) the MAT is below 18 ^{o}C.

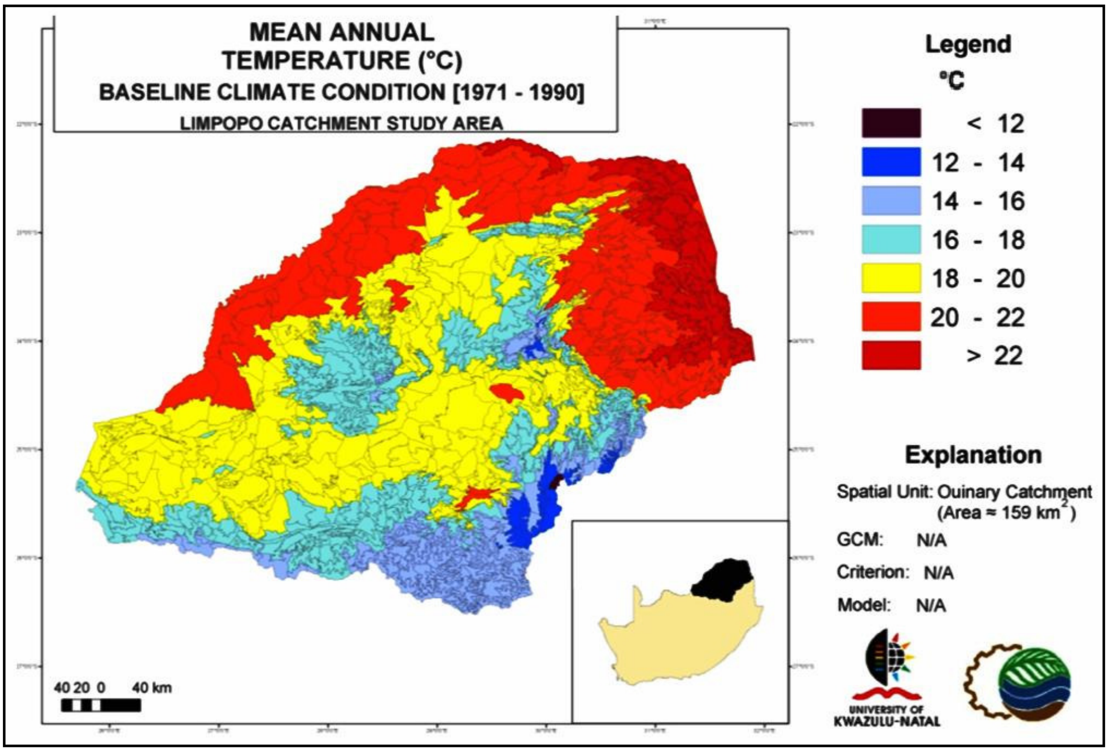

Figure 2.7 Mean annual temperature in the Limpopo Catchment (Source data: BEEH, 2008)

Summers in the Catchment are generally warm, with extreme daily maximum temperatures at times exceeding 40 ^{o}C, whereas in the winter season mild conditions are likely to be experienced. The average minimum temperature for the coldest month, *viz.* July (**Figure 2.8**), drops to below 0 ^{o}C only in the high-lying areas (> 1500 m). The Catchment warms from the northeastern towards the southern border during the warmest month, *viz.* January (cf. **Figure 2.9**), with the monthly means of daily maximum temperatures exceeding 32 ^{o}C mainly along the northern boundary of the Catchment.

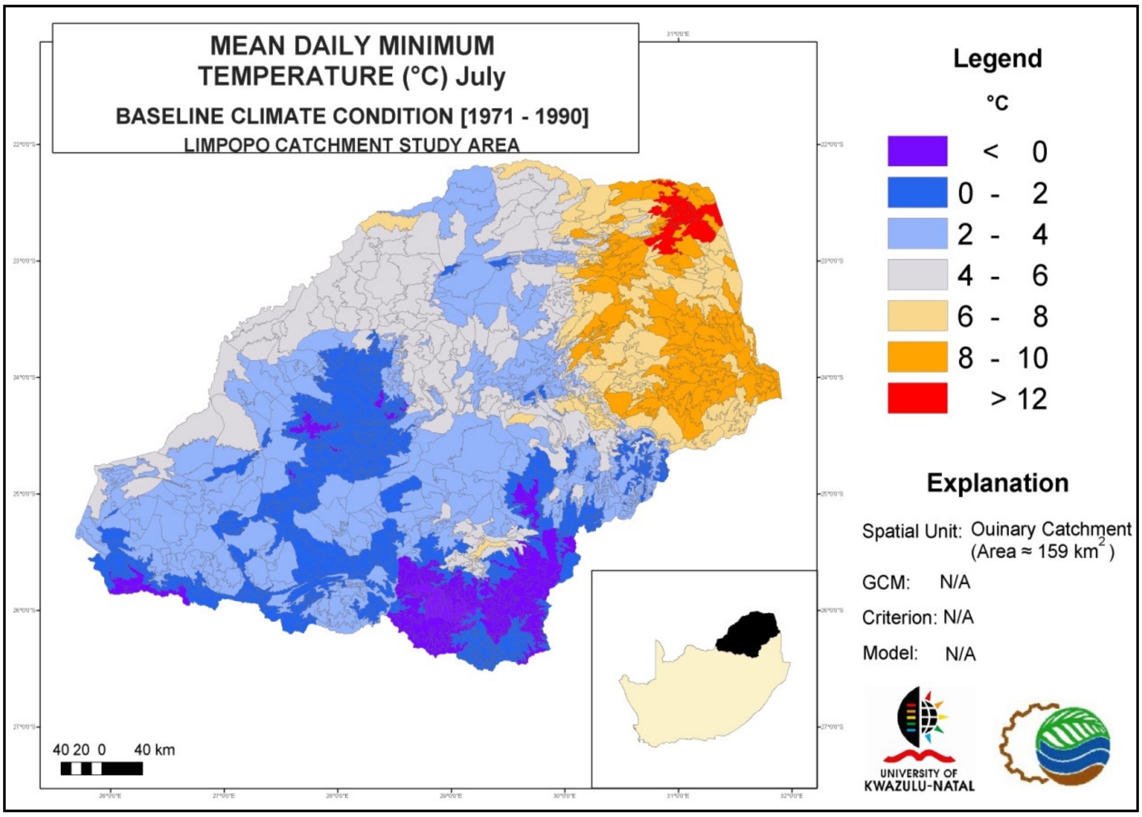

Figure 2.8 Means of daily minimum temperature in the Limpopo Catchment for July, the coldest month of the year (Source data: BEEH, 2008)

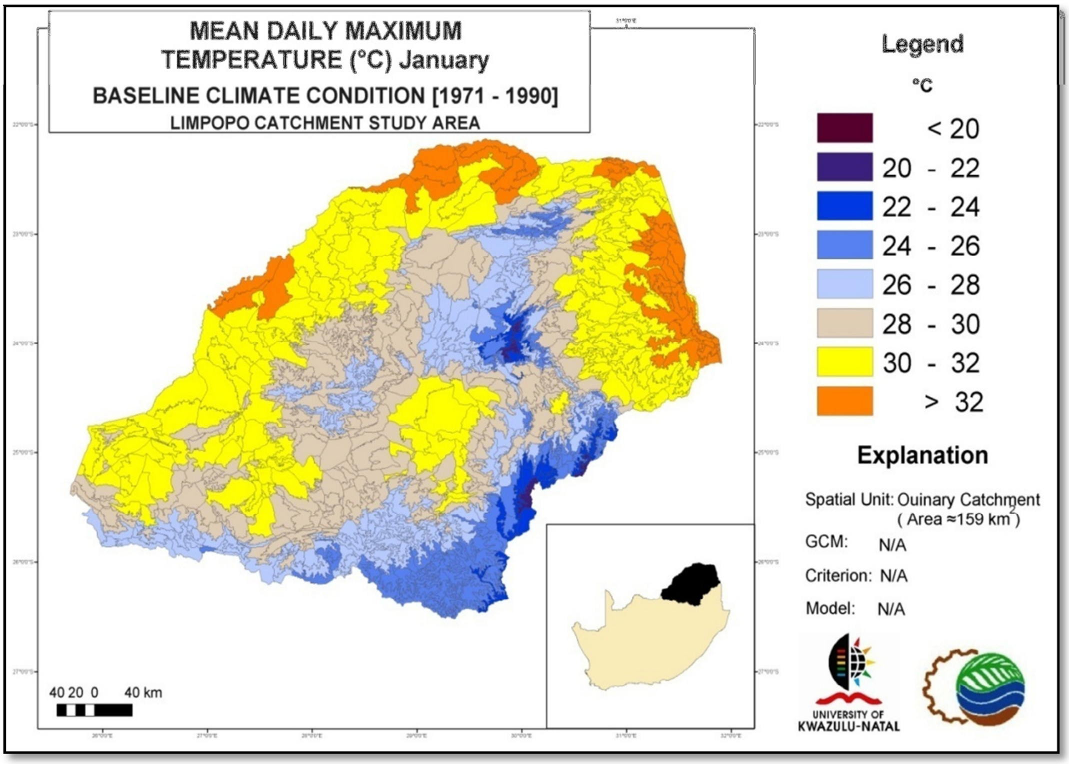

Figure 2.9 Means of daily maximum temperatures in the Limpopo Catchment for January, the warmest month of the year (Source data: BEEH, 2008)

2.4.3 Potential evaporation

Atmospheric moisture originates from water on the earth surface from; where it is transferred into the atmosphere by the process of evaporation loss from open water surfaces and through the plant leaves' stomata. The atmospheric water vapour demand, or potential evaporation, is regulated by the atmospheric water vapour holding capacity, the amount of latent heat energy for the process and the lower atmosphere's degree of turbulence. Potential evaporation occurs when there is enough water to fully satisfy the atmospheric demand (Schulze, 2008b). The high spatial resolution estimation of reference potential evaporation in **Figure 2.10**, estimated using the A-pan equivalent Hargreaves and Samani (1985) daily equation embedded into the *ACRU* agrohydrological model, is important particularly in a semi-arid and water limited region such as the Limpopo Catchment. The estimated potential evaporation is used as input for determining irrigation scheduling and evaporation from open water stores (e.g. dams). The Limpopo Catchment's mean annual potential evaporation (**Figure 2.10**) ranges from < 1 660 mm in cooler higher altitude areas (cf. **Figure 2.3**) mainly along the southeastern border, to over 2 260 mm in the warmer areas (cf. **Figure 2.7**) along the northern border.

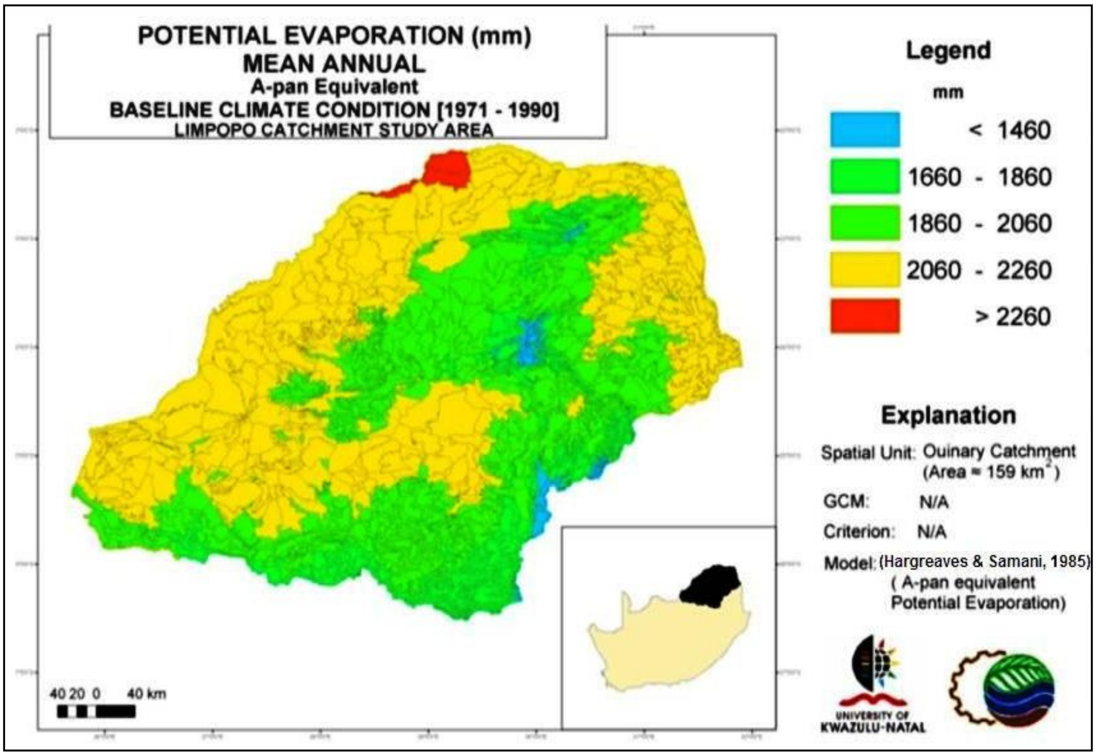

Figure 2.10 Mean annual A-pan equivalent potential evaporation in the Limpopo Catchment, computed from the Hargreaves and Samani (1985) equation (Source data: BEEH, 2008)

2.5 Land Cover

Low and Rebelo (1998) identified eight biotic plant communities, or biomes, in South Africa. In the Limpopo Catchment three of the eight biomes are found, *viz*. the Savanna, Grassland and Forest biomes (**Figure 2.11**). Each of these biomes is characterised by particular climatic conditions (Low and Rebelo, 1998; Mucina and Rutherford, 2006). The climatic conditions limiting plant distribution are the quantity and seasonality in rainfall, and the range in seasonal temperatures (Low and Rebelo, 1998).

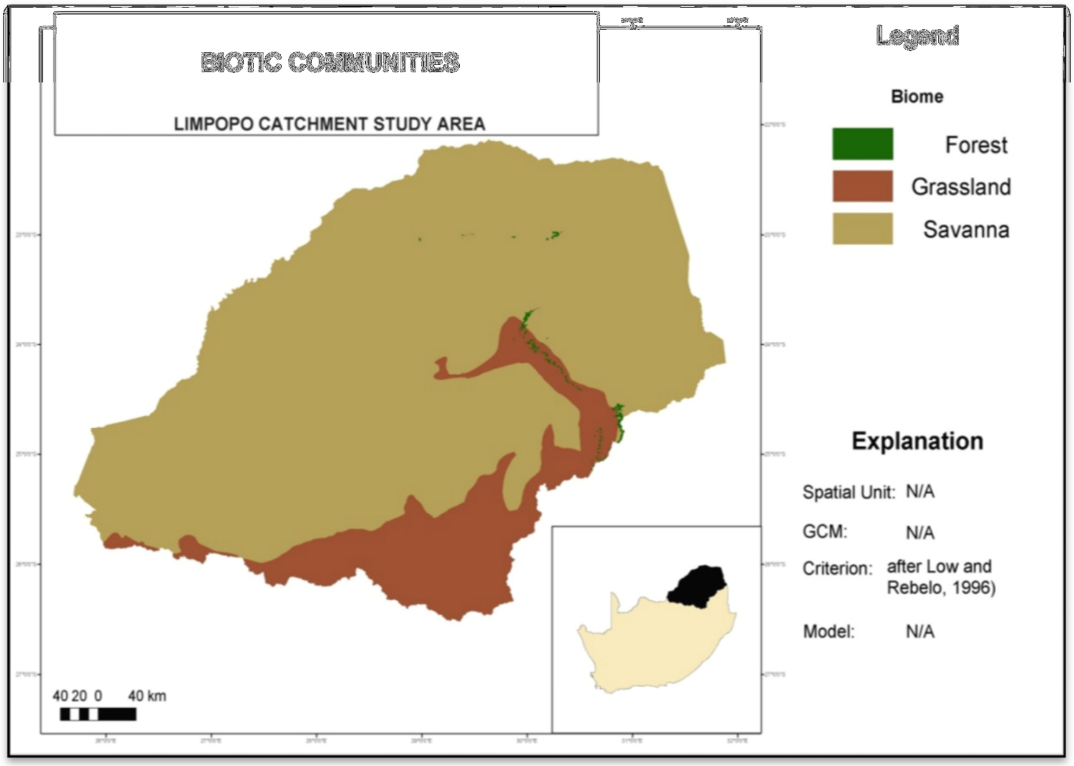

Figure 2.11 Biotic plant communities in the Limpopo Catchment (Source: Low and Rebelo, 1998)

The Savanna biome is made up primarily of a grass ground layer and a distinct woody plant upper layer, and occurs in summer rainfall regions (Rutherford and Westfall, 1994). In **Figure 2.11** the Savanna biome covers more than two-thirds of the Catchment. Savanna communities are distinguished from other plant communities by the two layers, referred to above, and by their receiving relatively low annual rainfall. Frost occurrence and soil type are not limiting factors to the final composition of the Savanna Biome, but rather the rainfall together with fires and grazing are, because these factors prevent the upper woody layer from being dominant. Insufficient rainfall results in the woody layer taking over the grass area. The occurrence of both layers within a common area is due to the summer rainfall, which is important for the dominance of the grass layer, as well as near- annual fires which are fuelled by the grass. The woody plants near the ground are referred to as a Shrubland, with Bushveld referring to areas with denser woody plants. Conservation of the Savanna biome is vital mainly due to the presence of game farms and National Parks (Low and Rebelo, 1998).

Unlike other biomes, the Grassland biome is found in higher altitude areas (cf. **Figure 2.4**) and is dominated by a grass layer. Conditions that maintain this biome are frost occurrence, fire and grazing, and the quantity of grass cover is dependent on rainfall and the grassveld management (Low and Rebelo, 1998). The Grassland biome in Limpopo Catchment is restricted to areas of high summer rainfall and to areas with relatively low temperatures. The Grassland biome in the past has been converted into farmlands, and small scale farmers in this biome produce mainly maize and sorghum (Low and Rebelo, 1998). The Forest biome is found only in patches and is characterised by a continuous canopy cover and multi-layer vegetation under the canopy. It is found in frost free summer rainfall areas receiving MAPs > 725 mm (cf. **Figure 2.5**). Fires in the catchment are not frequent because of generally high humidity (Low and Rebelo, 1998). In the catchment this biome constitutes the smallest area (cf. **Figure 2.11**) when compared to the Grassland and Savanna biomes. The Forest biome is characterised by the dominance of evergreen trees (Rutherford and Westfall, 1994) and provides valuable resources to ecosystems and humans, including habitat, carbon storage, medicinal plants and timber (Low and Rebelo, 1998).

2.6 Hydrology

2.6.1 Surface water resources

The Limpopo Catchment drains three main river reaches, *viz.* the Upper, Middle and Lower Limpopo River reaches (cf. **Table 2.2**). In the Limpopo Catchment the surface water resources utilised are mainly from rivers and dams (**Figure 2.1**, FAO, 2004).

The river reaches and their tributaries within the Limpopo Catchment are estimated to generate a naturalised Mean Annual Runoff (MAR) of 6 065 million cubic metres ($M.m^3.an^{-1}$) and 2 423 $M.m^3.an^{-1}$ for denaturalised conditions (cf. **Table 2.2**). The water resources estimated for the ecological reserve is 41 % (1 004 $M.m^3.an^{-1}$) of the denaturalised flow.

Table 2.2 Surface water resources of the Limpopo Catchment (Görgens and Boroto, 1999; GOSA-DWAF, 2003; FAO, 2004)

Reach	**Tributary**	**Catchment area (km²)**	**Naturalised MAR ($M.m^3.an^{-1}$)**	**Denaturalised MAR ($M.m^3.an^{-1}$)**	**Ecological reserve ($M.m^3.an^{-1}$)**	**Unit runoff (denat. MAR) ($mm.an^{-1}$)**
Upper reach	Marico	13208	172	50	29	3.8
	Crocodile	29572	391	205	82	6.9
	Matlabas	3448	382	21	76	6
	Mokolo	7616	No data	117	No data	15.4
	Lephalala	4868	150	99	17	20.3
	Mogalakwena	20248	269	79	41	3.9
Sub-total		*78960*	*1364*	*571*	*245*	*56.3*
Middle reach	Sand	15630	72	38	10	2.4
	Nzhelele	3436	113	89	12	26
Sub-total		*19066*	*185*	*127*	*22*	*28.4*
Lower reach	Luvuvhu	4827	520	492	105	102
	Olifants	68450	1644	1233	366	18
	Others	13996	2352	No data	266	No data
Sub-total		*87273*	*4516*	*1725*	*737*	*120*
Total		**185299**	**6065**	**2423**	**1004**	**204.7**

No data: information was not provided by the source

2.6.2 Groundwater resources

The groundwater store is used extensively in this Catchment, especially where recharge exceeds the Catchment's human and environmental requirements (Cavé *et al.*, 2003). The groundwater is used for irrigation and for domestic purposes in rural communities, especially those which reside far from access to surface water resources. In the Olifants Catchment groundwater resources are increasingly becoming a valuable source of water, particularly to the mining industry, as well as to many of the small towns, villages and small-scale farmers (Krishna *et al.*, 2006).

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This chapter on background information illustrated the Catchment's location, water management areas, history within the context of South Africa, as well as population and biophysical characteristics. A literature review on the effects of climate change related drivers on agricultural production, as well as its associated yield-*reduction* factors (e.g. pest and disease incidence) and yield-*limiting* factors (e.g. water for agriculture), is presented in **Chapter 3**.

SECTION TWO: LITERATURE REVIEW

3. THE EFFECTS OF CLIMATE CHANGE DRIVERS ON AGRICULTURAL PRODUCTION (CROP AND LIVESTOCK-PASTURE) AS WELL AS AGRICULTURAL YIELD-*LIMITING* AND -*REDUCTION* FACTORS

Having described historical and biophysical aspects of the Limpopo Catchment study area in **Chapter 2**, in this Chapter relevant literature on effects of climate change related drivers on agricultural production, and on agricultural yield-*reducing* and -*limiting* factors, is reviewed. These drivers do not occur in isolation, and therefore the interactions of effects of elevated atmospheric carbon dioxide (CO_2) concentrations and increases in temperature, as well as changes in precipitation, on agricultural production will also be reviewed.

3.1 Effects of Climate Change Related Drivers on Crop Production

The physical environment in which a crop plant grows will be altered by climate change. The atmospheric CO_2 concentrations as well as temperature, precipitation and potential evapotranspiration (E_{pm}) will be perturbed under climate change conditions. These changes are hypothesised to result in a cascade of crop responses and their associated pests and diseases, which may lead to agricultural production being affected severely (Rosenzweig and Hillel, 1998). In this section the effects of climate change related drivers on crop growth and growing season length, on plant water use efficiency, interactions with pests and diseases, competition with invasive alien plants and crop yields are discussed.

3.1.1 Effects of climate change on crop and land production

Plants' responses to changes in atmospheric conditions such as elevations in atmospheric CO_2, are determined by their photosynthetic pathways (Olesen and Bindi, 2002). Rosenzweig and Hillel (1998) explain that the process of carbohydrate production in plants, i.e. photosynthesis, can occur as the first product in the sequence of biochemical reactions with three carbon atoms (C_3; for example, in wheat, rice and soybean crops) or four carbon atoms (C_4; for example, the maize crop) in response to atmospheric CO_2. When their study was conducted the then 'current' level of atmospheric CO_2 was approximately 350 parts per million (ppm) by volume (Rosenzweig and Hillel, 1998) as against 380 ppm in 2009 (IGBP, 2009), and results yielded lower rates of net photosynthesis in C_3 than in C_4 crops. This lower net photosynthesis in C_3 crops results from the release of high chemical energy during photorespiration, which re-oxidizes the carbohydrate back into CO_2. This energy is initially absorbed as solar radiation when a portion of the carbon is reduced from CO_2 in the plant leaf to produce carbohydrates (Rosenzweig and Hillel, 1998).

Rosenzweig and Hillel (1998), as well as Olesen and Bindi (2002), stated that C_4 crops' photosynthetic rates will have smaller responses to enhanced CO_2 levels compared with those of C_3 crops (**Figure 3.1**). This is due to suppressed photorespiration in C_4 crops. Plants have the ability to acclimatises and adapt to new environmental conditions, in this case, to increased levels of atmospheric CO_2, by regulating their photosynthetic and respiration rates (**Figure 3.1**). This regulation/adaptation process is termed acclimation (Rosenzweig and Hillel, 1998).

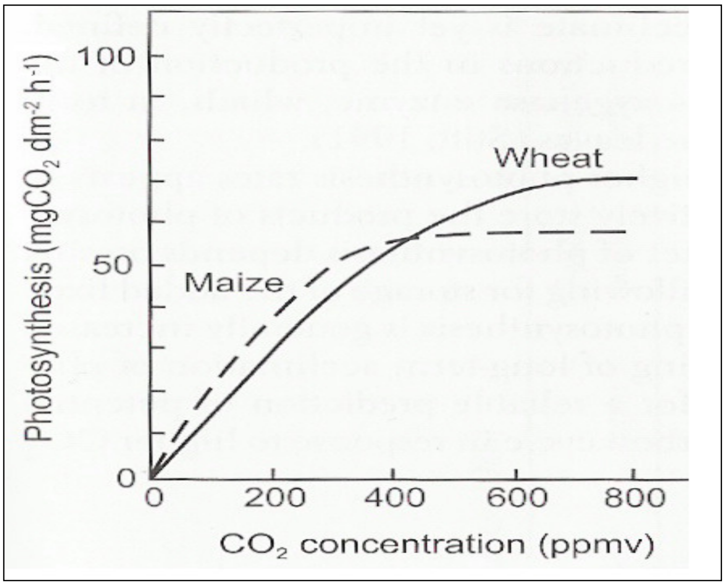

Figure 3.1 Responses of wheat (a C_3 crop) and maize (a C_4 crop) photosynthetic rates to the effects of atmospheric CO_2 levels, in controlled environments (Rosenzweig and Hillel, 1998)

Photosynthesis acclimation relates to reductions in Rubisco carboxylase-oxygenase enzyme production, which is associated with higher levels of carbohydrate production in the leaves. However, under prolonged exposure to CO_2-enriched environments the positive responses of photosynthesis in crops may diminish, depending on the physiological capacity of the plant to further store carbohydrates. Therefore, high levels of CO_2 in the atmosphere will result in an increase in the storage capacity of carbohydrates in plants' leaves and in the production of carbohydrates (Rosenzweig and Hillel, 1998). For example, in the case of soybeans, most studies indicate that the effects of prolonged exposure to elevated atmospheric CO_2 maintained the net photosynthetic rates. Therefore, the rates of photosynthesis in the soybean's leaf and canopy levels will increase in response to elevation in CO_2 until it reaches an optimum level before leveling off (Allen and Boote, 2000). The long-term acclimation of a plant's photosynthetic capacity, however, needs to be better understood first, before any reliable predictions can be made.

The free air CO_2 enrichment (FACE, i.e. *Free Air Carbon Dioxide Experiments*) study by Hunsaker *et al*. (1997) on plots of irrigated wheat showed a 5 % decrease in E_{pm} for a doubling of CO_2 concentrations, while in the drought season the E_{pm} increased by about 3 %. Therefore, the increased E_{pm} under water limiting conditions indicates that the plant water loss may not decrease with the effects of CO_2-enriched conditions of stomatal closure. The increase in E_{pm} may be the result of deep extraction of water by larger root systems, together with increased leaf area (Senock *et al*., 1996).

Furthermore, Lawlor and Mitchell's (2000) impact study suggests that the water use efficiency (WUE) in FACEs is likely to increase by up to 145 % in dry conditions, whereas in wet treatments by only 21 %. The low WUE under wet conditions was due to the increase in biomass, despite the relatively small (5 %) effects of CO_2 on E_{pm}. Their greenhouse experiment on the effects of drought conditions with enhanced CO_2 on wheat crop production indicated an increase of about 65 % in the WUE. The wheat crop's water use is therefore likely to decrease in wet conditions and to increase in dry conditions in response to elevated CO_2. Moreover, the stimulation of biomass and grain yields in CO_2-enriched conditions was shown to increase by more than 10 % in dry conditions compared to wet conditions (Lawlor and Mitchell, 2000).

The seed and biomass yields of soybeans estimated under current and elevated CO_2 conditions suggest that they are likely to experience drought stress during early and late stages of their development. Short and severe drought stresses on plants grown in CO_2-enriched conditions were shown to improve their yields by 20 % (Jones *et al*., 1985; cited by Allen and Boote, 2000). In a similar study, plant leaf temperatures were found to be 2 ^{o}C higher in elevated CO_2 atmospheric conditions compared to temperatures under present CO_2 levels. Similarly, increases in the drought related stress cycles resulted in a leaf temperature raised by about 7 ^{o}C (Allen *et al*., 1994; cited by Allen and Boote, 2000). Furthermore, the C_4 plants (for example, maize), being unable to photorespirate, prevent their internal cycling of CO_2, and hence in drought induced conditions the stomatal closure will prevent the uptake of CO_2, resulting in the plant being more prone to photo-inhibition of carbohydrate production (Young and Long, 2000). However, in C_3 plants such as soybeans, Huber *et al*. (1984; cited by Allen and Boote, 2000) found that the carbon exchange rates in drought-induced conditions decrease more than in the soybeans grown in a non-carbon-enriched atmosphere. Therefore, in CO_2 enriched conditions the impacts of drought on photosynthesis would be less severe.

According to Graves and Reavey (1996), different plant species have different temperature niches within which photosynthesis can occur, and plants can acclimate to the changes in temperature by changing the thermal stability of photosynthetic reaction enzymes. A plant species' ability to maintain photosynthesis over a range of temperatures is determined by the species' genetic make-up and its ability to adjust its photosynthetic physiology. According to Young and Long (2000), changes in temperature which are related to climate change will increase the crop's vulnerability to temperature stress, as temperature plays a major role in the performance and distribution of plants, and in the regulation of photosynthesis. Their findings indicate that crops with C_4 photosynthetic pathways (such as sorghum) are more tolerant of higher temperatures than C_3 crops, because C_4 photosynthetic pathways do not photorespirate.

Data on the rates of photosynthesis in the soybean leaf in response to temperature regimes, compiled by Hartley *et al*. (1985), were used by Allen and Boote (2000) to simulate the responses of soybeans to the effects of elevated CO_2. They found that the rates of photosynthesis in soybeans (a C_4 crop) under light and CO_2-saturated conditions increased with an increase in temperature (up to about 40 ^{o}C). In addition, Aggarwal *et al*. (2006) state that the plant's growth rates at sowing, seedling, anthesis and finally maturity stages depends on temperature and daily production of dry matter. The dry matter produced is separated and allocated towards the development of the crop's roots, leaves, stems and storage organs. Therefore, a rise in temperature will stimulate high production levels of carbohydrates, thus stimulating crop development. Recent research has shown that an increase in mean temperatures has impacts on the crop's growing season and yields, which can be counteracted by increases in atmospheric CO_2 (Slingo *et al*., 2005). It should be borne in mind that these conclusions have been drawn from studies on crops grown in controlled experimental environments, which experience fewer environmental stresses and competition for resources and, therefore, contain uncertainties when scaled up to field/farm scale.

Studies on C_3 crops grown in controlled environments with enhanced CO_2 indicate that concentrations up to 550 ppmv increase yields by 24 to 43 %. In contrast, studies based on near field conditions suggest that the effect of CO_2 enrichment on crops might be less than that concluded from chamber experiments (Long *et al.*, 2005). There are a number of factors not accounted for in non-FACE, and these have a great impact on crop responses to CO_2. These factors include interaction effects of changes in temperature, precipitation, crop management, fertilisation, increases in air pollution and changes in the incidence of pests, diseases and weeds. The parameters of empirical models based on non-FACE experimental data (i.e. under controlled environments) are stated to be consistent with FACE data. The responses of crops grown on-farm would, however, be lower than most of those from chamber experiments (Tubeillo *et al*., 2007).

Elevated CO_2 concentrations affect certain crops by reducing the nitrogen or protein content during their seed production (Bunce and Ziska, 2000), thus affecting the seed growth. Plant stress caused by the deficiency in water and nitrogen may affect the development of crops through the reduction of transpiration and the increase in canopy temperatures, which affect the crops' photosynthetic production. The partitioning of dry matter in a crop is a function of its developmental stage. Critical times in crop development stages, such as flowering and fruiting or grain filling, are sensitive to stress. Under water or nitrogen stress, the partitioning of dry matter will be mainly towards root development, while the other dry matter is partitioned to the shoots, where only a small amount is for stems, leaves and storage organs. Therefore, under severe water and nutrient stress, as with temperature stress, the crop growth and yields will be severely affected (Aggarwal *et al*., 2006).

Slingo *et al*. (2005) conducted chamber experiments to assess the effects of doubled CO_2 concentrations on rice, soybean and wheat (C_3 crops). The crops realised an increase in yields of approximately 24 to 43 %, compared to yields under ambient CO_2 concentration levels. In **Figure 3.2**, studies on 12 full growing seasons with various atmospheric CO_2 concentrations under a wide range of experimental conditions from both plot and field experiments showed a positive CO_2 fertilisation effect on wheat yields.

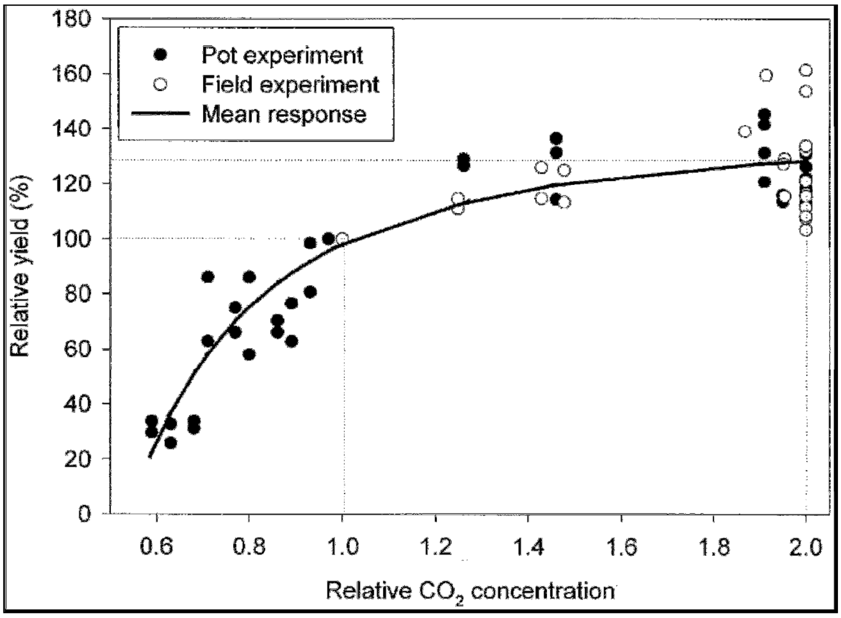

Figure 3.2 Effects of CO_2 concentrations, relative to ambient conditions, on relative yields of wheat (Slingo *et al.*, 2005)

Tubiello *et al.* (2000) assessed the effects of climate change scenarios on crop production in Italy. The study sites in Italy were at Modena, a temperate climate area with average crop yields that are 60 % higher compared to those at Foggia, a Mediterranean climate area with low summer precipitation. The yields from C_4 crops under warmer conditions were 13 % lower than the baseline yields with adaptation management, whereas the yields for C_3 crops were similar to those of the baseline.

Furthermore, the results from simulations without adaptation management indicated that the negative effects of an increase in temperatures on crop yields were stronger than the positive effects of elevated CO_2 levels, with a 5 to 15 % increase in wheat and maize yields, and more than a 20 % reduction in soybean, barley and sorghum yields at Modena (Tubiello *et al.*, 2000). In contrast, the yields of wheat and sorghum crops at Foggia decreased, respectively by 30 to 50 % and by 10 to 30 %. The reductions in the crop yields at Foggia were due to the baseline climate under which the crops were already suffering from water stress (Tubiello *et al.*, 2000).

Motha and Baier (2005) conducted a similar experiment on rainfed agricultural crops in the USA using output from Global Climate Models (GCMs), the climate projections of which suggested an increase in temperature and a reduction in water availability, resulting in significant reduction in most major crop yields in the south and southwest of the USA. As the relatively low temperatures are presently already a constraint on crop growth in the northern areas of USA, an increase in temperature will lengthen the growing season and increase the yields of rainfed maize and soybean there. The increase in atmospheric CO_2 levels may increase the yields in the northern areas of USA even further (Motha and Baier, 2005).

Apart from the effects of climate change and elevated CO_2 concentration scenarios being crop type specific, they were also found to be different in different locations. The differences were shown in both the baseline and climate change simulation results between study sites. These differences relate to the current climate, soil conditions and management practices, as well as the direction of climate change. Motha and Baier (2005) found that the physical potential for agricultural production in the USA under climate change could expand to the north, beyond the present more southerly growing areas, but may be limited by the lack of suitable soils for agriculture.

An integrated assessment of agriculture in sub-Saharan Africa using the agro-ecological zone (AEZ) model indicated a reduction in land which is currently highly suitable for crop cultivation, and more land under moisture stress (Fischer *et al*., 2005). The projections by Fischer *et al*. (2005) indicated that there could be an expansion in the area in Sub-Saharan Africa currently experiencing extreme climate severity and soil constraints, adding a further 30 to 60 million hectares to the 1.5 billion hectares of land currently not arable under rainfed agriculture. Similar patterns of reduction in suitable land were also observed under more extreme climate scenarios. Even the National Center for Atmospheric Research (NCAR) climate scenarios, which display large increases in precipitation together with an increase in temperatures, indicate that the land currently unsuitable for crop agriculture in Sub-Saharan Africa will be increased by about 15 million hectares (Fischer *et al*., 2005). The AEZ model projections suggest that the potential for production of cereal crops under rainfed conditions in South Africa might decline, while the NCAR climate scenarios indicate a slight increase. Similar variations in potential yields were found in projections made for Argentina and India (Fischer *et al*., 2005). The high variation in projections of potential yields for different countries results from the heterogeneity of the agro-climate resources and climate change projections from area to area (Fischer *et al*., 2005).

3.1.2 Effects of climate change on growing seasons

A review of studies on long-term observed surface climate data and remote sensing measurements on plant phenology by Sherry *et al.* (2007) found that the growing season of plants (which is sensitive, and responds, to changes in temperature) had started earlier over the 30 - 80 years prior to publication by 2 - 3 days per decade in spring and had ended later by 0.3 - 1.6 days per decade in autumn, hence resulting in extended growing seasons. The extension in the growing season may result in an increase in the productivity of both terrestrial and aquatic ecosystems (Sherry *et al.*, 2007).

Olesen and Bindi (2002) report similar extensions in the length of the growing season of crops in the middle and high latitudes of Europe, arising from increases in temperatures, and thus allowing for crops to be planted earlier in spring, to mature more rapidly and to be harvested earlier. By way of example, Richter and Semenov (2005) modelled the effects of climate change on wheat yields in England and showed accelerated plant development, with anthesis occurring 2 to 3 weeks earlier due to increases in temperatures. Their simulations indicated that the grain-filling period would be shortened by up to 2 days in moist soils, and by 5 or 10 days in dry soils. An increase in temperature is predicted to produce milder winters and lengthened growing seasons, which would increase the total leaf biomass.

Rosenzweig and Hillel (1998) report a lengthening in the potential growing seasons in response to global warming similar to that of Olesen and Bindi (2002), with their definition of the potential growing season being the period between the last spring frost and the first frost experienced in the following autumn season, on condition that there is sufficient water for the crops.

3.1.3 Effects of climate change on plant water use efficiency

Water use efficiency (WUE) describes the water used at leaf, canopy and crop levels. It may be equated to the amount of crop yield for each unit of water lost from a unit area through E_{pm}. The water absorbed by the plant is converted to water vapour and passes from the surface of the mesophyll cell wall through the internal air space to the stomatal leaf and from there into the atmosphere through the transpiration process. The water vapour uses the same pathway in the plant as the atmospheric CO_2 (through the stomata), and is thus subjected to similar restrictions of diffusion. This is termed CO_2 fertilisation. Theoretically, within the same environment, C_4 species will use less water for every gram of carbon assimilated than C_3 species (Young and Long, 2000). Plants under increased atmospheric CO_2 levels will respond by partially closing their stomata, resulting in a reduction in the rate of transpiration per unit of leaf area. However, the stomatal closure might not significantly change the crop's total transpiration because the increased leaf growth from higher photosynthesis rates partially balances the reduction in the unit leaf area of transpiration (Rosenzweig and Hillel, 1998). This may therefore increase the total crop WUE.

Global warming is likely to result in increases in the E_{pm} from dryland agriculture because of higher atmospheric demand (Izaurralde *et al*., 2003). In the short-term, exposure of the plant leaves to elevated atmospheric CO_2 concentrations is likely to result in a decrease in transpiration, as already alluded to above. Examples of short-term exposure CO_2 are given in the next two paragraphs. In response to increases in atmospheric CO_2 concentrations, maize and sorghum stomata apertures are stated to decrease, hence increasing their WUE (Young and Long, 2000). Izaurralde *et al*. (2003) assessed impacts of climate change on maize crop WUE by modelling conditions in the USA both with and without the effects of doubled atmospheric CO_2 (assumed to occur by the year 2030). Without the CO_2 fertilisation effects, the E_{pm} is simulated to increase in response to projected warming from west (by 32 - 81 mm per annum) to east (by 91 - 210 mm per annum), whereas with CO_2 fertilisation the E_{pm} might decrease by 8 % in the western region, to over 14 % in the eastern region because of the CO_2 feedback. Furthermore, they found that under ambient climate conditions the WUE ranges varied more than threefold from region to region from 3.2 to 10.9 $kg.ha^{-1}.mm^{-1}$ from western to eastern regions, respectively. In projected future climate conditions, without doubled atmospheric CO_2 concentrations, the WUE decreased in the range of 1.6 to 3.5 $kg.ha^{-1}.mm^{-1}$ for maize, whereas with doubled atmospheric CO_2 concentrations the reduction in WUE was halved by 0.7 to 1.5 $kg.ha^{-1}.mm^{-1}$ for maize. Andre and du Cloux (1993; cited by Lawlor and Mitchell, 2000), using glasshouse experiments on the effects of doubling atmospheric CO_2 under wet and slightly dry conditions, indicated that the water use would decrease by about 20 %. Furthermore, their controlled environment experiment exhibited similar reductions in transpiration during the vegetative growth, but by only 8 %.

Still on short-term CO_2 exposure, Lawlor and Mitchell (2000) found that lower transpiration rates and latent cooling in the plant's intercellular leaf spaces would increase water vapour pressure and decrease the air humidity in the boundary layer, thus resulting in an increase in the water vapour pressure gradient, together with an increase in transpiration. Similarly, Izaurralde *et al.* (2003) found that under elevated CO_2 conditions the reduction in transpiration rates resulting from the partial closure of the stomata might decrease the humidity around the leaf. They state that the predicted leaf stomatal resistance would have little effect at a regional scale. Therefore, increasing the leaf-atmosphere vapour concentration gradient would oppose any effects due to changes in stomatal apertures.

Long-term elevated CO_2 exposure and higher temperature predictions suggest that increases in leaf area and root growth may result in a reduction of the expected WUE. The high-predicted stomatal resistance at leaf scale may only have a small influence on WUE at a regional scale because of the adjustments within the planetary boundary layer of humidity (Lawlor and Mitchell, 2000). Elevated CO_2 is likely to reduce the plant's water use, thereby increasing its production with minimal water usage, whereas warming will increase the water consumed for carbohydrate production. Apart from climate, crop production is affected by biotic factors, such as pests, diseases and weeds.

3.1.4 Effects of climate change on pests

Because a major component of new work in this dissertation is on a pest, *viz.* the *Chilo partellus* Spotted Stem Borer, responses of pests to climate and climate change are reviewed below. The review is followed by a background information on *C. partellus*.

Pests such as cutworms, stem borers, termites and wilts may cause damage to the whole structure, or to a part, of the crop, i.e. to the roots, leaves and storage organs (Aggarwal *et al.*, 2006). The extent of damage depends on the ability of the remaining crops to develop mechanisms for counteracting the effects of pests and diseases (Bent, 2003). A number of pests are plant species specific and have specific impacts on those plants. Their damage on a crop may be by decreasing the emergence of seedlings and the plant stand, competing with the crop for resources, slowing down the uptake of water and nutrients, consuming the plant's tissue and assimilate, and impeding the rates of assimilation. Apart from their direct impact on the crops, pests could increase the plant's vulnerability to other stresses (Rabbinge *et al.*, 1994; cited by Aggarwal *et al.*, 2006).

The Goulson *et al*. (2005) study on effects of projected future climate conditions on insect pests indicated possible increases in insect pest populations with rising temperature regimes. Collier *et al*. (1991) found that with projected temperature increases likely to lengthen the growing season and reducing frost conditions, insect pests would be active earlier and expand their spatial distribution ranges. Fuhrer (2003) concurs with the findings of Collier *et al.* (1991) in that the effects of climate change on the shifts in climatic zones may affect the pest's spatial ranges. However, for specialist pests the spatial range will also depend on the host crop's ability to shift in response to the changes in the climatic zones. The response of migrant pests to changes in their environment will prompt migration to suitable environments. However, their migration is likely to be faster than that those of host plants (Cannon, 1998).

The potential production increases of C_3 crop in response to elevated atmospheric CO_2 concentrations (cf. **Section 3.1.1**) could change the C:N (Carbon:Nitrogen) ratios in leaves. With high C:N ratios reducing the crop's nutritional quality, this could result in increased consumption by insect pests in order to maintain their nutritional levels, hence causing greater crop damage (Rotter and Van de Gejin, 1999). Fuhrer (2003) reviewed numerous studies that indicated a relative reduction in nitrogen due to elevated CO_2 concentrations in crop and of carbohydrates in C_3 crops, which also seemed to stimulate high consumption levels in insect pests.

The elevated CO_2 concentration, together with increases in temperature, can thus affect pests and beneficial insects directly or indirectly by altering the host crop's physiology and composition (Fuhrer, 2003). Miglieta *et al.* (2000) found that the processes involved in the life cycle of an insect pest was driven by temperature; therefore, the insect pest could also be affected by changes in temperature regimes, which may possibly affect its behaviour and interaction with crops. For example, a change in plant leaf composition can lower the insect larvae protein intake (e.g. in Colorado beetles, *Leptinotarsa decemlineata*), thus decreasing the insect's growth rates.

Extreme events such as droughts (or water stress) can increase the vulnerability of the host crop to insect pests. In contrast, high amounts of precipitation can directly reduce the effect of insects (Watt and Lether, 1986; cited by Fuhrer, 2003). According to Fuhrer (2003), extreme events under ambient climatic conditions are significant to insect outbreaks, while climate change induced shifts in these trigger events may result in more frequent and destructive outbreaks.

Another natural enemy to crops (i.e. an agricultural yield-*reduction* factor), which will be affected by anthropogenically induced climate change, apart from insect pests, are pathogens (diseases).

The *Chilo partellus* (Swinhoe) Lepidoptera: Crambidae Spotted Stem Borer, indigenous to India (Kfir, 1992), invaded the Highveld maize production areas in South Africa during the late 1950s, where it gradually replaced the indigenous Stalk Borer *Busseola fusca* (Fuller) Lepidoptera: Noctuidae (Kfir, 2001).

Neupane *et al*. (1985) conducted a study in Chitwan, Nepal on *C. partellus* host preferences and its damage to maize, sorghum, rice, millet and sugarcane. In southern Africa, *C. partellus* was found to be a pest of grain crops such as maize, millet, sorghum and rice, as well as of sugarcane (Way and Kfir, 1997).

Rebe *et al*. (2004) reported that the *C. partellus* Spotted Stem Borer in the Limpopo Province was found infesting sweet sorghum grown in mixed farming systems with maize and grain sorghum. The sweet sorghum, commonly known as 'sweet reed', is consumed by the inhabitants or sold as a cash crop. Further uses of this sorghum include the production of syrup for household use (Rebe *et al*., 2004). These factors highlight the potential economic losses to crops in the region by *C. partellus* infestation. Rebe *et al*. (2004) investigated the potential of using sweet sorghum as a trap crop of *C. partellus* in maize, and their findings were that it is not a practical option. Based on their investigation, *C. partellus* cannot be trapped as it has no significant preference between crops (Neupane *et al*., 1985; Way and Kfir, 1997; Ofomata *et al*., 2000; Rebe *et al.,* 2004).

The *C. partellus* life cycle of 30 – 52 days is characterised by four distinctive life stages, *viz*.

- the egg stage,
- the pupal stage,
- the larval stage, and
- the adult stage (Dale, 1994),

with the egg stage at optimum conditions being 3 - 5 days, the larval stage 18 - 30 days, the pupal stage 6 - 12 days and the adult stage 3 - 5 days in duration (Dale, 1994). An adult *C. partellus* ensures the survival of the next generation by locating a host plant on which to lay its eggs. For successful survival of *C. partellus* the host plant must not be harvested before the stem Borer develops into a larva.

The development of an insect pest model assumes that a complete life cycle is characterised by a development period and mortality, both of which are important in each stage of the pest's life (Smerage, 1992). According to Smerage (1992), the development period (t) of a stage in a pest's life cycle is the recorded period for each survivor to emerge from that particular stage.

The development periods of the *C. partellus* life cycle stages, from egg to adult, are dependent on temperature (cf. **Figure 3.3**). Rahman and Khalequzzaman (2004) examined the effects of seven temperature regimes (i.e. 10, 15, 20, 25, 30, 35 and 40 ^{o}C) on the development period of each life stage of *C. partellus* in a laboratory experiment. In **Figure 3.3**, the development period of each stage has a distinct distribution by temperature regime.

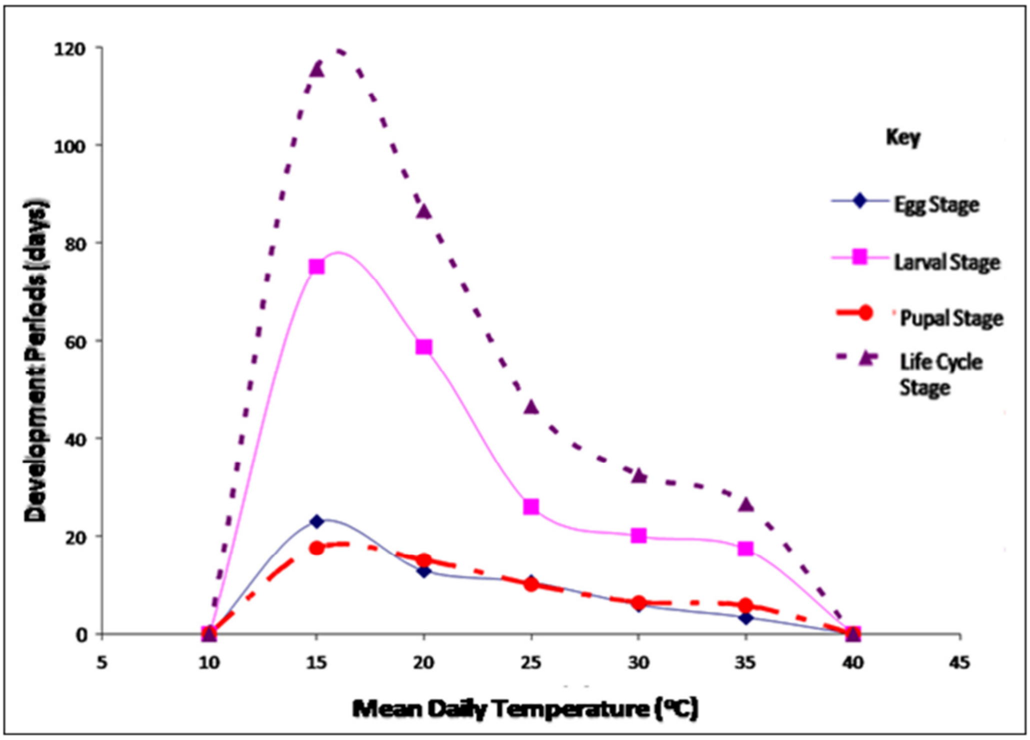

Figure 3.3 Length (days) of development stages of *Chilo partellus* vs. temperature (after Rahman and Khalequzzaman, 2004)

The development periods of *C. partellus* life stages are longer at lower temperatures and shorten with an increase in temperature. Rahman and Khalequzzaman (2004) observed no development at temperature regimes ≤ 10 ^{o}C and ≥ 40 ^{o}C. Similarly, in another laboratory experiment Singh (1991) found that all *C. partellus* females had laid unfertilised eggs at threshold temperatures ≥ 40 ^{o}C.

Zilahi-Balogh and Pfeiffer (1998) reported on observations made by farmers' over the years that the development of a specific insect pest coincided with plant flower, budding or development of leaves. This information allows farmers to predict the application time of insecticides in spring, i.e. when insect pests emerge. This method is said to be an indirect application of physiological time, which is the number of heat units required by each stage in the plant's development (Zilahi-Balogh and Pfeiffer, 1998). Forecasts over the growing season of insect pests life stages, especially important in pests such as the *C. partellus* which do considerable economic damage, are needed for pest control.

According to Kfir (2001) information on the *C. partellus* larval stage is very important for effective chemical control. The mature *C. partellus* larva bores into the host stalk where the insecticide cannot reach. The timing of insecticide applications are crucial before the mature larvae bore into the host stalk and again before the emergence from the egg stage. Equally, chemical control can be ineffective if there is an overlap in the *C. partellus* life cycles, leading to crops being infested throughout the growing season. There against, Kfir (2001) reported that biological control experiments with parasitoids conducted on *C. partellus* in the Highveld of South Africa proved to be ineffective owing to the harsh climatic conditions and a prolonged diapause (i.e. insect hibernation) period during which there are no alternative host plants for the parasitoids. After the harvesting season the host plant matter is removed from the field. During this period there are no crops and the temperature is not optimum for larval development. However, the use of parasitoids proved ineffective in the control of *C. partellus* as mature larvae undergo their diapause 25 to 50 mm below the ground level (Srivastava *et al*., 2003). Other studies have shown that *C. partellus* could find temporary hosts, such as wild grass, until the following growing season.

The older larvae of *C. partellus* enter diapause with the difference that they lose weight and/or fertility, depending of the length of the diapause period. The pest larvae enter the diapause stage when climatic conditions become unfavourable. These conditions occur at the end of the rainfall season in the tropics, where there is a distinct dry period, or in more temperate climates in winter. The diapause larvae pupate shortly after the first rains and emerge as moths a few days later (Dale, 1994; Kfir *et al*., 2002; Srivastava *et al*., 2003; Srivastava *et al*., 2004).

3.1.5 Effects of climate change on crop diseases

Worldwide there are many different types of viruses, bacteria and fungus species, which affect plants. Any given pathogen can cause a severe reduction in a crop's potential yield by causing tissue lesions, reducing its leaf area, root and seed growth, clogging vascular tissue and causing wilting (Bent, 2003). According to Bent (2003), pathogens can cause young seedlings to be overwhelmed, and result in failure in germination. They can also cause pre- or post-harvest damage to crops such as blemishing, total decay and general metabolic drain that reduce crop productivity even in the absence of observable symptoms. The interaction between the crop and specialised pathogens is frequently specific, while non-specialised pathogens have a potential to infect a range of crop species (Bent, 2003).

A pathogen's growth stages and rates of growth can change because of changes in the host crop's physiology and changes in its physical environment such as climate conditions (Coakley *et al*., 1999). The potential implications of these changes might result in shifts in the spatial and temporal distributions of the pathogen, and the potential interactions with host crop (Epstein, 2001; Garrett *et al*., 2006). The infestation rate of a pathogen in a given area is a function of its dispersal mechanisms, the suitability of the environment, its ability to survive between seasons, as well as alterations in the physiology of the host crop and the ecology of the new environment (Coakley *et al*., 1999).

Climate change could increase the vulnerability of plants to pathogens that are not presently a threat because present climate conditions are unfavourable to them. Furthermore, climatic changes could impose chronic stress on plants grown in marginal climatic regions, thus exposing them to an epidemic of insect pests and diseases (Coakley *et al*., 1999). Agricultural plants may give refuge to symptomless pathogen carriers, until the plant undergoes climatic stresses, in which the carried disease may cause damage to it (Dinnor, 1974; cited by Coakley *et al*., 1999). For example, *Eucalyptus* species in southern Australia are at present not threatened by the *Phytophthora cinnamomi* pathogen because the pathogen's niche climate ranges outside those of the *Eucalyptus* species, i.e. temperature ranges of 12 to 30 ^{o}C with moist soils. However, *Phytophthora cinnamomi* may become a serious threat if temperature and precipitation increase under projected future climate conditions. Therefore, increases in temperature may exacerbate the impacts of disease on plants (Lonsdale and Gibbs, 1996).

Plants have specific defense mechanisms for keeping infections under control. The plant develops these mechanisms after experiencing infection (Bent, 2003). Thus, the impact of the pathogen will be dependent on the nature of the interactions between the pathogen and host plant, and the plant's resistance mechanism. The physiology and resistance of plant will change with increases in temperature (Coakley *et al*., 1999). A rise in temperature could affect the plant by altering its susceptibility and resistance to disease (Martens *et al.*, 1967; cited by Coakley *et al*., 1999; Chakraborty *et al*., 2000). For example, an oats plant's stem resistance to rust is activated once temperatures increase above a threshold of 20 ^oC (Martens *et al.*, 1967; cited by Coakley *et al*., 1999).

The plant host-pathogen interactions under elevated CO_2 conditions may delay the development of a pathogen, depending on the aggression of the pathogen or the susceptibility of the plant to changing physical environments (Coakley *et al*., 1999). Coakley *et al*. (1999) reviewed numerous studies and their findings indicate that climate change was more likely to affect the plant host's morphology, physiology, nutrient and water balances, and thus its resistance to pathogenic infections. Furthermore, they also found that the pathogens might change in response to high CO_2 levels by increasing their infection rates considerably. Shin and Yun (2010) observed this increase in infection rates under elevated CO_2 and increase temperature conditions in four major chilli pepper diseases in growth chamber treatments under future climate conditions (with 720 ± 20 ppmv CO_2, and 30 ± 0.5 ^oC, as opposed to ambient conditions with 420 ± 20 ppmv CO_2, and 25 ± 0.5 ^oC). Findings from their treatments indicated a significant increase of about 24 % in bacterial wilt with its progress rate accelerated by 2 days, while for spot bacterial activity the progress rate accelerated by1 day with a 25 % increase compared to present climate conditions. Shin and Yun (2010) also conducted chamber experiments without elevated CO_2 and they observed acceleration in the bacterial disease progress rate resulting from to increased temperature regimes. This observation confirms the hypothesis by Lonsdale and Gibbs (1996), mentioned above.

With the effects of elevated CO_2 levels simulated to increase plant biomass production, the combination of high biomass with canopy humidity is likely to encourage the emergence of leaf diseases (Manning and von Tiedemann, 1995; cited by Coakley *et al*., 1999). According to

Coakley *et al.* (1999), the survival potential of a pathogen might increase owing to the high amounts of biomass, the slow decomposition rate of litter caused by an increase in the C:N ratio, the availability of an alternative host outside its original host growing season, and an increase in winter temperatures.

3.1.6 Effects of pests and diseases on crop yields under projected climate change

Coakley *et al.* (1999) demonstrated that changes in environmental conditions arising from climate change could pose a serious impact on incidences of insect pests and on prevalence of diseases. These impacts might have either not been a problem or only a small problem, in the past, but could become an epidemic to agricultural production in future climate conditions. The changes in CO_2 concentrations and climate could pose indirect effects in response to changes in the crop host, or direct changes in the insect pest composition, behaviour and population size. Increases in crop growing periods could mean prolonged exposure to pests, and thus greater reductions in crop yields. Changes in climate may result in new pests and diseases being introduced in new areas and/or changes in their composition, hence resulting in species which are more resistant to current control mechanisms, as well as more aggressive pests and diseases being introduced. For example, foliar diseases have niche environmental conditions of high temperature and humidity, and if future conditions favour the niche climate of the host within the same area, this may result in high crop yield losses. Alternatively, these environmental conditions may become unfavourable for the current pests and diseases (Coakley *et al.*, 1999).

Climate change and elevated CO_2 concentrations can also benefit crops. For example, in situations where the partitioning of dry matter to the roots is increasing, increased carbon stored in the roots will reduce root crop losses to soil borne diseases (Coakley *et al.*, 1999). Conversely, an increase in soil carbon may reduce the nutrient levels in the crop leaves and induce increased leaf consumption by insect pests in order to balance their nutrient requirements (Rotter and Van de Gejin, 1999).

3.2 Effects of Climate Change Related Drivers on Pasture and Livestock Production

While effects of climate change on pasture and livestock production are not addressed directly with new research in this dissertation, but only indirectly through an assessment of potential change in net above-ground primary production (NAPP), a review of literature on this theme is nevertheless presented for the sake of completeness.

Since livestock production is dependent on the supply of feed, changes in the growth rate of grass as a result of climate change will affect the feed supply in a given area. For example, if a particular area experiences increases in yields, then livestock production will be positively influenced (Reilly, 2002). Changes in the phenology and growth of species, in response to climate change, can result in the co-existence of numerous species during reproduction. Therefore, the competitive interactions will be affected, resulting in changes in species composition at a community level (Sherry *et al*., 2007). Similarly, findings by Olesen and Bindi (2002) on the effects of climate change with CO_2 fertilisation will be different from species to species and will thus affect the structure of the grassland community. Thus, the species richness and management of the grassland might increase the resilience of species to the changes in climatic conditions and reduce competition for resources.

Shaw *et al*. (2002) indicated that the net above-ground primary production (NAPP) in grassland is simulated individually and/or with interactive effects of CO_2-enriched environments and changes to temperature, precipitation and Nitrogen (N). The experiment was conducted using the Jasper Ridge Global Change Experiment , in which “four global change factors at two levels: CO_2 [ambient and 680 parts per million (ppm)], temperature (ambient and ambient plus 80 W m^{-2} of thermal radiation), precipitation (ambient and 50 % above ambient plus 3-week growing season elongation), and N deposition (ambient and ambient plus 7 g of N m^{-2} year-^{1}) make up a complete factorial design” (Shaw *et al.,* 2002: 1988). The responses were found to be stronger under conditions of limited availability of water or nutrients, and in regions with high species diversity. The grassland responses were found to be more reliant on two or more of the interactions, between temperature increases, elevated CO_2, nitrogen deposition and precipitation. The simulations with one, or a combination, of these interactions showed an increase in the net above-ground biomass (Shaw *et al.,* 2002: 1988). However, Owensby *et al.* (1999) stated that these high productivity responses to a CO_2-enriched atmosphere would not be realised if there were a lack of grazing, which tends to maintain the C_3 perennial grasses. The lack of management (grazing) would result in warm-season, C_4 perennial grasses to flourish, resulting in taller grasses. These taller grasses would shade the C_3 perennial grasses in the same region, hence reducing their growth. Furthermore, the reduction in the light received by C_3 perennial grasses would prevent the emergence of these grasses, and thus result in the potential CO_2

fertilisation not affecting the overall pasture productivity. The competition between C_3 and C_4 perennial grasses for light is similar to the observed invasion by woody species in natural grassland, where overgrazing could result in systems being vulnerable to invasion by woody or aggressive alien species. Therefore, good management practice in future will be more significant for high forage supply and thus livestock production.

The statistical results from Shaw *et al*. (2002), using a t-test at a 95 % confidence interval for the net primary production responses to interactive effects of increased temperature, precipitation and nitrogen deposition, showed a significant increase in the grass productivity. The effects of elevated CO_2 resulted in the reduction of NAPP by 44 %. The suppressed effects of elevated CO_2 were also evident across all the experiments of below-ground biomass with an averaged decreased effect of approximately 22 %. The suppression in the effects of elevation in CO_2 could arise from a number of mechanisms, of which the first identified is that responses may be dependent on the specific characteristic of the experiment. The simulated effects of precipitation in CO_2 driven water stress reduction are nullified by reducing the plant's stomatal conductivity and thus effectively its rates of transpiration. The grassland productivity seems to respond only to elevated CO_2 and water stress. Another, mechanism that can contribute to the effects of suppression by enhanced CO_2 arises from changes in the richness or composition of the plant species (Shaw *et al*., 2002).

Mooney and Koch (1994; cited by Rotter and Van de Gejin, 1999) found that under CO_2-enriched conditions, levels of the nitrogen content in the leaves are reduced and this affects the leaf tissues' nutritional quality. The study conducted by Shaw *et al*. (2002) suggests that dry matter allocation to the root growth is reduced as a response to the effect of elevated CO_2 and it may affect the balance between the supply and demand of nutrients. Therefore, the reduction in root growth will decrease the grazing and browsing capacity, and increase the herbivores' plant biomass consumption in order for the animals to maintain similar levels of mineral nutrients in their diets (Rotter and Van de Gejin, 1999).

Other climatic impacts that will affect grassland productivity are obviously precipitation and temperature. Rasmussen (2001) stated that the limitation in nutrients will increasingly become important to grassland productivity, should they not be mitigated through fertilizer applications. Therefore, if the effect of the temperature increase is significantly higher than that of precipitation, then E_{pm} will be increased, and this then translates to a reduction in grassland productivity (cf. **Chapter 6**).

3.3 Water Resources for Agricultural Production

Agriculture, when compared with other water consuming activities, uses an appreciable amount of a region's water resources. For example, in South Africa over 60 % of the water allocations are for agriculture (DWAF, 2009). Frischel (2006) stated that climate change could affect the reliability of water allocations by changing precipitation, evaporation, soil moisture and runoff, which would change the amount and supply of water for irrigated agriculture. The reduction in water allocation could then have a significant impact on farmers practising dryland agriculture, as well as on other water users, such as industries and the environment. This may lead to increases in the competition for water resources between the different sectors.

Crops are subjected to evaporative demand, which is influenced by climate parameters such as air surface temperature, atmospheric humidity, net radiation and wind, which results in an increase in the crops' transpiration rates (Schulze, 1995). Rosenzweig and Hillel (1998) stated that the effects of climate change are more likely to be manifested in the above-mentioned climate variables, hence resulting in changes in the hydrological cycle. In the broader hydrological cycle an increase in evaporation should result in an overall increase in precipitation; however, this relationship between precipitation and evaporation may not be experienced within the same area. GCMs suggest that E_{pm} will increase in the low to middle latitudes, where temperatures are already high, as well as in the higher latitudes. At lower latitudes near the oceans, the air is already cooler than in the interior and therefore more readily saturated with additional moisture. Hence the E_{pm} will be lower there and an increase precipitation is expected. Changes in the hydrological cycle will affect a crop's irrigation water demand as well as the supply of water for irrigation (Rosenzweig and Hillel, 1998).

Hardy (2003) stated that an increase in E_{pm} would reduce the soil water content and that it could increase the frequency of droughts. An increase in drought frequency would reduce the annual water supply and summer soil moisture, thus resulting in higher plant water deficits. Schulze (2005a) indicated that in South Africa an increase in the E_{pm} could affect future irrigation requirements and runoff generation. The increase in E_{pm}, and thus water demand, will affect dryland agriculture. Either water stress caused by an increase in the water deficit, or a change in total seasonal and variability in precipitation patterns during critical times for the crop (e.g. during seedling, flowering and grain filling stages) can cause failure in many crops (Rosenzweig and Hillel, 1998).

Karol *et al*. (2005) found dryland crops to be affected the most by climatic changes when simulating the effects of climate change on crops in semi-arid northeast Brazil. Their simulations were obtained using two downscaled GCMs, *viz.* ECHAM-4 and HADCM-2. The difference between the models is that the projected changes in precipitation over the region between 1961 - 1990 and 2070 - 2099 (for a 1 % annual increase in greenhouse gases) are + 21 % for HADCM-2 and - 50 % for ECHAM-4. The models indicated a 12 – 55 % reduction and a 4 - 23 % increase in dryland agricultural yields for the ECHAM-4 and HADCM-2 scenarios, respectively, depending on the crop. Simulations from ECHAM-4 for banana, mango, cotton and cashew nut production under dryland conditions indicated a high reduction in yields, whereas under irrigation the effects were less severe. For HADCM-2, the simulation indicated an increase in the production of the above dryland crops and a slight yield decrease for crops under irrigation. They found that the positive effects from the HADCM-2 overlapped the natural climate variability, whereas the negative trends of ECHAM-4 were more clearly visible. However, in irrigated crop production both GCMs showed much less sensitivity to climate change than under rainfed conditions (Karol *et al*., 2005). The findings from Izaurralde *et al.* (2003) in a climate change impact modelling study indicated that by 2030 dryland maize production in the USA would be exposed to additional days of water stress resulting from an increase in E_{pm} in response to warmer conditions, while the WUE was projected to be reduced. The production from irrigated land was less affected by climatic changes compared to that under dryland conditions. Karol *et al*. (2005) estimated that in the forthcoming decades the irrigated areas would increase because of water stress on dryland agriculture.

If the available water resources do not meet the irrigation demand, the actual benefit of any recovery of land may be limited by a change in climate. Irrigated crop production under both ECHAM-4 and HADCM-2 climate scenarios was projected to increase until 2025, primarily due to the increase in irrigated area (Karol *et al.*, 2005). The crop production would then begin to decline after the growing water demand could no longer be met because of a decrease in precipitation. Izaurralde *et al.* (2003) reported that the balance in irrigated maize water demand and supply in the USA under climate change predictions would be sensitive to the geographical variation in temperature and precipitation changes. Furthermore, the water balance for irrigated maize and alfalfa under climate change conditions with the effect of CO_2-fertilization seemed to improve nationally, compared to conditions without simulated elevated CO_2.

Rosenzweig *et al*. (2004) used complex climate scenarios of interactions of the effects of elevated atmospheric CO_2 together with temperature and precipitation on crop growth and water use in numerous study areas. They found that the crop water demands varied between the areas and within different water regions in each area. Schulze (2005a) reported that under climate change conditions without elevated atmospheric CO_2, the potential evaporation by year 2050 might vary across South Africa, ranging from 5 to 15 %, with the highest evaporation increases in the central plateau regions. These impact assessment studies provide information on future water requirements, which might be useful in implementing adaptation strategies, such as investing in irrigation systems or a change in farmed areas and crops. Irrigated areas have significant impacts on water resources, which are likely to be more severe under climate change conditions (Rosenzweig and Hillel, 1995).

An increase in temperature (and thus higher E_{pm}) and a change in precipitation have been shown from a number of studies to severely affect dryland crop production, more so than on irrigated crops (Fischer *et al.*, 2007; Dinar and Mendelsohn, 2009). The likely positive effects of CO_2, such as transpiration suppression and photosynthesis enhancement might reduce projected negative impacts.

An increase in temperature and changed precipitation will generally intensify the annual variability of water-related extreme events such as floods and droughts and their effects on water resources and agricultural production.

Water stress on plants is exacerbated by an increase in temperature, which results in high vapour pressure deficits (evaporative demand). Thus, if the plant's growth is limited by a water deficiency, then low photosynthesis rates will be experienced in the plant's leaves (Norberger *et al.*, 2000). However, under moderate drought stress with elevated CO_2 and increased temperature conditions, the findings by Casella's and Soussana's (1997; cited by Norberger *et al.*, 2000) suggest that the photosynthesis rates in the canopy will increase to a larger degree during the summer season. Conversely, the canopy photosynthesis rates declined during drought stress under CO_2-enriched conditions with a 3 ^{o}C temperature increase. Aggarwal *et al*. (2006) related an increase in canopy temperature and a reduction in transpiration to water deficiency, which they used to indicate that under water stress alone, crop development would increase at accelerated rates. If the water stress is coupled with an increase in air temperature, the severity of the stress on crop development will increase, thus inhibiting development. The inhibition of crop development can be translated into losses in potential yields. The effects of floods or waterlogging on crop development will be similar to those under drought conditions; however, impacts will depend on the growth stage and sensitivity of the crop to waterlogged soils. The stress from flooding is induced by the waterlogged soils reducing oxygen availability to plants and hence water uptake, except in crops such as rice (Aggarwal *et al.*, 2006).

The effects of changes in droughts and floods were shown to have a great impact on crop production. Flood and drought conditions are likely to cause water stress in crops, resulting in a reductions in carbohydrate production and hence development, which can be translated into a reduction in yields.

3.4 Implications of Climate Change Effects on Farmers

An "understanding of how best to support those most vulnerable to climate stress is imperative, given expected changes in climate variability" (Ziervogel *et al.*, 2006:1).

Small-scale farmers are faced with numerous constraints, such as poor soil quality, financial constraints and lack of access to markets, apart from the climate variability effects on their production (Kurukulasuriya and Rosenthal, 2003). However, climate change will be an additional stressor (Ziervogel *et al.*, 2006). This additional stressor can be translated into production risk, which is related to crop and livestock yields (discussed in **Sub-sections 3.1** to **3.3**), to the probability of more extreme events, the timing of field operations and investment in new technologies (Kurukulasuriya and Rosenthal, 2003). The investigation in this study focuses on the potential realised yields and hydrological seasonality. The current constraints faced by emerging farmers, especially in developing economies, may contribute to the farmers' vulnerability to climate change. The intensive agricultural practices, coupled with improper farming techniques and the expansion in agriculture as a response to increases in consumer demands, by and large contribute to the steady degradation of resources (such as soils, forests, water and plants) on which farmers depend (Alcadi *et al.*, 2009).

According to the conclusions reached at the Thirteenth Conference of the Parties to the United Nations Framework Convention on Climate Change, the projected effects of climate change in semi-arid regions have a significant impact on agriculture. A rise in temperature regimes results in reduced crop productivity in crops such as wheat. The significance of the impacts are particularly important on rainfed agriculture, since the majority of the population in semi-arid regions are dependent on it, given that the adverse conditions resulting from changes in rainfall and water availability would, globally have an effect on the livelihoods of approximately 500 million people (Pachauri, 2007).

A case study by Ziervogel *et al*. (2006) on local adaptation strategies to climate variability of poorer farmers in Vhembe District of Limpopo Province suggests that the farmers' vulnerability is a result of their direct dependency on climatic conditions. The vulnerabilities faced by the poorer farmers are due to limited opportunities in accessing resources such as fertilizer, transport and alternative income opportunities. The projected increase in climate variability and extreme conditions under climate change is an additional stressor of concern (Ziervogel *et al*., 2006). Further to this, Bharwani *et al*. (2005) studied two groups of farmers (i.e. the rich and poorer farmers) with the aim of assessing whether individuals who were adapting gradually to climate variability in the Vhembe district might be better prepared to cope in a sustainable manner to the long-term climate variability and change. Their findings showed that the lack of knowledge and trust in climate forecasts, including their limited resources to overcome climate variability, would have negative impacts on their agricultural production. Under climate change conditions, the study indicated that the rich farmers might be able to overcome the effects of projected climate change. Therefore, improving the forecasts for farmers might increase trust and be of benefit in their response to enhancing their crop yields. For poorer farmers these benefits will not be realised, except if their skills to act on climate forecasts were to improve considerably. The improvement of the poorer farmers' skill to interpret the forecast information concerning their practices and thus to respond appropriately, but with no benefit, is attributed to the fact that they do not have enough resources to act on the climate forecasts. Furthermore, the rational response to forecasted conditions often stems from material knowledge available and from past experience of such events (Washington *et al*., 2005).

The study by D'Hease *et al.* (1998) identified strategies for solving problems faced by Black African small-scale commercial mango farmers in a region of Venda in the Limpopo Province. Findings from the group discussions indicated that the main constraint these farmers faced was low farm income. The three causes contributing to the low income were identified to be poor commercialisation, poor infrastructure and low farm productivity. Poor commercialisation is the farmers' lack of knowledge of markets and their inability to make the most of the domestic and international markets. The farmers' limited access to resources, such as credit, inhibits their investment in on-farm infrastructure, and the system in operation is not equipped to support the transition of these small-scale farmers to commercial production. Low farm productivity was found to be a result of reduced productivity of land, labour resources and crops. These result from the lack of land and water management, skilled labour availability and management thereof, and poor farming techniques (D'Hease *et al.*, 1998). In their study conducted in the Venda region, it was found that the problems faced by these so-called emerging farmers were similar to those in most emerging commercial farming communities.

The overall conclusion from in the Limpopo Catchment concurs with one by Mortimore and Adams (2001), *viz*. that the inability of a farmer to cope with disaster in the past, paints a catastrophic picture of disasters that he/she is likely to experience under future climates.

3.5 Summary

Studies conducted in controlled chamber and greenhouse environment experiments were reviewed in this chapter in order to assess the direct effects of climate change related drivers on agricultural crops (e.g. Long *et al.*, 2005; Slingo *et al.*, 2005). There are many uncertainties associated with such information when applied to the farm scale, one of which is that the crops grown in these controlled environments are less exposed to additional environmental stressors (such as pests and weeds), than those grown under field conditions. Hence, it is worthy of note that there would be differences in crop responses under climate change in open fields compared to those in controlled environmental conditions.

Elevated CO_2 concentration conditions in crops in most studies were generally found to have positive effects on crop yields. These positive responses were mainly observed in C_3 crops, where the CO_2 fertilisation effect stimulates the production of carbohydrates in the leaves, which the plant uses to develop its different components, i.e. roots, stems, shoots, leaves and fruit. After the plant matures, most of the dry matter produced will be allocated for grain production or fruiting. However, in C_4 crop such as maize, the opposite responses to CO_2 fertilisation were found. The positive responses of C_3 crops to CO_2 fertilisation will be largely negated by an increase in warming, while in C_4 crops most studies indicated an increase in crop yields. Furthermore, an increase in temperatures was found to lengthen the growing seasons, thus enabling early crop planting and early harvesting.

In dryland crop production, the effects of elevated CO_2 concentration were observed in numerous studies to reduce the plant's water loss, thus increasing the WUE. Increases in temperatures were found to increase the rates of E_{pm} and reduce the WUE. The interactive effects of elevated CO_2 with an increase in temperature will increase the WUE by half of the WUE experienced under elevated CO_2 effects alone. Studies on short-term exposure of crop plants to elevated CO_2 concentrations indicated that the effects of CO_2 would increase the WUE and would be of benefit to farmers in regions where water resources are limited. However, studies on long-term crop plant exposure to elevated CO_2 concentrations and increased temperatures, suggested that crop growth would be increased, particularly the canopy and root system, thereby reducing the WUE. The reduction in the WUE results from high water losses, which are caused by deeper roots abstracting deep soil water resources and the high canopy biomass.

Elevated CO_2 concentrations not only affect the biomass of crops, but also its quality. High levels of carbon in the crop plant will increase the C:N ratio and thus result in lower leaf nitrogen content. The high crop biomass of low nutritional quality in CO_2-enriched conditions will result in the increased consumption of crops by insect pests in order to sustain their nutritional levels. An additional effect on crop production is that C_3 IAPS (invasive alien plant species) are stimulated by the elevated CO_2 conditions to grow and expand, thus increasing the chance of IAPS invasion. The invasion is more likely to occur if the crops are C_4 species. However, if they are of the same photosynthetic pathway the survival rate will be determined by their biological characteristics. These effects on crops will affect the production areas and potential yields.

It was assumed that an increase in grassland biomass would directly increase livestock consumption, and hence the production of livestock. The projected increases in extreme heat conditions were found to be likely to intensify the frequency of fire occurrence. More frequent fire recurrence in grassland regions may result in the degradation of grasses, and hence the emergence of woodier species in response to increased atmospheric CO_2 concentrations. Frequent grazing that is well-managed might reduce the threat of invasive woody vegetation. A reduction, or change, in pasture composition is projected to result in the reduction of livestock production.

Extreme climate effects such as higher temperature and reductions in rainfall are hypothesised to reduce the availability of water, thus increasing irrigation water requirements. As agriculture is a major water user, the reduction in water availability will affect dryland crops severely and, to some extent, the irrigated crop under changed conditions, particularly in extreme climatic events such as droughts. Water stress caused by droughts will affect the production of dry matter and the development of the crop, and thus crop yields. Similarly, flood events can induce crop water stress through soil waterlogging. The stress posed is dependent on the crop's sensitivity to water logging and the stage of its development.

Climate change is likely to cause a reduction in agricultural production in the semi-arid regions of the Limpopo Catchment, the population of which depends largely on subsistence agriculture for food. Subsistence farming is projected to be more sensitive, and thus more vulnerable, to changes in climate because of the farmers' current social and economic conditions. Therefore, it is imperative to understand how emerging farmers, such as those in the Limpopo Catchment, are likely to be affected by change in climate, and what steps they could take to reduce their vulnerability.

In conclusion, the climate change drivers will affect agricultural production in various ways depending on the current location of production, i.e. the current climate, altitude and the type of crop planted. In this study the effects of climate change drivers are assessed by using net above-ground primary production, to represent estimated agricultural production, in order to determine the likely impacts on productivity (cf. **Chapter 6**). Furthermore, climate change will affect crops through changing their resource availability and natural enemies (such as pests, diseases and Invasive Alien Plant Species), and these factors will either individually, or interactively, affect a location's agricultural production. Potential distributions of *Chilo partellus*, a spotted stemborer, are assessed under climate change conditions in **Chapter 7**, and those of *Striga asiatica* Witch Weed are presented in **Appendix E**. Furthermore, the agricultural water use and productivity in the Limpopo Catchment are estimated for dryland agriculture under projected future climate conditions in **Chapter 8**.

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Following the review of literature on effects of climate change on potential agricultural production in this chapter, a review of uncertainties associated with the downscaled GCM derived climate projections is presented in **Chapter 4**, together with a description of methods of quantifying uncertainties and examples of uncertainty analyses in the Limpopo Catchment.

4. UNCERTAINTY ANALYSIS OF CLIMATE PROJECTIONS

The information from uncertainty analyses in climate projections is of importance in communicating climate impacts to decision-makers, thereby enabling them to assess how policies can be used to reduce risks of climate impacts (Webster *et al*., 2001). The uncertainties arising from the impact assessment process *per se*, which are not covered in this study, include the uncertainty inherent in the baseline climate data, and the uncertainty arising as a result of forcing by emission scenarios, initial conditions assumed in the General Circulation Models (GCMs), model imperfections and resultant imperfections in the results. These uncertainties should also be considered.

In this chapter the uncertainties associated with the downscaled GCM derived climate projections (scenarios) are first reviewed, methods of quantifying uncertainties are then described and thereafter examples are presented of uncertainty analyses in the Limpopo Catchment.

4.1 Introduction

The methods used for projecting likely future climatic conditions consist of climate change scenarios, discussed in **Chapter 3**. These methods are derived either with or without GCMs (cf. **Chapter 3**). The impact assessments in this study were projected from GCM climate change scenarios. These climate change scenarios have inherent uncertainties due to the different parameterisations of variables and the internal structures of different GCMs. The GCMs' output predictor variables (for example, temperature and precipitation) will therefore vary from GCM to GCM and the projections from climate change scenarios include many uncertainties. In recognition of the differences between GCMs, it is important to consider outlooks from a range of projections rather than using only one plausible climate change outcome (Hewitson *et al*., 2005; Stainforth *et al*., 2007).

The main guideline for selecting methods of uncertainty analysis is that it must be documented (preferably peer-reviewed) and reproducible. Furthermore, it is important that uncertainties in the GCM projections are communicated cautiously and from a neutral perspective, in order to avoid misinterpretation and any ambiguity in the interpretation (Webster *et al*., 2001). Such guidelines are important in uncertainty analyses, because they provide decision- or policy-makers with information allowing, and/or enabling, them to assess how policies might lead to reducing the risk of the impacts of climate change (Webster *et al*., 2001). The various approaches for expressing uncertainty are through qualitative, quantitative and probabilistic analyses (IPCC, 2007).

The methods around *probability analyses* have a limited documented literature and there is limited understanding of causative factors, such as the joint effects of different assumptions made in different GCMs (Allen *et al*., 2001). A 20-year record length of a climate change projection is not long enough for probability analyses, according to Allen *et al*. (2001), because such statistical analyses ideally require a 100-year climate change projection. A *quantitative analysis*, on the other hand, assess uncertainty using expert judgment on the correctness of the underlying data and models, and therefore confidence scale levels are used to express the relative correctness of model output. Thirdly, the *qualitative analysis*, provides "a relative sense of the amount and quality of evidence… and the degree of agreement" (IPCC 2007: 27). In this study the quantitative analysis approach was used to assess the uncertainty in the predictors from GCMs (cf. **Section 4.3**).

The objective in this Chapter is to evaluate the uncertainty associated with GCMs by examining the differences in the predictors of the GCMs, *viz*. daily temperature and precipitation values. A brief review of literature on uncertainty associated with GCMs is presented as a preface to the analyses later in this Chapter.

4.2 Uncertainties Inherent in Projections of Future Climates: A Literature Review

General Circulation Model climate projections are derived from different physically based GCMs for a range of plausible future greenhouse gas (GHG) emission scenarios as a major input, as well as consideration of population and economic growth projections (cf. **Table 4.1**). The emission scenarios contribute significantly to uncertainty in climate change projections (Hewitson *et al*., 2005). In **Figure 4.1** the fractional uncertainty in the emission scenarios, i.e. the predicted error over its central estimate (range 0 to 1), increases with lead time of the predictions, which range from 10 to 100 years (Cox and Stephenson, 2007). The effects of other forms of fractional uncertainty which contribute to the overall uncertainty in predicted average temperatures are also shown in **Figure 4.1**. Bergant *et al*. (2006) stated that assumptions made in the development of future socio-economic scenarios and associated emissions of GHGs and sulphur dioxide are basic sources of unavoidable uncertainty. The emission scenarios form the basis of parameters used as inputs into GCMs to postulate past, present and future climates. Outputs from GCMs are used as a basis for climate change impact assessments (Hewitson *et al.*, 2005). Bergant *et al.* (2006) used observed patterns from a wide range of possible future emission scenarios suggested by the Intergovernmental Panel on Climate Change (IPCC) and a range of different GCMs to estimate the uncertainty of future emissions. They found that different GCMs responded slightly differently to the same scenarios, as well as to the levels of greenhouse gases and sulphate aerosols.

Table 4.1 Assumptions made in four emissions scenarios used in the IPCC Special Report for Climate Change Forcing (Slater *et al.*, 2007)

IPCC Scenario	A1F1	A2	B1	B2
Population in 2010	7 billion	15 billion	7 billion	10 billion
Economic growth	3.50 %	2.00 %	2.75 %	2.00 %
Emission levels	High	Medium high	Low	Medium low
Temperature increases (°C)	2020: 0.70 2050: 1.96 2080: 3.67	2020: 0.59 2050: 1.59 2080: 2.90	2020: 0.54 2050: 1.15 2080: 1.76	2020: 0.61 2050: 1.31 2080: 2.08

Sources: Stern (2006); Note: Many different GCMs are used to process the basic scenario inputs, each using different assumptions.

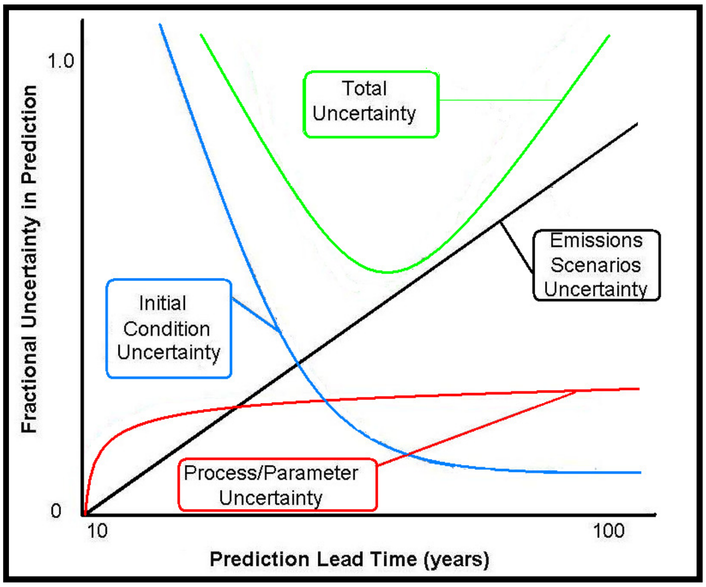

Figure 4.1 Contributions of uncertainties in predicted mean annual temperature with changes in prediction lead time (After Cox and Stephenson, 2007)

The shortcomings in process representation in the climate models are another source of uncertainty, mainly related to the unresolved description of processes using statistical parameterisation schemes. The variability resulting from different model parameterisations is evident in the outputs from different GCMs with the same emission scenarios, as illustrated in **Figure 4.2**. The shaded area represents the range of projections, with the white line being their average and the black line the average of the A2 scenarios from the different selected GCMs. For example, in the year 2090 an increase in air temperature is projected to range between 1.5 to 5.3 ^{o}C, with 3.5 ^{o}C as an average relative to that of the year 1990 (Bergant *et al.*, 2006).

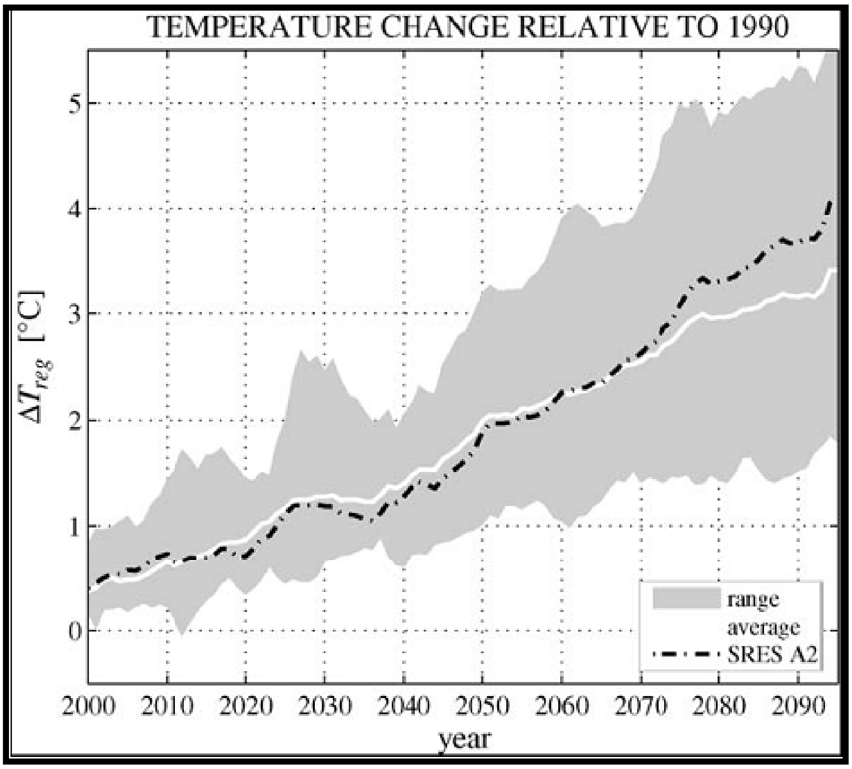

Figure 4.2 The range in projections of surface air temperature change for western and central Europe, relative to the year 1990, and using only the SRES A2 emissions scenario (Bergant *et al.*, 2006)

Outputs from GCMs are downscaled to the regional/local scale using downscaling methods such as Regional Climate Models (RCMs) or empirical downscaling (cf. **Section 3.1.2** of **Chapter 3**). The use of outputs from GCMs as input parameters, as well as initial conditions in downscaling methods, result in a transfer of the uncertainty inherent in the global scale to the regional/local scale (Krysanova *et al.*, 2007). The uncertainty found in the spatial scale of scenarios can be as large as those of the differing global climate response models (Mearns *et al.*, 2003). Therefore, uncertainty in climate change projections can, in theory, become greater with downscaling.

Downscaling to the regional/local scale provides a spread in results between different downscaling tools, thus making it difficult to place a probability on the scenario because the climate change signal might have become contaminated by the different sources of uncertainty. These uncertainties are in the tools, the comprehension of the physical processes, and the physics of the atmosphere/land/ocean systems and the minimal inclusion of feedbacks between components of the climate/land/ocean systems. Despite the sources of uncertainty, GCM simulations are generally in broad agreement with one another. Additionally, the uncertainties are physically explainable and consistent with the present understanding of climate processes as well as with observed historical changes (Hewitson *et al.*, 2005).

In **Figure 4.3**, the stages involved in the simulation of climate change and the manner in which uncertainty increases with a reduction in the level of focus, are illustrated. Further assumptions, therefore, can cumulatively increase the uncertainty in quantitative estimates of climate change at global, regional and especially local scale (Bergant *et al.*, 2006).

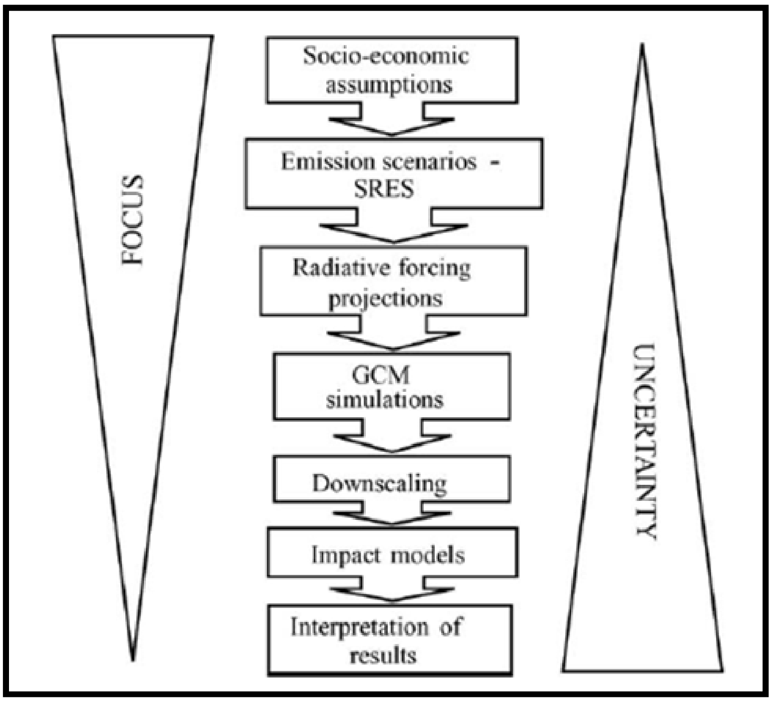

Figure 4.3 Changes in the uncertainty found in the process from developing climate change scenarios to interpretation of impacts assessments (Bergant *et al.*, 2006)

In the future, new knowledge on the climate system's responses to the changes in the atmospheric composition, and on the climate-dependent processes resulting in climate variability, will probably reduce uncertainties. Enhanced horizontal resolution of GCMs and improvement in the description of model physics will reduce the importance of downscaling approaches and related uncertainties. Furthermore, this might reduce the inter-model differences, and as a result make available more reliable estimates of climate systems responses to change at the regional/ local level (Bergant *et al*., 2006).

4.3 Methods of Expressing Certainty/Uncertainty in Projected Future Climate Scenarios

The first IPCC report, published in 1990, stated that projections of the global average temperatures for the period 1990 to 2005 would probably increase by approximately 0.15 to 0.30 ^{o}C per decade. These projections can now be validated by comparing them with post-1990 observations. An evaluation presented in the IPCC's (2007) Fourth Assessment Report indicates a 0.20 ^{o}C increase per decade, thus strengthening the confidence in future climate projections. The advancements in climate modelling, particularly in the prediction of global warming from various GCM emission scenarios, can give both the best representative estimates and the uncertainty ranges.

The quantitative analysis approach adopted in this study for assessing uncertainty in GCM projections was based on that used in the three Working Groups (WGs) of the IPCC. This approach uses a series of explanatory terms indicated in **Table 4.2**.

Table 4.2 Scale of confidence levels for quantitative assessment of uncertainty, as defined by the IPCC (2007)

Confidence Terminology	Degree of Confidence in Being Correct
Very high confidence	At least 9 out of 10 chance
High confidence	About 8 out of 10 chance
Medium confidence	About 5 out of 10 chance
Low confidence	About 2 out of 10 chance
Very low confidence	Less than 1 out of 10 chance

Knoesen (2010) reclassified the IPCC's explanations to accord with the number of GCMs currently (2010) used in detailed South African impact studies, *viz.* five. These GCMs are CGCM3.1 (T47), CNRM-CM3, ECHAM5/MPI-OM, GISS-ER and IPSL-CM4 (cf. **Table 4.3**).

In these studies (e.g. Schulze *et al.*, 2010b) the intermediate future climate scenario [2046 – 2065] were delimited into confidence levels with five categories based on the concurrence of results from the GCMs, while the distant future climate results [2081 – 2100] were assessed with only four of the above-mentioned GCMs. This is due to the CGCM3.1(T47) model's projections being limited to the intermediate future climate scenarios only. The confidence levels are shown in **Table 4.4**.

Table 4.3 The GCMs used in 2010 in South African impact studies (After Schulze *et al.*, 2010b)

M odel ID and Vintage	Description	Institution	Country of Origin
ECHAM5/MPI-OM, 2005	Fifth Generation Atmospheric General Circulation Model	Max-Planck Institute for Meteorology	Germany
CGCM3.1 (T47), 2005	Third Generation Coupled Global Climate Model	Canadian Center for Climate Modelling and Analysis	Canada
CNRM-CM3, 2004	Coupled Global Climate Model, Version 3	Centre National de Recherches Météorologiques	France
GISS-ER, 2004	Goddard Institute for Space Studies, Version ER	National Aeronautics and Space Administration (NASA)	United States of America
IPSL-CM4, 2005	Climate Assessment Model 4, Version 1	Institut Pierre Simon Laplace	France

The confidence levels were computed for the above-mentioned GCMs climate predictors, i.e. temperature and precipitation, and are discussed below. The confidence level scale in this study (**Table 4.4**) indicates the consistency in the distribution of the predicted variable of interest by different GCMs, whereby higher confidence levels represent higher agreement in distributions of predicted variables of interest of the GCMs, which are based on very different assumptions and parameters (Knoesen, 2010).

When mapping confidence levels using the approach given in **Table 4.4**, the confidence is expressed by posing a hypothesis related to the projected change and then assessing for how many GCMs the specific hypothesis was met for each spatial unit (Schulze, 2010, personal communication), in this case for each Quinary in the Limpopo Catchment.

Table 4.4 Scale of confidence levels for quantitative assessment of uncertainty in this study (Knoesen, 2010)

Confidence Terminology	**Degree of Confidence when 5 GCMs are Used (Intermediate Future relative to Present Climate Scenario)**	**Degree of Confidence when 4 GCMs are Used (Distant Future Relative to Present Climate Scenario)**
Very high confidence	5 out of 5 GCMs give same signal	4 out of 4 GCMs give same signal
High confidence	4 out of 5 GCMs give same signal	3 out of 4 GCMs give same signal
Medium high confidence	3 out of 5 GCMs give same signal	N/A
Medium confidence	N/A	2 out of 4 GCMs give same signal
Medium low confidence	2 out of 5 GCMs give same signal	N/A
Low confidence	< 2 out of 5 GCMs give same signal	< 2 out of 4 GCMs give same signal

4.4 Review of Projected Temperature Increases from Downscaled General Circulation Models in the Limpopo Catchment

The quantitative uncertainty assessment between outputs from multiple GCMs is expressed by the index of concurrence. In the first example, used to illustrate this, the hypothesis is made that under projected future climate conditions temperature will increase by more than 10 % over the Limpopo Catchment between the intermediate future and present. The index consists of 5 confidence levels ranging from *Very high* (i.e. for 5 out of 5 GCMs the hypothesis is shown to hold true) to *Low* (for < 2 out of 5 GCMs the hypothesis holds). For the distant future, for which one less GCM was available, 4 confidence levels are used (cf. **Table 4.4**). The assessment of percentage changes in temperature, while not meaningful *per se*, does make it possible to identify areas that are relatively sensitive to future temperatures relative to those of the present (Schulze and Kunz, 2010a). The information used in this review as examples of uncertainty in projected temperatures (in this section), as well as for uncertainty in projected precipitation (in **Section 4.5**) were extracted for the Limpopo Catchment from work conducted by Schulze and Kunz (2010a).

The uncertainty analyses indicates that increases in annual temperatures of > 10 % by the intermediate future [i.e. 2046 – 2065 vs. 1971 – 1990] and the more distant future [i.e. 2081 – 2010 vs. 1971 – 1990] are projected to be experienced virtually throughout the Limpopo

Catchment, implying that all 5 GCMs postulate at minimum a 10 % increase in mean annual temperature (cf. **Appendix F**).

On the other hand, maximum temperatures in January (the hottest mid-summer month) were found to be sensitive to a 10 % rise in temperature in the intermediate future with < 2 of the GCMs succeeding, while in the distant future all GCMs project temperature increases over 10 %.

However, relative increases were found in minimum temperatures in July (the coldest mid-winter month), both the intermediate and distant future climates from all the GCMs' outputs display > 10 % increases in minimum temperature virtually throughout the Catchment (cf. **Appendix F**).

4.5 Review of Projected Precipitation Changes from Downscaled Global Circulation Models in Limpopo Catchment

Schulze and Kunz (2010a) indicate with *very high* confidence that the mean annual precipitation is projected to increase over the study area in both the intermediate and distant future (cf. **Appendix F**). However, the confidence in the hypothesis that the inter-annual variability of precipitation will increase in future generally varies from *low* to *very high* for both the intermediate and distant future climate scenarios (Schulze and Kunz, 2010, Personal Communication; cf. **Appendix F**).

In regard to the hypothesis that January (mid-summer month) precipitation would increase in the intermediate future, the five GCMs used concur at the a *very high* level of confidence that this would occur over most of the southern part of the Limpopo Catchment, but reducing to *high* to *moderate* confidence levels in patches in the northern and central interior (Schulze and Kunz, 2010d cf. **Appendix F**). For the distant future, the index of concurrence is more patchy, ranging from *low* to *high* levels of confidence.

The patterns of the index of concurrence for projected precipitation increase in the intermediate future in July (Schulze and Kunz, 2010d; cf. **Appendix F**), displaying a wider range of confidence levels than those of January's, by ranging from *medium low* in the central interior to *very high* over most of the study area. What is evident is a smaller area of *very high* confidence levels for projected precipitation increases. However, the distant future the confidence levels are generally *very high* over most of the Catchment, hence implying likely increases in projected precipitation in winter months in this part of the summer rainfall region when compared to increases in the summer months.

4.6 Summary

The literature reviewed points out that uncertainties associated with GCM derived climate projections increase with the reduction in the focus scale from derivation of emission scenarios through to the interpretation of the impacts assessments. The uncertainties in GCM derived climate projections can be analysed using a number of methods, *viz. probabilistic*, *quantitative* and *qualitative*. Uncertainty in GCMs' future climate projections were assessed quantitatively using the index of concurrence that in future climates attributes of both temperature and precipitation would increase, with confidence levels indicating the 'degree' of agreement in the direction of change from different GCMs. The uncertainty analyses showed significant concurrence levels in climate projections across the Limpopo Catchment, with projected increase in future temperature generally displaying higher confidences than projected increases in precipitation.

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Following the literature review in this Chapter on the uncertainties associated with the downscaled GCM derived climate projections, the description of methods of quantifying uncertainties, and then providing some examples of uncertainty analysis in the Limpopo Catchment. In the following chapter the databases and models used in all the simulations in the study area are discussed.

SECTION THREE: METHODOLOGY

5. DATABASES AND MODELS

Having reviewed literature on uncertainties, described methods of quantifying them and evaluated uncertainties associated with downscaled General Circulation Models (GCMs) in **Chapter 4**, in this Chapter the baseline data as well as tools and the general methodology used in this study are discussed.

5.1 Application of Climate Scenarios

Climate scenarios are tools used in sensitivity and impact studies when projecting future climates (NRC, 2006). They are applied for their reasoned, internally consistent, plausible description of a likely climatic state (IPCC, 2001). These scenarios are, however, not predictions of the future, but rather representations of numerous probable ranges of future climatic conditions. Furthermore, they are tools for communicating what is known and unknown. For example, it is known with confidence that in future there will be an increase in surface air temperatures (Hewitson *et al*., 2005; IPCC, 2007). Plausible climate scenarios should therefore not project lower temperatures compared to the present climate conditions. However, as the direction of change in precipitation is not known with certainty, the climate scenarios used in sensitivity studies should indicate both increases and decreases in precipitation (Mearns *et al*., 2001). In addition, climate scenarios give information which could be used in impact assessments, as well as vulnerability and adaptation studies, and hence they raise awareness of the potential impacts of climate change and related issues. Unlike output from General Circulation Models (GCMs), climate sensitivity scenarios consider uncertainty through a range of plausible future climates (NRC, 2006).

General Circulation Models, on the other hand, are key tools used in the projection of future climates and are capable of simulating large global scale dynamics of the atmosphere. For that reason they are not suitable for use at a finer regional/local scale in their original form (Hewitson *et al*., 2005). Downscaling is therefore essential in deriving climate scenarios appropriate for regional/local analyses from the GCM outputs. Within the South African literature downscaling techniques are discussed in detail by Perks (2001), Hewitson (1999), Hewitson *et al*. (2004) and Hewitson *et al*. (2005). General Circulation Models use the physical representation of the atmosphere, land and sea surface together with greenhouse gas emissions scenarios to project climate conditions. General Circulation Models with the same input emission scenarios are more likely to provide distinct geographical distributions of temperature, and to a lesser extent, of precipitation (Hewitson *et al*., 2004; Kundzewicz *et al.*, 2007; Randall *et al*., 2007). No single GCM may be considered to be the best, as each has different strengths and weaknesses. Therefore, it is of importance for a modeller or user to apply output from a wide range of GCMs, in order to ideally obtain a probability distribution of likely future climates, as each GCM is based on slightly different process representations in reflecting plausible future climates. Use of output from multiple GCMs accounts for the uncertainties in future human-induced greenhouse gas (GHG) emissions.

Climate projections used in this study were derived from station-level downscaled GCM outputs, with the GCMs being selected for the physically based principles on which they were developed (IPCC, 2001; Hewitson *et al*., 2005). The climate projections used were downloaded from the School of Bioresources Engineering and Environmental Hydrology (BEEH) at the University of KwaZulu-Natal, who originally obtained downscaled daily values to climate station level from the Climate Systems Analysis Group (CSAG) at the University of Cape Town. The daily rainfall and temperature station values were derived from GCM outputs which had been empirically downscaled from global to regional level using the methods of Hewitson and Crane (2006), for a continuous climate time series representing present climate conditions [1971 – 1990], as well as for intermediate future [2046 – 2065] and more distant future [2081 – 2100] climate scenario time series, with the GCMs being forced using the so-called SRES (Special Report on Emissions Scenarios) A2 greenhouse gas emissions scenario (IPCC, 2007). The A2 greenhouse gas emissions scenario is a part of the four narrative storylines (cf. Nakicenovic *et al*., 2000; IPCC, 2007) and assumes a heterogeneous world with continuously increasing global population and regionally oriented economic growth that is more fragmented and slower than in other storylines (Nakicenovic *et al*., 2000).

The downscaling of daily values were validated by CSAG using techniques presented by Christensen *et al.* (2007). The fifth generation atmospheric general circulation model developed by the Max-Planck Institute for Meteorology in Germany, *viz.* the ECHAM5/MPI-OM GCM, forced by the A2 emissions scenario, was used to generate daily station climate values for the three climate scenarios, i.e. present, intermediate future and distant future, alluded to above. The ECHAM5/MPI-

OM GCM climate scenarios were selected for impact analyses as they were considered to represent future climate projections that are generally midway between the extremes from other GCMs for southern Africa and, at time that analyses for this study were conducted in 2008/2009, were the only downscaled climate projections available at the School of BEEH at the high temporal and spatial resolutions used. No climate change impact studies had been performed prior to 2008 at such fine spatial scales in South Africa to the knowledge of the author and his supervisor (Schulze, 2008; personal communication).

Output from the ECHAM5/MPI-OM GCM does not account for adaptation or mitigation measures *per se*, but only for projected future climates. At the outset it should be stressed that outcomes derived from only one GCM's climate scenarios are not recommended for use in decision-making, because they represent only one of a range of plausible future outcomes. In climate change studies a series of future outcomes should be used in order to reduce uncertainties, because each GCM has different representations of the atmosphere and assumes different boundary conditions.

The datasets for climate projections were prepared by Lumsden *et al*. (2010) for various climate change impact studies in agriculture and water, for example the *Atlas of Climate Change and the South African Agricultural Sector: A 2010 Perspective* (Schulze, 2010).

5.2 Description of Quinary Catchments

The spatial scale at which this study was undertaken was the Quinary Catchment level. Background information on the Quinaries is given below, before its application in the Limpopo Catchment is discussed.

5.2.1 The concept of Quinary Catchment in southern Africa

Southern Africa, defined here as the Republic of South Africa, plus Lesotho and Swaziland, has been delineated into 22 Primary Catchments, each of which has been further sub-delineated into smaller Secondary Catchments, thereafter into even smaller Tertiary Catchments and finally into 1 946 Quaternary Catchments (QCs) by the Department of Water Affairs and Forestry (Midgley *et al.*, 1995). The QCs were originally considered to be homogenous enough for operational water resources analyses and day-to-day decision making until recently, when Schulze and Horan (2010) identified more than half of the QCs to be agrohydrologically too heterogeneous for effective agricultural and water management, and possibly even more so in their responses to perturbations in climate.

Therefore, each of the 4^{th} level QCs was sub-delineated into three agrohydrologically more homogenous 5^{th} level Quinary Catchment (QnCs) using the Jenks' optimisation procedures (Schulze *et al.*, 2010a) in ArcInfo 9.3 (and later version) which identify natural breaks based on altitude. These QnC spatial units have been shown to be relatively homogenous with respect to evaporation, rainfall, soils and slopes, all of which are strongly dependent on altitude (Schulze *et al.*, 2010a). In total, 5 838 hydrologically interconnected Quinaries were delineated for the southern Africa. The QnCs were numbered in a hydrologically cascading order, similar to the QCs. For example, the QnC numbered A12E1 is interpreted as:

- 1^{st} level: The 'A' represents that the QnC is within Primary Catchment A. The study area in this dissertation is made up of the A and B Primary Catchments.
- 2^{nd} level: The 1 represents that the QnC is in the 1^{st} Secondary Catchment of Primary Catchment A.
- 3^{rd} level: The 2 represents that the QnC is in Tertiary Catchment number 3 of Secondary Catchment 1.
- 4^{th} level: The 'E' represents that the QnC is in Quaternary Catchment (QC) E of Tertiary Catchment 3 (Midgley *et al.*, 1995).
- 5^{th} level: The 1 represents that the QnC is the first (i.e. upper altitude) Quinary of three in QC E (Schulze and Horan, 2010).

The QnCs delineation (**cf. Figure 5.1**) based on altitude is illustrated on the left of the diagram and the three-fold subdivisions in different shades of green in the middle diagram. Lastly, the surface and subsurface flow paths were sub-delineated, as shown on the right hand diagram of **Figure 5.1**, with flow occurring from the upper (i.e. highest altitude) QnC to the second QnC in the middle to the third QnC at lowest altitude at the outlet of the QC (Schulze and Horan, 2010).

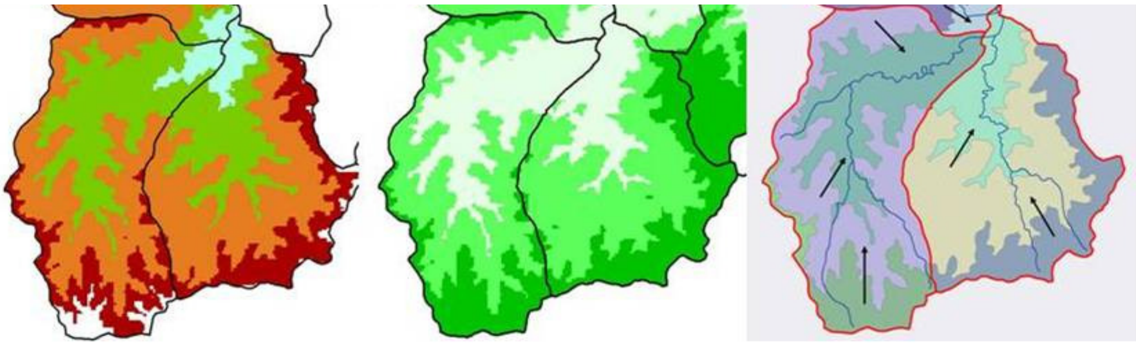

Figure 5.1 Schematic of Quaternary Catchment subdivision into three Quinary Catchments (depicted by different colours) by (left) altitude and (middle) natural breaks, as well as (right) surface water flows paths (Schulze and Horan, 2010)

5.2.2 Surface flow routing between Quinary Catchments

The distributed simulation mode option in *ACRU* (i.e. Agricultural Catchments Research Unit) agrohydrological model (cf. **Section 5.5**) enables it to account for the spatial variability in rainfall, land uses and soils, thus increasing the accuracy of simulations of hydrological and agricultural responses (Schulze *et al*., 1995). The subdivisions of the QC into QnCs in the model are represented as discrete 'cells' (Schulze and Horan, 2010).

The cells in distributed mode are shown as an assembly of interlined units of area, with each QnC considered a lumped representation of that particular area (Schulze, 1995). A schematic layout of flows between the QnC is depicted in **Figure 5.2**. The QnCs consist of runoff flow paths in a QC from the upper to the middle and then the lower QnC, designated for QC V11A as V11A1 (upper Quinary), V11A2 (middle Quinary) and V11A3 (lower Quinary) in **Figure 5.2**. The outflow from the lower QnC of the QC flows into the lower QnC of the next downstream QC. The reason for this is that the upper Quinary of a downstream QC has higher altitude than the lower QnC from the immediate upstream QC (Schulze and Horan, 2010). It is therefore important that the sequence of flows from cell to cell is accurately defined. This is achieved by assigning a number to each cell which is smaller than the one it flows into (i.e. downstream of it).

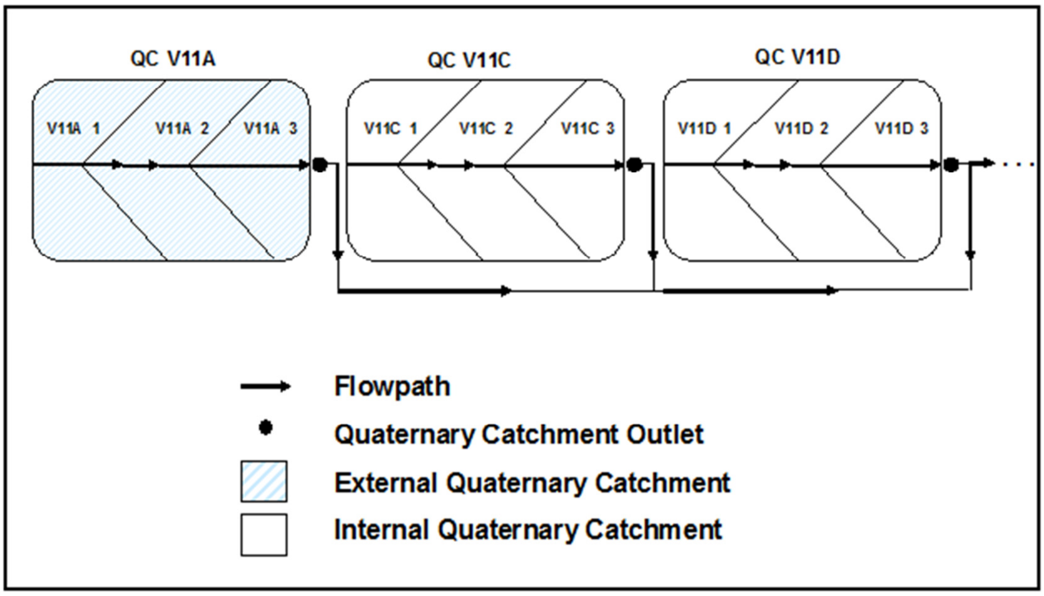

Figure 5.2 Schematic of the Quinary Catchments' sequence of hydrological flows within and between Quaternary Catchments (Schulze and Horan, 2010)

5.3 Application of the Quinary Catchments Database in the Limpopo Catchment

The delineation of southern Africa into QnCs (Schulze and Horan, 2010) formed the basis of a database which was used in the Limpopo Catchment. Daily rainfall and temperature values from different stations were assigned to a specific QnC within the Limpopo Catchment. Their data were assumed to be representative of the climate of the QnC. Methods are discussed below, from which the climatological, hydrological and agricultural processes under baseline climate conditions and future climate change scenarios could be estimated.

5.3.1 Estimation of daily rainfall and temperature values for baseline climate conditions

The procedure used in the selection of the rainfall stations, the data from which "drive" agrohydrological responses from the QnC, was adopted by BEEH from *ACRU* user manual version 3.00 (Schulze, 1995) and Warburton (2005). The basis for station selection was a comprehensive state-of-the-art rainfall database from 12 153 daily rainfall stations in southern Africa, compiled by Lynch in 2004, and consisting of quality controlled and infilled (where data were missing) daily rainfall data.

The centroid coordinates in each of the 852 QnCs which make up the Limpopo Catchment were computed using the Arc View 3.2a GIS extension, *ACRU* GRID EXTRACTOR tool. The Daily Rainfall Extraction Utility developed by Kunz (2004) was used to extract the 20 closest potential driver rainfall stations which have quality controlled daily rainfall data. The daily Rainfall Extraction Utility used to extract rainfall stations was based on the following criteria:

- Selection of 20 rainfall stations in the vicinity of each QnC,
- Fifty years of daily rainfall record [1950 – 1999], and
- Where infilled, the maximum missing rainfall data could not exceed 30% of a selected station's record.

These stations were ranked in the Utility based on their distance from the centroid of each QnC and hence stations near and around the centroid, with the highest reliabilities, were extracted by the author using the *ACRU* grid extractor. The 'driver' rainfall station for each QnC was then selected from the extracted rainfall stations. The methodology, adopted from a study by Warburton (2005), was used by the author to select driver stations for the Limpopo Catchment. The procedure used was visual observation, when using the Arc View 3.2 tool, to match a potential driver station based on its location to a QnC, as well as on the basis of both the station and QnC characteristics, such as altitude and Mean Annual Precipitation (MAP), where a station and a QnC with similar characteristics are paired. Quinary Catchments without suitable rainfall stations were assigned the station previously selected for the entire QC.

The methodology for selecting daily temperature stations, outlined by Schulze and Maharaj (2004), was the same as used in previous studies (e.g. Schulze *et al*., 2010a), and no new research in this regard was undertaken by the author, with all information gleaned from Schulze *et al*. (2010a).

5.3.2 Estimation of daily rainfall and temperature values for GCM derived future climate scenarios

The ECHAM5/MPI-OM GCM outputs of daily of rainfall, as well as maximum and minimum temperatures, were provided for the following climate scenarios:

- Present climate [1961 – 2000], from which the 20 year time period 1971 – 1990 was selected for this study to enable comparison with other 20 year GCM climate scenarios, and with an observed 20 year baseline climate record for the same period,
- Intermediate future climate [2046 – 2065], and
- Distant future climate [2081 – 2100] scenarios.

Downscaling of daily precipitation values from the GCM scenarios was undertaken at over 2 600 rainfall stations in southern Africa, while the daily maximum and minimum temperatures were downscaled to 440 temperature stations were obtained from work by Lumsden *et al.* (2010). For the GCM scenarios, each QnC was assigned a rainfall station using the same approach as was used for selecting a 'driver' station for the baseline climate conditions. Only 1 023 rainfall stations which had been selected for baseline climate conditions corresponded with the > 2 600 stations to which the GCM data had been downscaled. The data from these 1 023 stations were therefore assumed to represent the future climate projection of their associated QnC (Lumsden *et al.,* 2010).

The point scale temperatures values from the GCM scenarios, however, were represented at a QnC scale by selecting the two most representative daily temperature stations for each Quinary. A daily weighted average was determined by averaging the two selected stations values in a Quinary. Only 404 of the 440 stations were used, owing to the fact some of the stations were at the same spatial location (Lumsden *et al.,* 2010). The adiabatic temperature lapse rate determined by Schulze and Maharaj (2004) for each month's minimum and maximum temperatures for each of the 11 defined lapse rate region in southern Africa (Schulze, 1997), was used to account for the difference in the QnC's altitude compared to that of the two 'driver' temperature stations (Lumsden *et al.,* 2010). The temperature 'driver' stations selected were based on the criteria that they were primarily of the same lapse rate region and had a similar altitude to that of the particular QnC. The algorithms developed and used for selecting the temperature stations are discussed in detail in Schulze *et al.* (2010b). The selection of temperature driver stations QnCs was conducted by Lumsden *et al.* (2010).

5.4 Agrohydrological Modelling for Climate Change Impact Assessment: Points to Consider before Selecting a Biophysical Model

Schulze (2005) suggested that a modeller should consider the following points when selecting a tool for simulating the agrohydrological system:

- appropriateness of the model for the required simulations;
- level of model complexity;
- ability of the model to account for, and perform simulations for, various climate regimes and topographic conditions; and the
- ability of the model to mimic the relevant processes and their impacts.

A wide range of modelling tools are available for specific purposes, while others have more generalised applications. Models can consist of an extensive range of mathematical formulae, describing various components of the processes, and with models varying in their levels of complexity (Schulze, 2007). Hence, the selected modelling system should reasonably represent the relevant processes, and provide a good reproduction of the modelled variables such as breeding cycles or development time periods with pests and diseases, or flows and soil water fluxes in regard to hydrological responses. This is done in order for the models to provide representative answers and to be transferable over time, space and with changes in input (Schulze, 2007). Schulze (2005) identified three basic resources to be considered when selecting or developing an appropriate model, *viz.* the availability of data, access to expertise, and resources available.

Thus, to be able to simulate the agrohydrological responses in line with the above-mentioned model requirements for climate change requires a model that is ideally conceptually sound, process-based and account for dynamic non-linear responses (Schulze, 2005). Furthermore, to assess the climate change impacts on water resources through modelling, the simulation needs to be performed at a daily time step because most of the agrohydrological processes can be represented on a daily time scale (Schulze, 2005). Schulze (2005) stated that agrohydrological modelling at a daily time step provides output with a large range of potential applications and that it is relevant for climate impacts assessments.

For example, *ACRU* simulations of interception, reference potential evaporation, the soil water budget, streamflow generation, land use impacts, wetlands response and crop yields have been verified in over 150 studies over the past decades (Schulze, 2008c). *ACRU* has also been used in many agrohydrological impact assessment studies (summarised by Schulze and Smithers, 2004) and in climate change impact and detection studies (e.g. Schulze, 2005; Warburton, 2005). A brief description of the model now follows.

5.5 Agrohydrological Modelling for Climate Change Impacts Assessment: The *ACRU* Agrohydrological Model

The *ACRU* (i.e. Agricultural Catchments Research Unit) agrohydrological model (Schulze, 1995 and updates) was selected as the tool for simulating the agrohydrological processes over the Limpopo Catchment, because the model meets most of the criteria suggested above and the model was developed in-house (i.e. BEEH), hence there was access to expertise.

The daily time step, physical-conceptual and multi-purpose *ACRU* model, originally developed for southern African conditions, but subsequently tested in many different regions of the world for simulating agrohydrological responses (Schulze, 1995; Schulze and Smithers, 2004; Schulze, 2008c) was used, *inter alia*, for the agricultural production simulations. The model simulates daily values of various agrohydrological processes (cf. **Figure 5.3**), either for current climatic conditions or for climate change projections. *ACRU* is centered on the basic premises and principles indicated in **Figure 5.3** and **Figure 5.4** (Schulze, 1995).

Figure 5.4 depicts a generalised schematic structure of the model and indicates the soil water and evapotranspiration pathways. Model responsiveness and sensitivity to changes in climate and land use on regimes such as soil water, runoff, or crop yields are made possible by its core structure of daily multi-layer soil water budgeting (Schulze, 1995).

Schulze (1995) states that the *ACRU* model's total evaporation routines are capable of separating transpiration from soil water evaporation, making it useful for crop yield analysis, and it also contains a function related to elevated CO_2 concentrations, by virtue of which transpiration rates can be suppressed. This and other modifications enable the evaluation of climate change impacts with the model. Further climate change related modifications include input options to change the daily temperature and precipitation values, which might be used for climate perturbations.

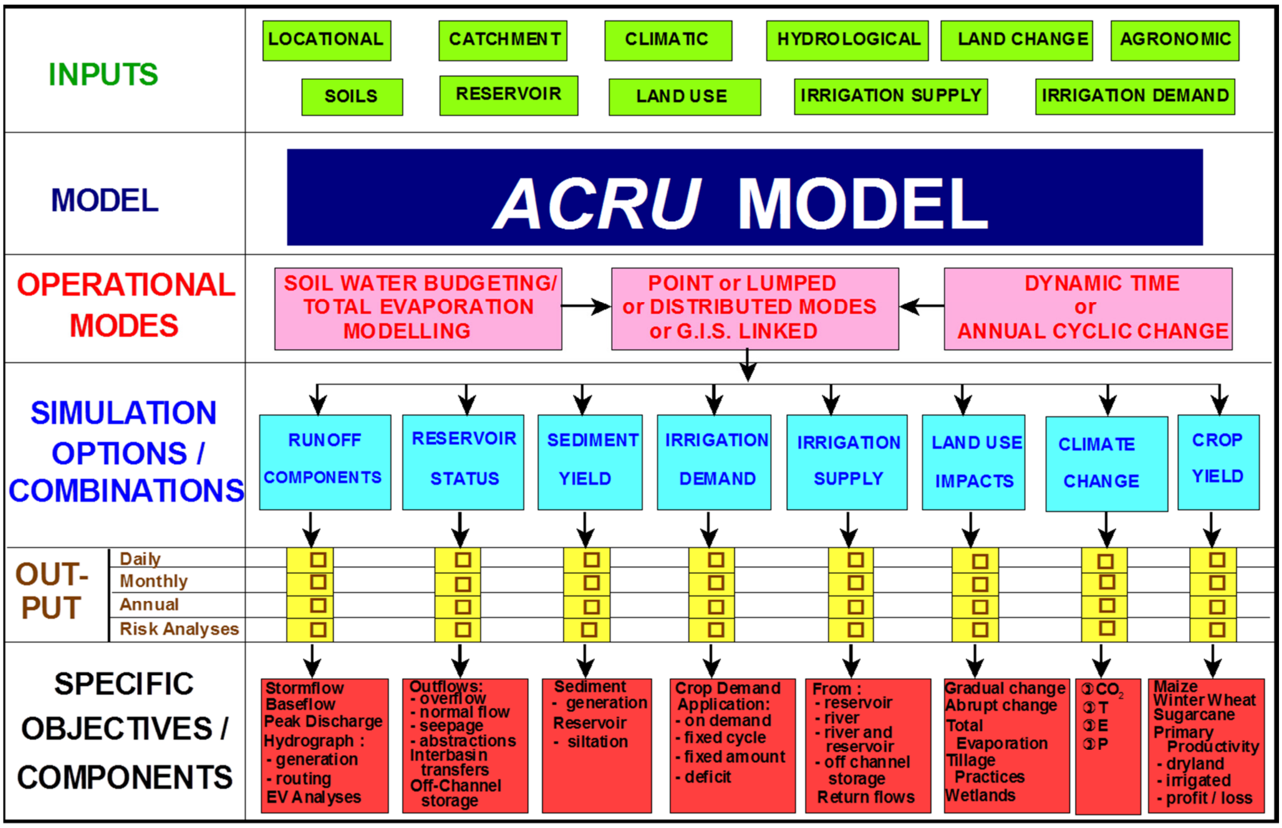

Figure 5.3 Concepts of the *ACRU* agrohydrological model (Schulze, 1995)

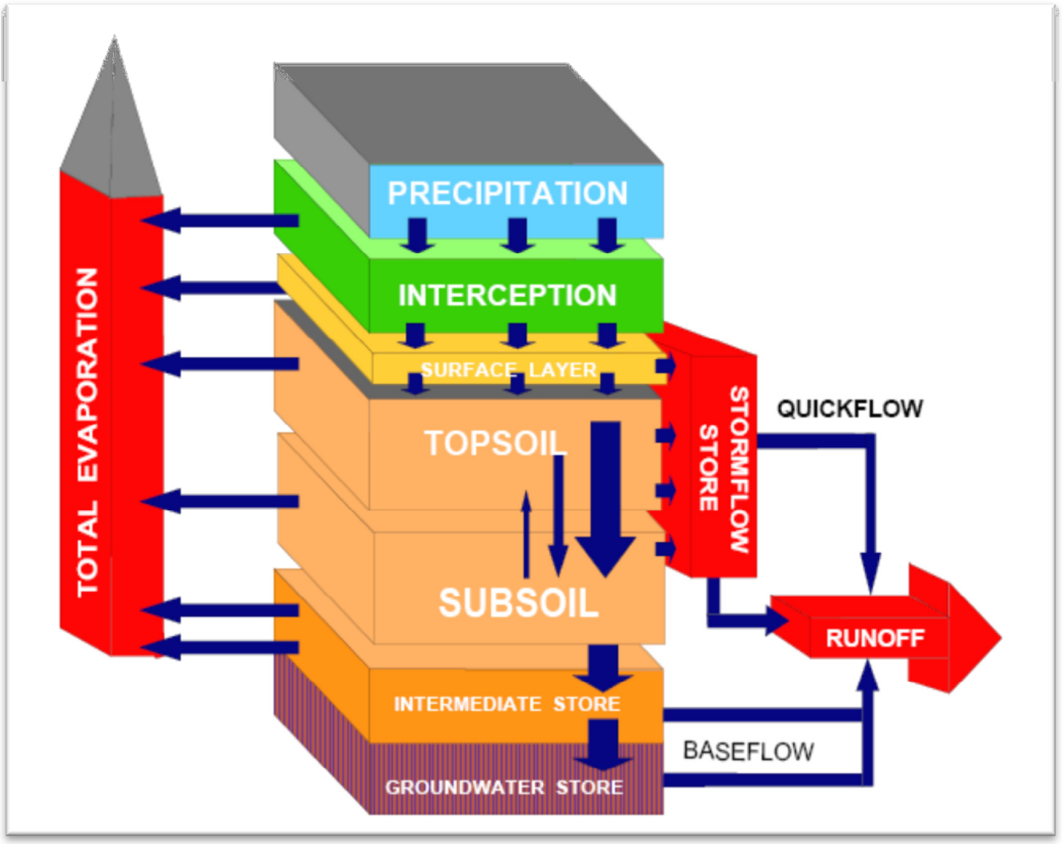

Figure 5.4 General structure of the *ACRU* agrohydrological model (Schulze, 1995)

5.5.1 The *ACRU* model input database

The Quinary Catchments (QnC) database was linked with the *ACRU* agrohydrological model (Schulze *et al*., 2010a). This was done to simulate the agrohydological processes and responses at a higher spatial resolution than in previous climate change studies. The model's input information required for simulating the agrohydrological processes is the climate, soil, land cover, physical environment (i.e. altitude, location, slope) and catchment information.

The baseline climate conditions (i.e. historically observed climate data) for the time period between 1971 and 1990 was selected for simulations in order to be able to compare the baseline simulations with those of the GCM scenarios, for which the "present" time period covers the same years (cf. **Section 5.3**).

5.5.2 Populating the Quinary Catchments database for use with the *ACRU* model

For baseline land cover, the Acocks' (1988) Veld Type classification for South Africa was used. The most dominant land cover within each Quinary covering the Limpopo Catchment was selected to be the representative baseline land cover of that QnC. **Figure 2.11** indicates the broad groups of the biotic communities which the Veld Types make up. Eighteen different Veld Types were identified in the Limpopo Catchment. Each Veld Type has specific hydrological attributes with regard to monthly values of the water use coefficient, canopy interception loss per rainday, root distribution, a coefficient of infiltrability, soil water evaporation suppression by litter and a soil loss factor related to vegetation cover (Schulze, 2004). Each of Acocks' (1988) Veld Types is associated with certain agricultural activities. Other baseline data inputs to the *ACRU* model were soils information, including the soil horizon thicknesses and water content at porosity, the permanent wilting point and the drained upper limit for both the topsoil and subsoil horizons, all obtained from Schulze (2008c). This work was conducted by the technical staff at BEEH for a series of projects on climate change and agriculture.

The effects of the climatological drivers, i.e. daily rainfall and temperature, on the Catchment's agrohydrological responses were performed with the model using the QnC database of daily rainfall and maximum and minimum temperature values for baseline climate conditions and the GCM derived present and future climate scenarios, as discussed in **Section 5.3**.

5.6 Agrohydrological Modelling for Climate Change Impact Assessment: Net Above-Ground Primary Production

Net above-ground primary production (NAPP) is defined by Schulze (1997) as the amount of the "vegetation matter (e.g. harvestable yields) which can be produced (e.g. in tons) by the natural environment at a location per unit area (e.g. per hectare) over a given period of time (e.g. in a season or a year)" (Schulze, 1997: 191). In this study, NAPP is an abstract representation of the generalised expected amount of harvestable estimate of agricultural production (AP) that is sustainable. It is determined indirectly at a Quinary Catchment scale under rainfed conditions over a period of years.

The comparison of this potential harvestable agricultural production (AP) between the Quinary Catchments in the Limpopo Catchment was carried out by assessing NAPP. The rationale behind the use of NAPP estimations to indicate AP is discussed in **Chapter 5.6.1.** This method of estimating AP was selected for its suitability in overall agricultural planning on a large geographical scale, such as the Limpopo Catchment, towards which this impact assessment study contributes. This type of impact analysis could be used in "objectively assessing the intrinsic environmental biomass production capability between one region and the next and in comparing the environmental resource potential of one location with others" (Schulze, 1997: 191).

5.6.1 Estimation of net above-ground primary production with the *ACRU* model

There are two approaches used for estimating NAPP, *viz.* direct and indirect. The direct estimation approach is more accurate given that multiple vegetation sampling is done in the field, and then analysed in the laboratory to obtain NAPP. This approach is not practical in large scale studies, such as the Limpopo Catchment Study, as it is expensive and time consuming. An indirect approach is therefore used for large scales, in which equations are used to estimate NAPP according to the climate and biological factors (Monterroso Rivas *et al.*, 2011). The Rosenzweig (1968) equation is the most widely and frequently used for estimating NAPP in most parts of the world, including in southern Africa, for estimating NAPP (Alba *et al.,* 2003; Monterroso Rivas *et al.*, 2011).

The Rosenzweig (1968) equation is a generic equation that relates NAPP to actual evapotranspitation. Even though this equation is dated, it is a well established approach in biomass modelling, including crop yield modelling (Schulze, 1997; Kaspari *et al.*, 2000; Monterroso Rivas *et al.*, 2011). NAPP "may be conceptualized as a general expression of the sustainable agricultural production expectation and is a quantification of the long term and basic environmental status of a location under rainfed (i.e. non-irrigated) conditions." (Schulze, 1997: 192). These are the reasons for selecting Rosenzweig equation. It is for these reasons also that the equation was embedded in the agrohydrological *ACRU* model (cf. **Section 5.5**).

The equation has been shown to successfully estimate NAPP in both the local and international literature (Schulze, 1995; Kaspari *et al.*, 2000; Monterroso Rivas *et al.*, 2011). The Rosenzweig (1968) equation was developed from annual total (i.e. actual) evaporation, which was correlated to the NAPP of 26 undistributed plant communities under natural conditions. These plant communities ranged from desert scrublands to tundra vegetation, and from grasslands to tropical forests (Rosenzweig, 1968; Schulze, 1997).

The equation for estimating NAPP, i.e. the harvestable dry organic matter produced per unit of time, is given by

$$\log_{10}NAPP = 1.66(\pm0.27)\log_{10}E - 1.66(\pm0.07) \quad [5.1]$$

where NAPP = net above-ground primary production ($gm^2.an^{-1}$), and
E = annual total evaporation ($mm.an^{-1}$).

The equation's limitations are its inability to effectively represent individual plant conditions and explain local- and/or farm-scale variations. The equation was selected for this study because of its universal application nature and because it accounts for interactive effects of climate, soil and plant physiological responses (Schulze, 1997). The Rosenzweig (1968) equation is a function of total evaporation, which is comprised of plant transpiration and soil water evaporation. The key drivers of total evaporation are a reference crop evaporation (a function of temperature in this study) and the plant's water use coefficient (Schulze, 1995 and updates).

The baseline input data used in the *ACRU* model were the hydrological attributes of Acocks' (1988) Veld Types for baseline land cover (as determined by Schulze, 2004), as well as daily maximum/minimum temperatures, daily reference crop evaporation and daily precipitation to represent baseline climatic conditions [i.e. historical data, 1971 – 1990]. The ECHAM5/MPI-OM GCM daily minimum/maximum temperature and precipitation values for present [1971 – 1990], intermediate future [2046 – 2065] and distant future [2081 – 2100] climate scenarios were assigned to the Limpopo Quinary Catchments as inputs for projecting future estimates of AP. The carbon dioxide feedback option in the *ACRU* model, which can to account for transpiration suppression, was not invoked in this simulation. The simulation outputs from the *ACRU* model, run in the School of Bioresources Engineering and Environmental Hydrology (BEEH), were used to produce maps in ArcGIS.

The statistics used in describing the estimated agricultural production were the mean and the inter-annual coefficient variability (Schulze, 1995). A further statistical analysis performed was the ratio change, i.e. a dimensionless index of the variable of interest (i.e. NAPP) between two time periods for different climate scenarios.

5.6.2 Correlation between estimated net above-ground primary production and agricultural crop yields

In this section the hypothesis is tested that the NAPP of a biome (i.e. a broad plant community) can be correlated with the yield a crop typical found in that biome. Specific biomes typically show a relationship with different NAPP values (e.g. Briggs and Knapp, 1995; Fang *et al*., 2001; Shaw *et al*., 2002; Bradford *et al*., 2005; Zhong *et al*., 2007).

Fang *et al*. (2003) estimated NAPP for the period 1982 to 1999 in China, and results indicated a substantial increase of about 18.7 % in the NAPP over that period which corresponded with an increase in crop yields. Similarly, the investigation by Bradford *et al*. (2005) on the relationships between impacts of various crops and the region's NAPP indicated that crops such as wheat, maize, soybean, sorghum and hay have a significant correlation to the predicted NAPP, as shown in **Table 5.1** below.

Table 5.1 Correlation between agricultural crop yields and net above-ground primary production in China (After Bradford *et al*., 2005)

Crop	**R^2 against NAPP (n = 18)**
Maize	0.79
Wheat	0.85
Soybean	0.88
Hay	0.89
Sorghum	0.89

While the Rosenzweig (1968) equation (cf. **Equation 5.1**) for NAPP gives an estimate of harvestable yield (Schulze, 1997), the percentage of potential production (PPP), discussed in **Appendix C**, relates the harvestable yields to the potential production assuming the crop never to be water stressed. This makes NAPP and PPP good indicators of general agricultural production and potential production. Some results of NAPP are presented in the sections below.

5.7 Agrohydrological Modelling for Climate Change Impact Assessment: Water Accounting Indicators

The South African National Water Act of 1998 emphases the assurance of water allocation for human use, the ecological reserve and downstream flows for international obligations before any other uses, and includes the management of resources for future generations. The increasing demand on already limited water resources, attributed to increased development and population growth, requires management of these resources, especially with the uncertainty of demands on the resources due to potential impacts of climate change. Effective allocation approaches that might ensure water resources and minimise conflicts are needed. For these goals to be accomplished, improved methods of accounting for water use and productivity in a Water Management Areas (Catchment) are required. Further the water accounting factors allows for decision makers to begin understanding the impacts of their actions and they could also be used to indicate areas were more indepth studies would be required (Molden, 1997).

In order to measure the impacts of numerous factors on water resources for agricultural crop production over the Limpopo Catchment, Molden's (1997) water accounting performance indicators were used. They were selected because they are clear and measurable.

Concepts of water accounting procedures presented by Willardson, *et al.* (1994) and Keller and Keller (1995) were further developed by Molden (1997), Molden *et al.* (2001) and Molden and Sakthivadivel (1999), Sakthivadivel *et al.* (1999) to describe the status of water use and productivity from different water use sectors, such as the environment, industry, agriculture, municipal and others, and at different scales (i.e. from field to catchment level). The procedure is based on an integrated water balance approach (cf. **Figure 5.5**), which classifies in- and out-flow path components in an area into water accounting classes (**Table 5.2**). Furthermore, the procedure is based on the law of conservation of mass, where total inflows are equal to total outflows plus any changes in storage in a given area. As productivity of water is generally expressed as the benefit attained by means of water use, it can be related to different classes of use (Molden, 1997; Molden and Sakthivadivel, 1999; Molden *et al*., 2001).

An important step in water accounting is to first define the spatial and temporal boundaries of the water balance area, then to specify the flows of water within the area of interest over a certain period of years, including surface and groundwater and their interrelationships. The inflows and outflows in the procedure are classified according to their water uses and productivity (Molden, 1997; Molden and Sakthivadivel, 1999). This methodology accounts only for water quantities.

Table 5.2 Catchment / sub-catchment level water accounting components (Molden, 1997)

Inflows	Precipitation
	Trans-basin diversions
	Groundwater inflows
	River inflow into basin
Storage changes	Soil moisture changes
	Groundwater storage changes
	Reservoir storage changes
Process depletions	Crop transpiration
	Municipal and industrial uses
	Fisheries, forestry, and other non-crop depletions
	Dedicated environmental wetlands
Non-process depletions	Evaporation from free water and the soil surface, weeds, phreatophytes, and other non-crop plants
	Flow to sinks (saline groundwater, seas, oceans)
	Evaporation from ponds/playas
	Water rendered unusable owing to degradation of quality
	Evapotranspiration from natural vegetation
Outflows	Instream commitments, e.g. environment and fisheries
	Downstream commitments
	Outflow commitments to maintain the environment
	Uncommitted outflows

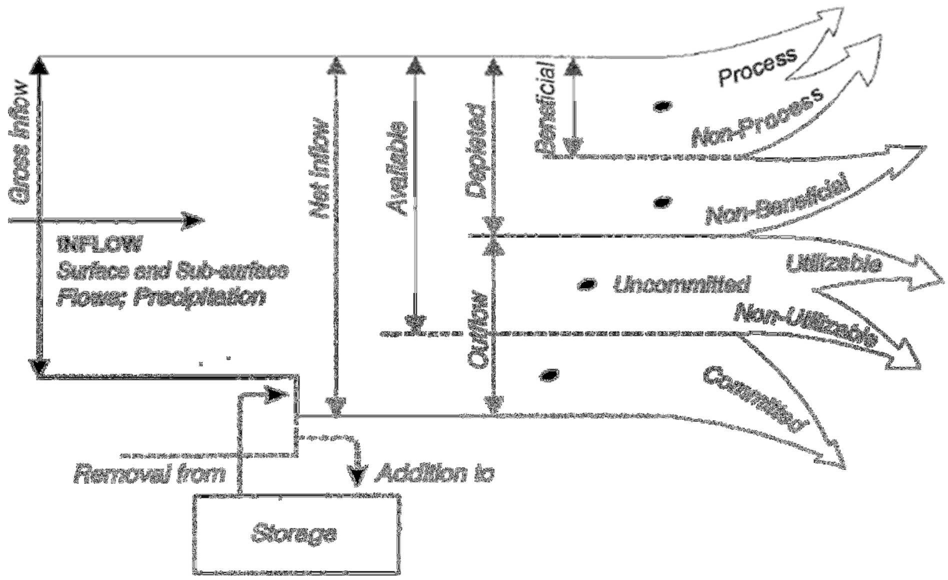

Figure 5.5 Concepts of water accounting (Molden and Sakthivadivel, 1999)

Two performance indicators are presented in this dissertation for water accounting over the Limpopo Catchment. They are an agricultural water use indicator and an agricultural water productivity indicator.

5.7.1 Agricultural water use indicator

The agricultural water use indicator (Molden, 1997) refers to crop water use and is expressed as a process fraction (denoted as $PF_{depleted}$) expressed as the ratio of water that was depleted for crop production by transpiration (*Process Depletion*) to total water depletion from the soil profile (*Total Depletion*). Where, the *Process Depletion* is the quantity of water used for crop production (mm), via the transpiration process, from both the topsoil and subsoil horizons, and *Total Depletion* is the removal of water by soil water evaporation from the topsoil and by transpiration (mm) from both topsoil and subsoil horizons.

In *ACRU* model terminology the "Total Depletion" variable is evapotranspiration (i.e. E_T) and in regard to "Process Depletion" is transpiration from the topsoil is E_{t1} and transpiration from the subsoil is E_{t2}.

5.7.2 Agricultural water productivity indicator

In this research the productivity of water, according to Molden (1997), was measured as the fraction of biomass produced per millimetre of water transpired and expressed as *Productivity of Water* ($PW_{Process}$) physical amount of biomass production (*Productivity*) measured as process depletion (*Process Depletion*; kg/m^3). Where the *Productivity* is the net above-ground primary production, converted from t/ha to kg/ha by multiplication by 1000, and the *Process Depletion* is the removal of water from a catchment by the process of transpiration, converting millimetre to cubic metre equivalents of transpiration.

The agricultural water productivity indicator is similar to the concept of water use efficiency (Howell *et al*., 1990) which relates the amount of production to water application. The agricultural water use and productivity indicators were computed at a daily time step using Visual Basic for each Quinary Catchment, with variables estimated from *ACRU* agrohydrological model output.

5.7.3 Use of *ACRU* agrohydrological model simulations

The Limpopo Catchment is made up of relatively homogenous agriculturally and hydrologically response areas called Quinaries, which are hydrologically interlinked similar to Quaternary Catchments, with the upper and middle Quinaries of a Quaternary flowing into the lower Quinary (cf. **Figure 3.2**). Owing to the complexity of the hydrological system, the *ACRU* agrohydrological modelling system outputs were used as inputs to the two performance indicators. The *ACRU* model was selected for this study because of its capability to perform water budgets in complex interlinked catchment systems with agrohydrological processes which are simulated from algorithms based on sound theory (cf. Schulze, 1995), its conceptual-physical structure, the use of daily climate input, its multi-purpose modelling functionality and the availability of technical support. It accounts for all inflows (including upstream subcatchments' contributions), outflows and storages in a catchment. A schematic of water accounting components in a catchment, given in **Figure 5.6**, indicates the inflows, storages, water depletions and outflows. The *ACRU* model simulates processes in a similar manner.

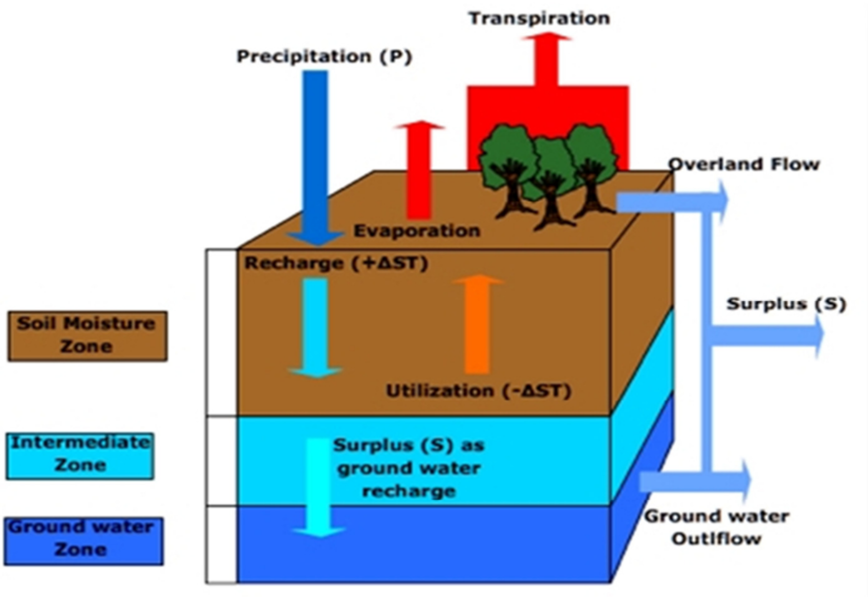

Figure 5.6 Schematic of a water balance profile (after Strahler and Strahler, 2006)

The water accounting components (cf. **Table 5.2**) in the Catchment at Quinary level were estimated from the *ACRU* model for the agricultural water use and productivity indicators presented in **Section 5.7.1** and **5.7.2** above, with Acocks' (1988) Veld Types representing the baseline land cover. The water use and productivity patterns were analysed for general dryland agricultural production. Agricultural production was estimated using the Rosenzweig (1968) equation for simulating net above-ground primary production (NAPP), with the equation being is imbedded within the *ACRU* model. This equation (cf. **Equation 5.1**) was selected mainly due to its parameters being based on extensive research and having been demonstrated to successfully estimate NAPP (Rosenzweig, 1968; Schulze, 1995, and updates). Moreover, the NAPP was assumed to be representative of broad vegetation productivity, based on studies conducted in different regions linking agricultural crop yields with NAPP values (Fang *et al*., 2003; Bradford *et al*., 2005).

As stated before, the *ACRU* model operates at a daily time step and, moreover, climate change analyses can be performed by accounting for the effects of climate change on processes operating at daily and higher temporal step, for example, monthly and annual seasonality (Schulze, 1995and updates). This capability is expressed in the model's input menus, where climate change scenarios of daily precipitation and temperature could be input.

The *ACRU* model was used to simulate the NAPP, which was assumed to be representative of the likely agricultural production. Outputs from the ECHAM5/MPI-OM GCM climate scenarios were then used to assess water use and productivity with the *ACRU* model, for both present and future climate conditions. The model was integrated with water accounting and productivity indicators developed by, and adopted from, Molden (1997 and updates), and then incorporated into a GIS to process the large number of spatial datasets and display the outputs in map form.

5.8 Agrohydrological Modelling for Climate Change Impact Assessment: Determination of the Distribution Spotted Stem Borer *Chilo partellus*

The assessment of the effects of climate change related drivers on the plant-insect-pest system is difficult, owing to the complex interactive between the pests and crops, with the overall responses being dependent on the plant-pest-enemy relationship. This relationship is of importance particularly in maintaining and predicting the agricultural production. It is worthy of note that the responses of the pest to the impacts of climate change on a specific plant species will depend on the nature of the effects of climate change on the relationship between host plant and pest (cf. **Chapter 3**). However, this is not assessed in the analyses which follow.

The objective of this analysis was to develop techniques which could be used in determining the potential distribution patterns of *Chilo partellus* over the Limpopo Catchment, both spatially and temporally. Algorithms were constructed by the author from a literature review (cf. **Chapter 3.1.4**; Singh; 1991; Smerage, 1992; Rahman and Khalequzzaman, 2004) on *C. partellus* development periods and life cycles. The mortality index of *C. partellus* was also used as one of the techniques for determining the pest's distribution patterns, and because of length limitations of this dissertation those results are presented in **Appendix D**.

The techniques developed were based on the dependence relationship, shown in **Figure 3.3**, between the development of *C. partellus* and temperature variables. The techniques do not consider mechanisms which might affect changes in the population development other than the climate parameter. Thus, changes in the host plants' and enemies' distributions or of management practices are assumed not to affect this relationship. These techniques were evaluated for baseline climate conditions and for projected climate scenarios.

The effects of climate change related drivers could either increase or decrease the chances of an encounter between the insect pest and the host plant, through shifts in the likely establishment ranges of the two. The predicted distribution patterns of *C. partellus* closely correlated with documented observations by Kfir (2001). However, it is worthy of noting that the use of controlled chamber experiment data cannot be extrapolated directly to the farm scale. Uncertainties arise from the insect pest distributions which were modelled in controlled chambers being less exposed to environmental stresses (e.g. interactive with its host plant, enemies and other environmental factors) which occur under natural conditions in the field. These uncertainties or limitations should be considered when modelled information is used in decision-making.

5.8.1 Determination of development periods of the *Chilo partellus* life cycle

In this study interpolation equations were developed by the author to estimate the time taken by the Spotted Stem Borer *Chilo partellus* Swinhoe (Lepedoptera: Crambidae) to complete various stages of its life cycle. The data for the development time and survival of *C. partellus* which were used in this dissertation were obtained from a study by Rahman and Khalequzzaman (2004) on the temperature requirements of Spotted Stem Borers under laboratory conditions. They kept the *C. partellus* Spotted Stem Borers at immature stages in seven constant temperature incubators in order to investigate the effects of those temperature regimes on the development of the eggs, larvae and pupae. As suggested by Andrewartha (1961), the temperatures were kept at 10, 15, 20, 25, 30, 35 and 40 (± 0.5) ^{o}C in the incubator for a period of ten months (April 2000 to January 2001). The relative humidity in each incubator was kept at 70 %, with 12 hours of night and light cycle hours, respectively. The findings by Rahman and Khalequzzaman (2004) indicated that at 10 ^{o}C the *C. partellus* eggs failed to hatch, even when they were maintained for > 60 days. Egg hatching was observed at 15 ^{o}C, with the lower threshold of development thus being between 10 and 15 ^{o}C. The eggs which hatched at 40 ^{o}C desiccated after 2 days of exposure to this constant temperature regime. The total developmental period decreased at an upper threshold temperature between 35 and 40 ^{o}C. The relationship between the Spotted Stem Borer development and its response to temperature regimes is shown in **Section 3.1.4.1**.

The observed *C. partellus* developmental time periods were averaged for each incubator's constant temperature (cf. **Figure 5.7**). The rationale behind using average developmental time periods was to develop an equation which could be used to predict the time it may take for the *C. partellus* to complete each stage of its life cycle and be applicable in all climatic regions over a crop's growing season. Furthermore, this equation was developed to be generic rather than being only site specific.

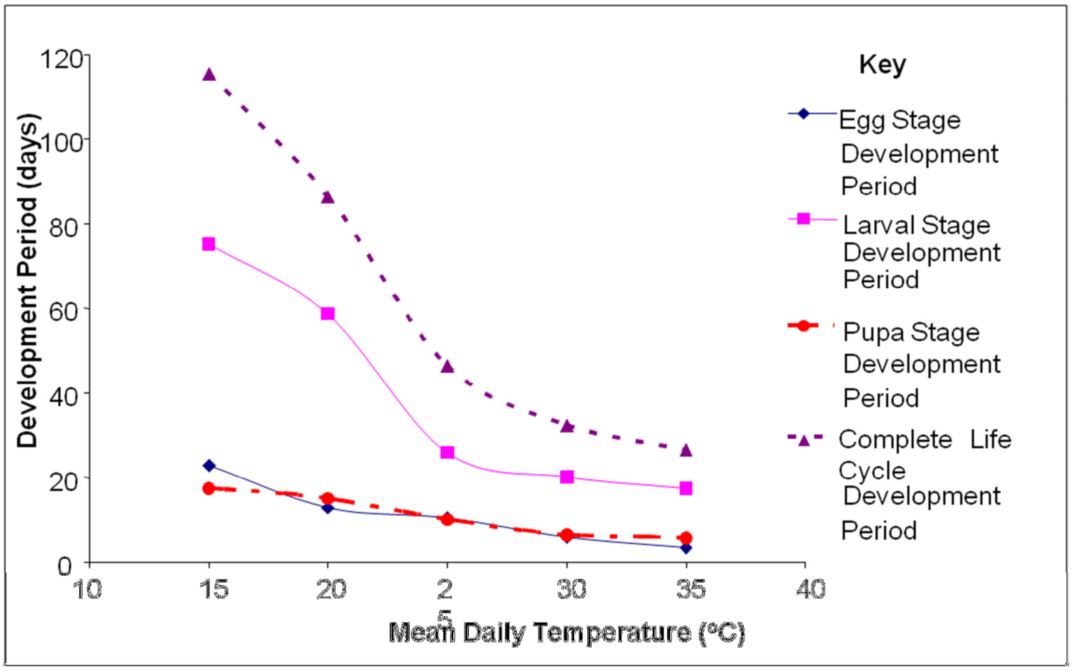

Figure 5.7 Means of development time periods of *Chilo partellus* life stages in response to temperature regimes (developed by the author using data from Rahman and Khalequzzaman, 2004)

In this study a range of regression curve models was fitted to the observed data using the GenStat (11th Edition) statistical package, in order to determine the best estimation equation. The 4th order quartic polynomial equation, shown in **Equation 5.7**, was selected to interpolate the data points in **Figure 5.8** . It was assumed that the interpolation equations predicts the likely mean development periods of *C. partellus* life cycles.

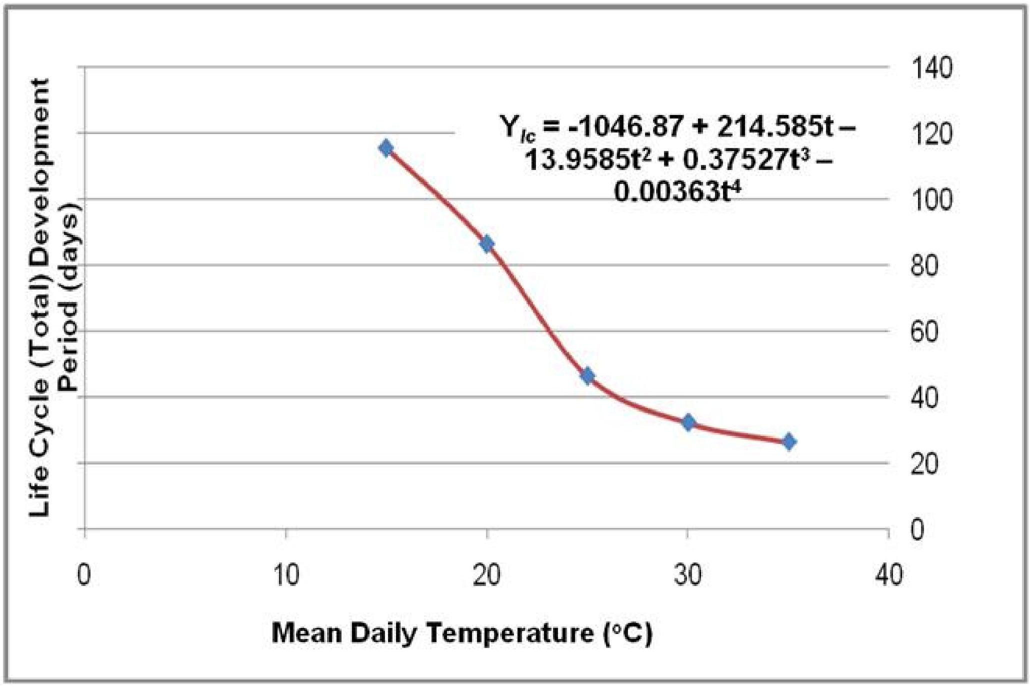

Figure 5.8 Interpolated life cycle development period of *Chilo partellus* based on temperature [Simulated (Quartic Polynomial Model); ◆ Means of observations at specified temperatures]

The complete life cycle equation for *Chilo partellus* developed by the author on assumption that the development will follow the fit is given below as

$$Y_{lc} = -1046.87 + 214.585t - 13.9585t^2 + 0.37527t^3 - 0.00363t^4 \quad [5.2]$$

where Y_{lc} = life cycle development period (in days), and

t = mean daily temperature (°C) for the qualifying temperature range.

The equations for estimating the development period for all the *C. partellus* stages were determined. In the main body of this dissertation only the equation for the complete life cycle development period has been presented (cf. **Figure 5.8**), with the models for the egg, larval and pupal life stages given in **Appendix D**.

The equation of the complete *C. partellus* life cycle development time period in **Equation 5.7** and **Figure 5.8** is only valid for the temperature range between 15 and 35 ^{o}C, since this was the temperature range of the original experimental data used. Equations similar to that of the complete life cycle were produced for the egg, larval and pupal stage development periods (cf. **Appendix B**). At 10 and 40 ^{o}C minimal to no egg development was observed (Rahman and Khalequzzaman, 2004), with unfertile eggs laid by the females at threshold temperatures higher than 40 ^{o}C (Singh, 1991). Because the temperatures for successfully deriving the various equations range between 15 and 35 ^{o}C, hence the models should not be used for extrapolations outside the above specified temperature range.

5.8.2 Determination of number of life cycles per annum of *Chilo partellus*

In **Section 3.1.4** the development of *C. partellus* was shown to be dependent on temperature (cf. **Figure 3.3**) for each stage of its life cycle, for a range of temperature regimes. Because temperature influences the development of *C. partellus*, each stage of its development will require a certain number of degree days before transition to the next stage. Degree days are an accumulation of temperatures between critical thresholds, and different accumulations of degree days are related to the different stages of development of the organism (Smerage, 1992; Rahman and Khalequzzaman, 2004).

To determine the potential number of *C. partellus* life cycles (generations) per annum in the region, the lower threshold temperatures (i.e. temperatures below which development ceases) and total degree days for the life cycle were determined by Rahman and Khalequzzaman (2004). Their study on pest development was conducted under laboratory chamber environmental conditions. The degree days (^{o}days) were computed as in **Equation 5.5**, *viz*.

$$DG = (K + C_f) \qquad [5.3]$$

where DG = degree days per generation (^{o}days),

K = total thermal constant (days), and

C_f = degree days of the ovulation period of the adult female stem Borer (^{o}days).

Based on the research by Rahman and Khalequzzaman (2004) the lower threshold temperature of the combined egg/larval/pupal stages was found to be 8.56 ^{o}days, the accumulated degree days for these stages to be completed (termed the "total thermal constant") was 703.30 ^{o}days and the accumulated degree days of the adult stem Borer ovulation period was 99.29 ^{o}days, giving a total of 802.59 ^{o}days per generation.

The expected number of *C. partellus* life cycles per annum is defined as the degree days per annum (base: 8.56 ^{o}C) divided by the degree days per generation, *viz.* i.e. 802.59 ^{o}days (cf. **Equation 5.6**). The degree days were computed using the daily minimum and maximum temperature databases generated by the methods of Schulze and Maharaj (2004), described in **Section 5.3**. The higher the number of life cycles, the more likely it is that pest infestation will proliferate and/or that the life cycles will overlap over the growing season. The assumption made in this analysis was that no other factors, except for the 802.59 ^{o}days per life cycle would affect the *C. partellus*. It should be noted that *C. partellus* is already a pest in the Limpopo Catchment.

$$EG = (DG / AD) \qquad [5.4]$$

where EG = expected number of life cycles per annum,
AD = annual degree days (^{o}days), and
DG = degree days per generation (^{o}days).

5.9 Other Statistics Used

The outputs from the models were analysed using numerical techniques. The general methods used in this study are described below. Output statistics from *ACRU* are detailed in Schulze (1995).

5.9.1 Ratio change

The dimensionless index of ratio change is used in this dissertation and is discussed below. It was adopted from the concept of the ratio of two mean values, as presented by Keller and Warrack (2003) in **Equation 3.2**, *viz.*

$$\Delta_{ratio} = \beta_{(scenario)} / \beta_{(baseline)} \qquad [5.5]$$

where Δ_{ratio} = ratio change,

$\beta_{(scenario)}$ = mean of a variable/parameter derived from output from a GCM's present climate scenario,

$\beta_{(baseline)}$ = mean values of the same variable/parameter derived from historical observed (i.e. baseline) climate data for the same time period.

The ratio change index was also used for analysing the change in the projected variables concerned (e.g. pest incidence between two GCM time periods such as 20 years in Future vs. 20 years at Present).

The index can range from mean values of zero to infinity, with mean values around unity (1) signifying no significant change in mean values of a variable between the two time periods. Mean values of the ratio change index < 1 and > 1 signify a reduction and an increase (respectively) in the variable of interest between the two time periods.

5.9.2 Validation analysis

"Validation is the process of determining the degree to which the model or simulation is an accurate representation of the real world from the perspective of the intended uses" (DHS, 2006:2). This definition has also be adopted the by the US Department of Defence Directive (DoDD,1994; 2003) and the US Department of Army Regulation (AR, 2005).

From the above definition of validation above, it refers to a process of determining whether a model, in this case GCM outputs, accurately represents the real world system(s). In this study, the validation analyses refer to how accurately the simulated mean annual values of agricultural production derived from the ECHAM5/MPI-OM GCM present climate input (1971 - 1990) mimics those simulated from historical data for the same time period. The historical data used in this study was assumed to be valid based on the fact that it has been quality controlled (Lynch, 2004; Schulze and Maharaj, 2004). Hence the validation analyses proposed in this study are basically a process for confirming that the GCM used is applicable for its intended use and representative, i.e. in this case to assess agricultural productivity. This assessment is conducted both spatially and statistically to determine if there was a relationship between results. Successful validation of GCM simulations against those for baseline climate conditions is signified by a good relationship found both spatially and statistically. Successful validation is assumed to raise confidence in the model-based predictions when considering climate change.

Two approaches were used for performing the Validation analysis, *viz.* relative difference and correlation analyses. These Validation methods were used because they can be reproduced and are quantitative measures of the validity of variables derived from the GCM's present climate scenario to baseline climate conditions. The relative difference was used to determine if the GCM's present climate scenario estimation followed similar spatial trends to those derived from historical observed baseline climate conditions. The relative difference was computed using **Equation 5.6**. The geospatial correlations were indicated by signs, with '-' denoting under-estimation and '+' denoting over-estimation in regard to baseline climate conditions, and the magnitude of an under- or over-estimation of the particular variable at the QnC spatial scale. A difference in estimation between - 10 and + 10 % was assumed to indicate no significant difference.

$$\Delta_{\%} = [(\beta_{scenario} - \beta_{baseline}) / \beta_{baseline}] \times 100 \quad [5.6]$$

where $\Delta_{\%}$ = relative difference,

$\beta_{scenario}$ = mean values of a variable/parameter derived from output using the GCM's present climate scenario, while

$\beta_{baseline}$ = mean values of the same variable/parameter derived from historical observed (i.e. baseline) climate data for the same time period.

The graphical method used was the scatter diagram to usually present the relationship between variables of interest, where simulations from the ECHAM5/MPI-OM GCM's present climate scenario are the dependent variable on the y-axis and those from baseline climate conditions are on the x-axis. A linear trendline was fitted through the point values, which represent the individual QnCs values. Furthermore, the Pearson correlation coefficient (r) shows how strongly the GCM present climate scenario values mimic those of baseline climate conditions, with the validation being most reliable when the r approximated unity. A linear model was generated from the trendline that describes the fitted points.

****

Following the descriptions of the temporal databases, both for baseline and GCM derived climate scenarios, as well as the geospatial databases and the models used in this study, an assessment of the impacts of climate projections on agricultural production over the Limpopo Catchment is given in **Chapter 6**.

SECTION FOUR: RESULTS AND DISCUSSION

6. EFFECTS OF PROJECTED FUTURE CLIMATE CHANGE ON NET ABOVE-GROUND PRIMARY PRODUCTION

Having discussed the temporal databases, both for baseline and General Circulation Model (GCM) derived climate scenarios, as well as the geospatial databases and the models used in this study, climate projections are used in this chapter to assess impacts of climate change on agricultural production over the Limpopo Catchment. Agricultural production in this study is represented by net above-ground primary production estimated using the Rosenzweig (1968) algorithm which has been imbedded in the *ACRU* agrohydrological modeling system.

Note: Where the Source Information is given as "BEEH 2008" this refers to simulations which were not run by the author; however, the author produced the maps.

6.1 Net Above-Ground Primary Production Patterns over the Limpopo Catchment

6.1.1 Mean annual net above-ground primary production

The estimated mean annual agricultural production, represented by NAPP, is shown in

Figure 6.1. The spatial range over the Limpopo Catchment is from < 0.5 tons per hectare in an average growing season ($t.ha^{-1}.season^{-1}$), mainly in the low altitude (< 200 m, cf. **Figure 2.3**) northern and eastern periphery of the Limpopo Catchment, to over 18.0 $t.ha^{-1}.season^{-1}$ in the moderate to high relief terrain (cf. **Figure 2.4**) along the southern periphery. The regions of low NAPP (< 4.0 $t.ha^{-1}$. $season^{-1}$) correlate with areas receiving mean annual precipitation (MAP) < 550 mm (cf. **Figure 2.5**). The areas along the southern to southeastern borders of the Catchment and inland which receive the highest MAP in the Catchment (at altitudes > 1 250 m), correspond with the estimated NAPP > 6.0 $t.ha^{-1}.season^{-1}$. The areas shown as "undefined" Quinaries in

Figure 6.1 reflect limitations in the logarithmic Rosenzweig (1968) equation (which have as yet not been recognized, to the knowledge of the author) for estimating NAPP. Quinaries show up as undefined when annual actual evapotranspiration values are lower than those used by Rosenzweig when he developed his equation.

Visual comparison shows that the NAPP map displays a close relationship spatially with the biomes as defined by Low and Rebelo (1998). This relationship is more evident in the Quinary Catchments covered by the Savanna biome (cf. **Figure 2.11**) in which NAPP ranges from < 0.5 to 6.0 $t.ha^{-1}.season^{-1}$ (cf.

Figure 6.1) and in which grazing is important. The Grassland and Forest biome regions within the Catchment, shown in **Figure 2.11**, correlate spatially with NAPP > 6.0 $t.ha^{-1}.season^{-1}$. The latter two biomes are associated with high summer rainfall, and are suitable for grain crop and livestock farming, including natural grazing, as well as for forest plantations (Low and Rebelo, 1998). These very broad relationships show that NAPP could be used as an indicator of the Catchment's potential agricultural productivity.

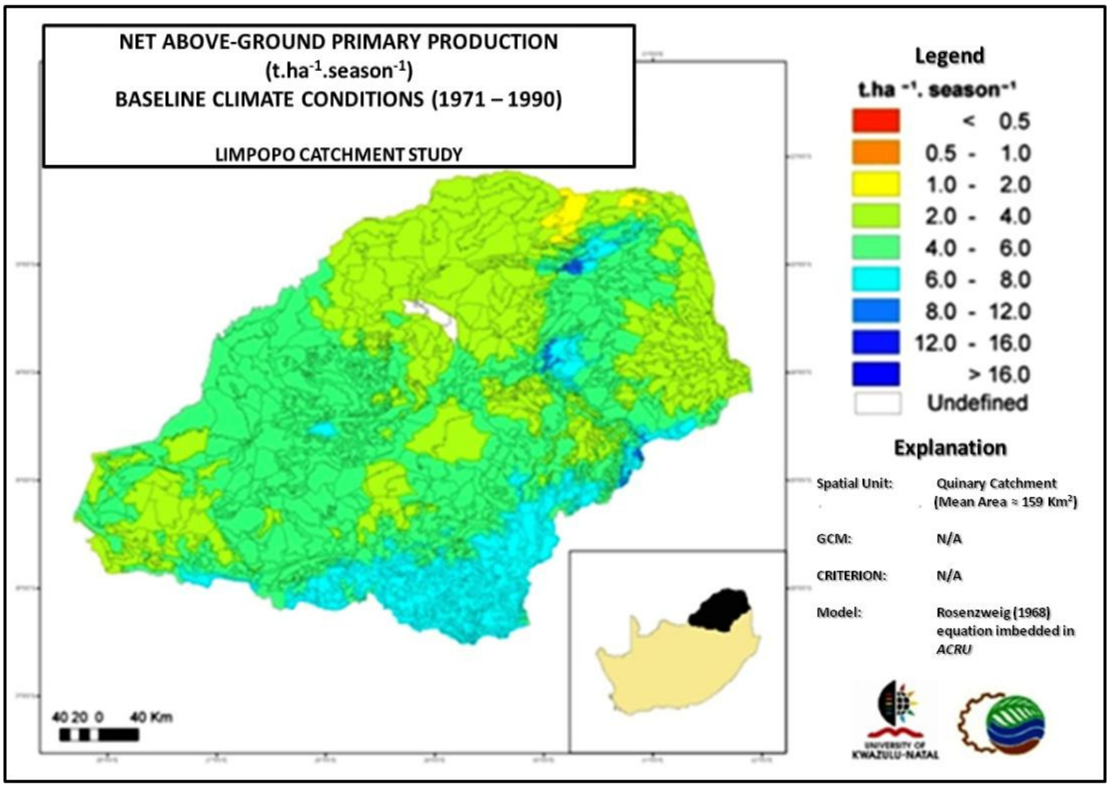

Figure 6.1 Mean annual net above-ground primary production under baseline climate conditions (Source information: BEEH, 2008)

6.1.2 Inter-annual variability of net above-ground primary production

The high risk natural environment in the Limpopo Catchment is shown in the maps of inter-annual variability of primary production (**Figure 6.2** top and bottom), expressed in absolute terms through the standard deviation ($t.ha^{-1}.an^{-1}$), and in relative terms through the coefficient of variation, CV (%). The Standard deviation varies across the catchment from approximately 0.50 to over 4.00 $t.ha^{-1}.an^{-1}$. The CV (%) in **Figure 6.2** decreases from northern parts of the Catchment toward southern borders. This demonstrates the influence of the mean on the CV. The Quinaries with the low year-to-year variability correspond to areas of high rainfall, while areas with high variability are found in the drier areas receiving low rainfall (Schulze and Kunz, 2010a).

In **Figure 6.2**, the inter-annual variability in NAPP is over 40 % in the northern parts of the Catchment, which overlaps with the Grassland biome (cf. **Figure 2.5**) and which receives high MAP and is thus suitable for a variety of agricultural activities. On the other hand, areas with the high CVs in the Catchment correspond spatially with the Savanna biome (i.e. the dominant biome in the Limpopo Catchment) which experiences low MAPs (cf. **Figure 2.6**).

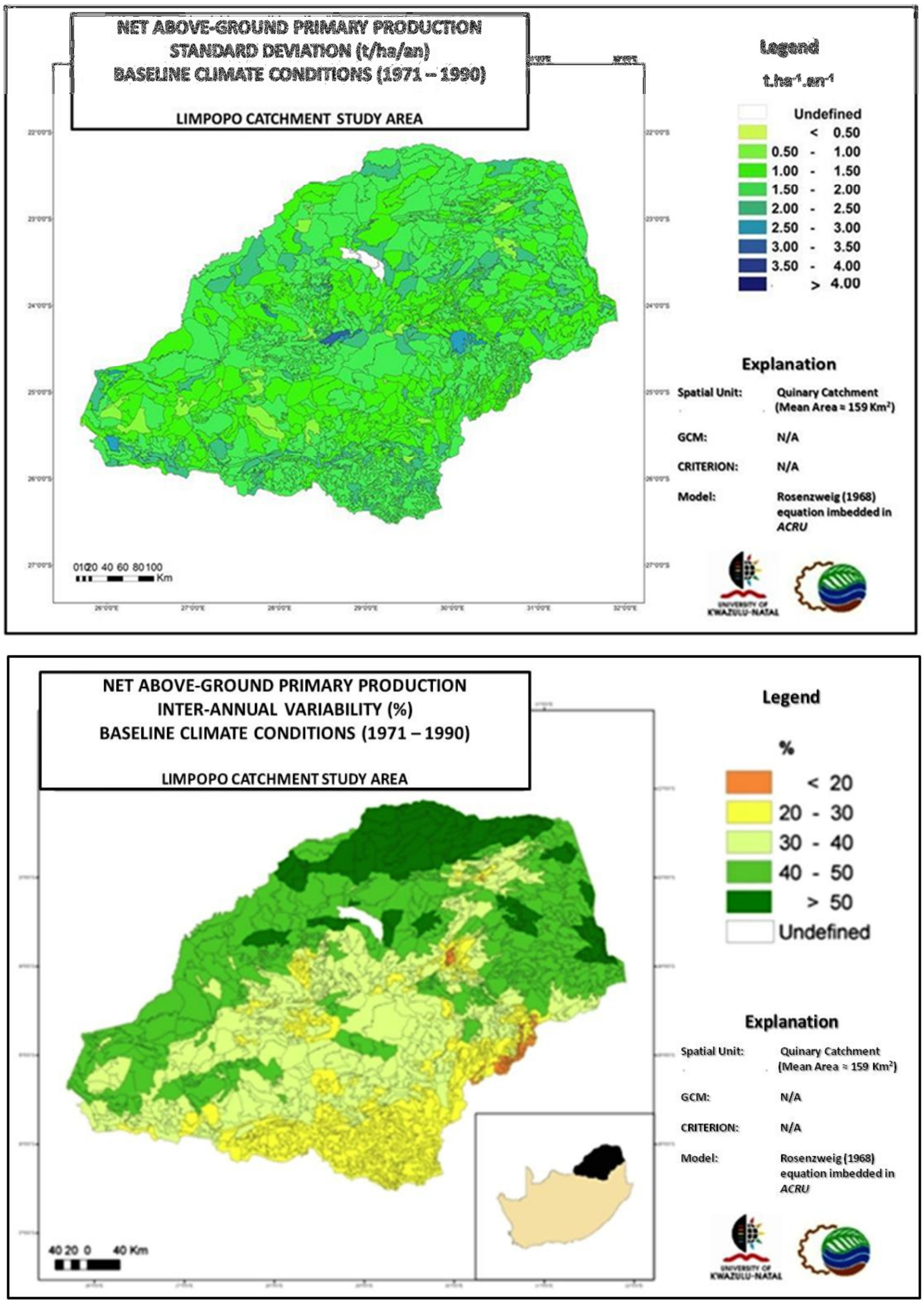

Figure 6.2 Inter-annual variability in net above-ground primary production, expressed through standard deviation (t.ha^{-1}.an^{-1}) and coefficient of variation (%), under baseline climate conditions (Source information: BEEH, 2008)

6.2 Validation of the ECHAM5/MPI-OM GCM's Output Against that of Baseline Climate Conditions for the Prediction of Net Above-Ground Primary Production

In this section a Validation analysis was performed to determine if the NAPP derived from output of the ECHAM5/MPI-OM GCM's present climate scenario is representative of that simulated from historical data (assumed to be valid, cf. **Section 5.9.2**), for identical period of 1971 - 1990. This type of analysis had not been previously undertaken in South Africa to the author's knowledge. The Validation analysis techniques used were based on relative differences and regression analysis, discussed in **Section 5.8**. The relative difference in production was computed using **Equation 3.3** and was mapped in **Figure 6.3**.

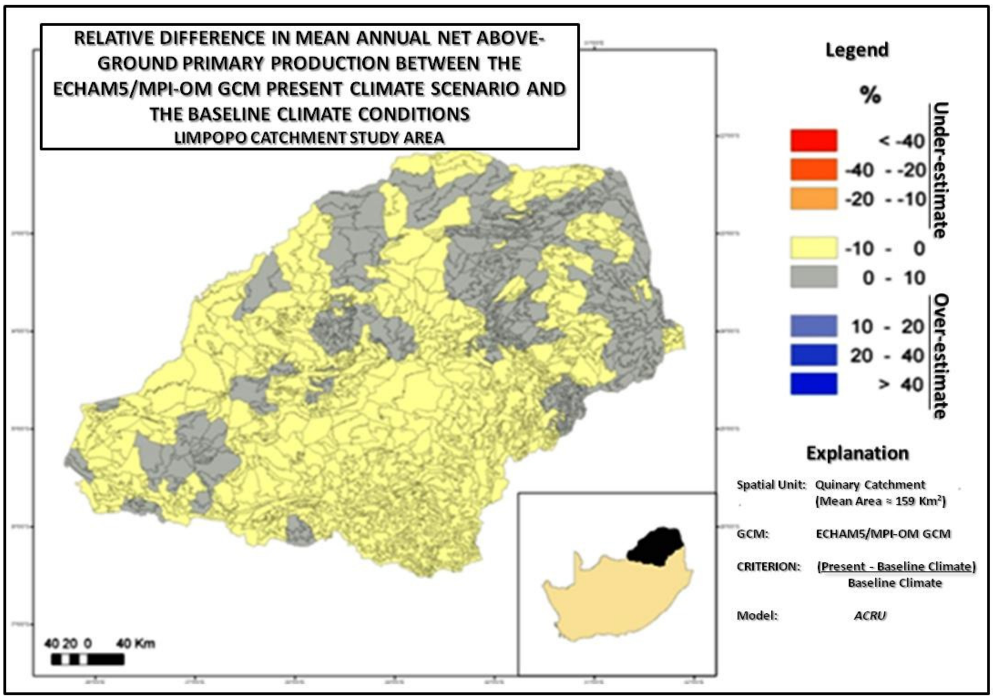

Figure 6.3 Relative difference in mean annual net above-ground primary production generated from the ECHAM5/MPI-OM GCM present climate scenarios vs. those from baseline climate conditions

The relative difference in NAPP depicted in **Figure 6.3** shows that the simulated NAPP derived from the ECHAM5/MPI-OM GCM's present climate scenario corresponds well to those derived from baseline climate conditions, i.e. they are within an acceptance range of ± 10 %. This implies that there is spatial correlation between the predictions of NAPP from the GCM's present climate scenario and those from baseline climate conditions. A further analysis conducted was a regression analysis (**Equation 6.2**) to establish if this relationship was statistically significant. A good fit is shown in **Figure 6.4**, in which the regression was forced through zero, with a strong positive linear relationship, R^2 of 0.61 and a slope of 0.92 that indicates only a slight under-estimation of GCM derived NAPP. Hence the analyses indicated that the GCM derived NAPP is representative of that simulated from historical data, which is assumed to represent real world NAPP.

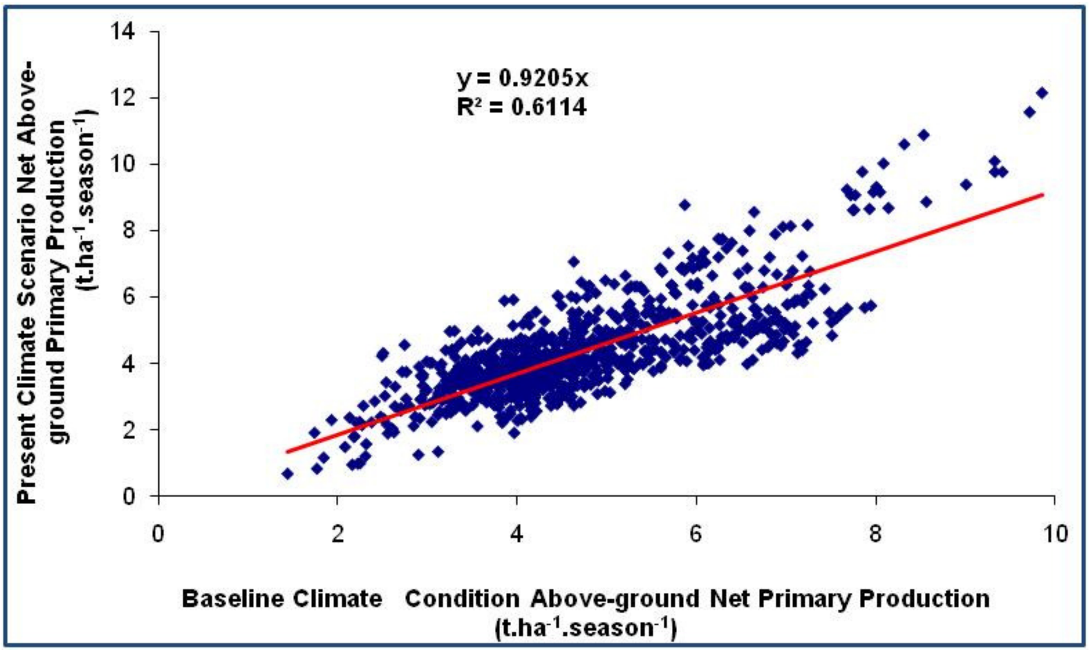

Figure 6.4 Relationship between the NAPP generated from the ECHAM5/MPI-OM GCM's present climate scenario and baseline climate conditions for the same period [1971 – 1990], with each point representing a Quinary Catchment

$$PNAPP = 0.8664\ BNAPP + 0.2779 \qquad [6.1]$$

where, PNAPP = net above-ground primary production ($t.ha^{-1}.season^{-1}$) from the ECHAM5/MPI-OM GCM's present climate scenario, while

BNAPP = net above-ground primary production ($t.ha^{-1}.season^{-1}$) from baseline climate conditions.

6.3 The Influence of Climatic Variables on Net Above-ground Primary Production

Rosenzweig (1968) showed a relationship between NAPP and annual total evaporation, i.e. annual actual evapotranspiration (AET). However, AET depends, *inter alia,* on temperature and rainfall. NAPP is limited by both water availability (rainfall) and solar radiation (Kaspari *et al*., 2000; Monterroso Rivas *et al*., 2011) the latter being closely related to temperature (Bristow and Campbell, 1984; Bandyopadhyay *et al*., 2008). Hence it is expected that both rainfall and temperature would have a direct impact on NAPP.

In this section, the aim was therefore to determine the role that averaged climate variables, i.e. mean annual precipitation (MAP), and temperature (MAT), might play in driving NAPP. Such an assessment is important for effectively determining the impacts of climate variability and change on the response of harvestable yield. The selection of the best model for describing the relationship between production and climate variables, was determined by

- defining the independent variable (i.e. MAP or MAT) and the dependent variable, NAPP, for baseline climate conditions; and then
- selecting the best equation (based on the goodness of fit statistics) between NAPP and either MAP or MAT; and then
- performing regression analyses on NAPP against either MAP or MAT.

In **Figure 6.5**, the pearsons correlation coefficient (r) between NAPP and MAP indicates a strong positive linear relationship with $r = 0.77$. The relationship between NAPP and MAP implies that the rainfall is a strong determining factor of NAPP. According to Zhong *et al*. (2007) such a direct relationship implies that wetter parts of the Catchment might be using precipitation more efficiently for NAPP. Precipitation is therefore one of the important variables determining NAPP, as shown by the NAPP:MAP relationship.

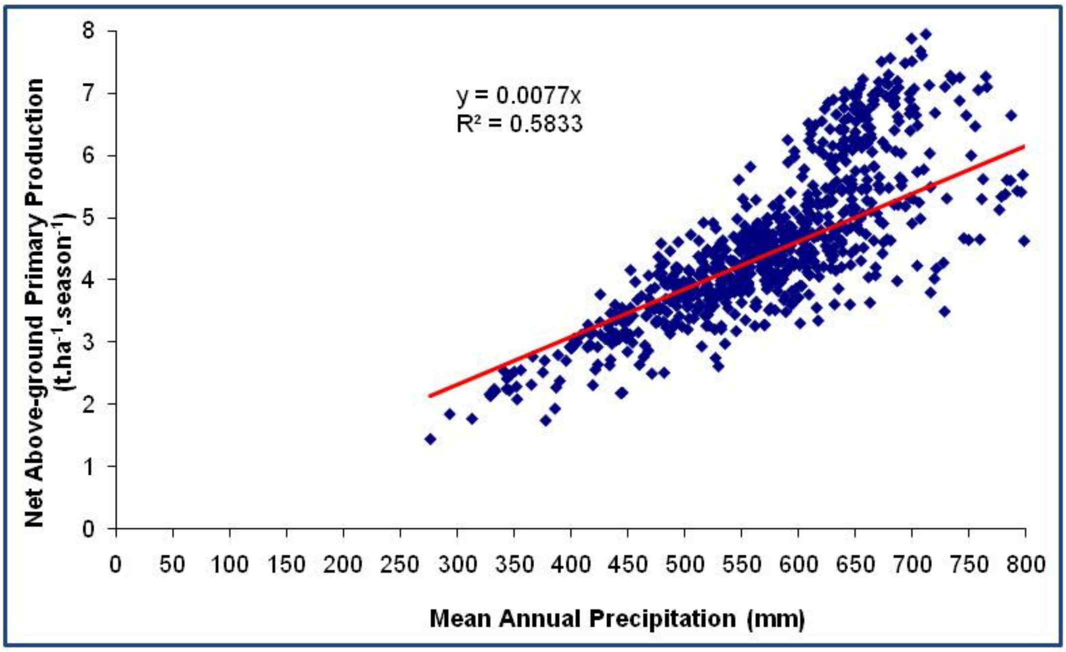

Figure 6.5 Mean annual net above-ground primary production as a function of mean annual precipitation in the Limpopo Catchment, with each point representing a Quinary Catchment

The statistical comparison of NAPP: MAP in **Figure 6.5** is in agreement with the visual assessments made in

Figure 6.1 and **Figure 2.5**. The distributions of MAP and MAT in **Figure 2.5** and **Figure 2.7** (respectively), indicate a correspondence between high rainfall areas (at high altitudes) and low temperatures areas, which were simulated to have high potential production.

Thus, on the basis of this r, an analysis was carried out to determine if there was an inverse relationship between NAPP and MAT. The relationship between NAPP and MAT is shown in **Figure 6.6**. The *r* of the NAPP: MAT is -0.52 and shows a weak inverse relationship between NAPP and MAT. This effect might be as a result of the higher temperatures being associated with drier climatic conditions, directly increasing the atmospheric water demand, and hence the plants' potential evapotranspiration. The projected future increase in temperature regimes can indirectly affect the production by increasing the rate of decomposition of soil organic matter, and hence lowering the organic matter content in the soil, which lowers the soil's water holding capacity. This would therefore result in the soil being unable to retain as much moisture as under cooler conditions, thus, contributing to the plant water stress (Rosenzweig *et al*., 2000).

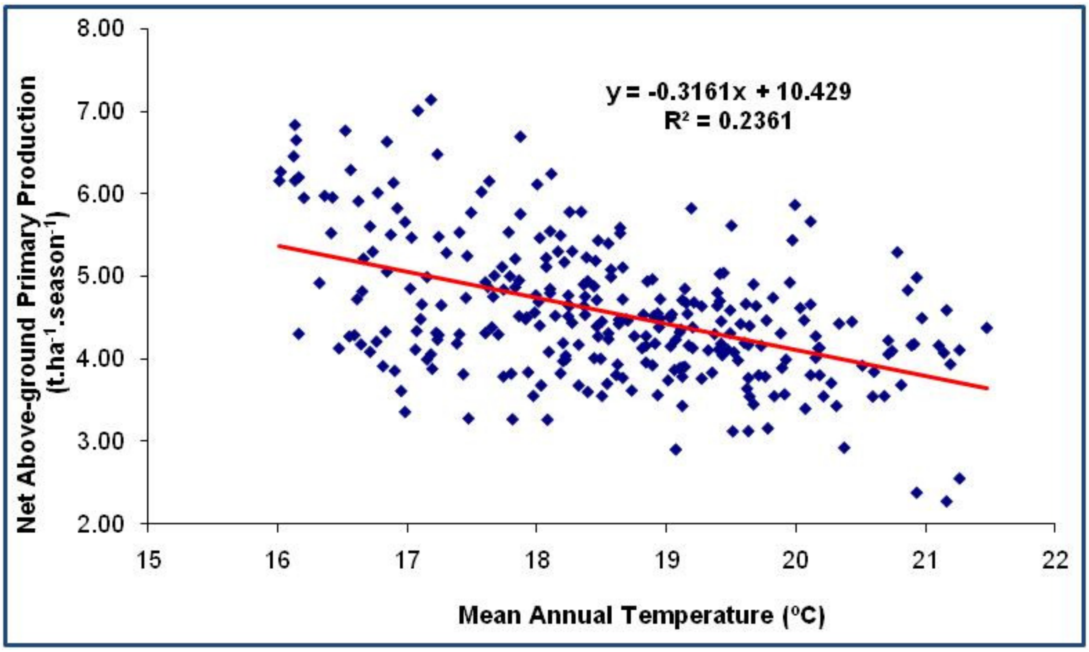

Figure 6.6 Mean annual net above-ground primary production as a function of mean annual temperature in the Limpopo Catchment, with each point representing a Quinary Catchment

The findings on the effects of the climatic variables controlling the rates of agricultural production in the Limpopo Catchment were that the MAP indicates a strong positive correlation with NAPP as estimated by the Rosenzweig (1968) equation, and MAT a weak negative correlation. This shows that the availability of water and energy are major drivers, of the geographical distribution NAPP over the Limpopo Catchment. The effects of increases in both climate change related drivers would have different implications on the agricultural production. If precipitation only were to increase over the Catchment, it would result in an increase in the production, whereas higher temperature conditions by themselves would tend to decrease the production.

6.4 Determination of Projected Distributions of Net Above-Ground Primary Production Under Conditions of Climate Change

The relationship between NAPP and climate change related drivers (i.e. temperature and rainfall) was determined in **Section 6.3** to better understand the effects and interactions of climate variables on the terrestrial ecosystem's production. Thus, on basis of the findings in the previous section it was hypothesised that the effects of projected future effects of temperature and rainfall would have a direct effect on NAPP, implying that if the water availability over the Catchment were to increase due to climate change, then the NAPP would increase and expand to areas previously of lower production, whereas if the temperature increased the opposite would be true, although not as strongly.

This hypothesis was tested by estimating the NAPP using the Rosenzweig (1968) equation, which is a function of AET, and thus indirectly of temperature and rainfall. The NAPPs were projected by inputing daily maximum and minimum temperature and precipitation outputs from ECHAM5/MPI-OM GCM for present, intermediate future and distant future climate scenarios of 20-year time periods into the *ACRU* model (Schulze, 1995 and updates). The output statistics from the *ACRU* model were then mapped for mean annual and inter-annual variability of NAPP. Further statistics performed were the ratio changes in NAPP. Because of space constraints, the maps of these further statistics are given in the **Appendix B**, while a summary of all statistics is given in the section below.

6.4.1 Projected changes in mean seasonal net above-ground primary production

Maps of NAPP for the present climate scenario derived from the ECHAM5MPI/OM GCM, shown in **Figure 6.7** (top left), indicate that NAPP ranges from > 4.0 $t.ha^{-1}.season^{-1}$ in parts of the southern and the central interior of the Limpopo Catchment to < 2.0 $t.ha^{-1}.season^{-1}$ in the northern parts of the Catchment which receive relatively low rainfall.

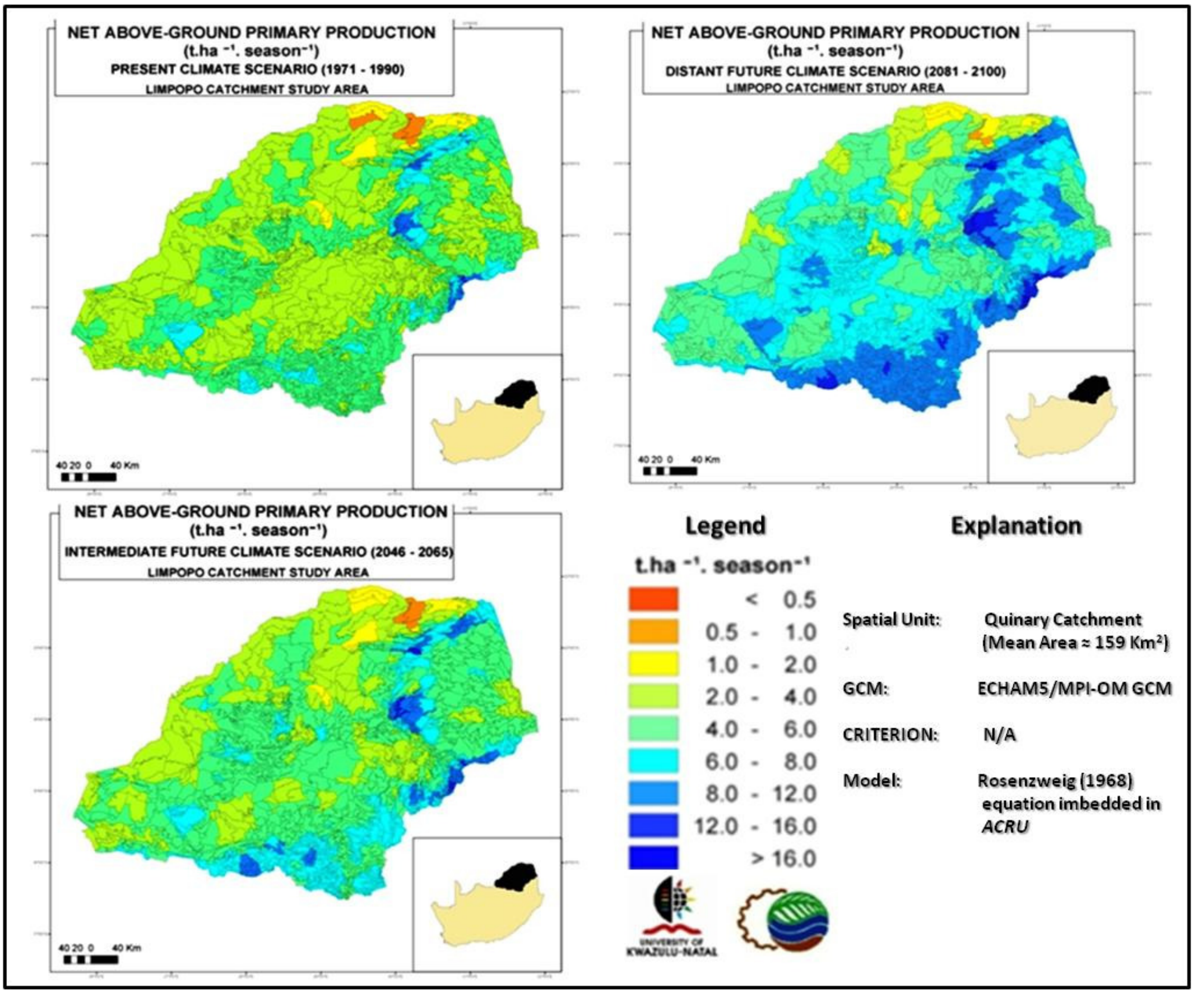

Figure 6.7 Mean annual net above-ground primary production under present (top left), intermediate future (bottom left) and distant future (top right) climate scenarios derived from the ECHAM5/MPI-OM GCM (Source information: BEEH, 2008)

The map of NAPP derived from the ECHAM5/MPI-OM GCM's intermediate future climate scenario, in **Figure 6.7** (bottom left), indicates a likely expansion in areas with > 4.0 t.ha^{-1}.season^{-1} when compared with the present climate scenario, mainly along the southern to eastern border of the Catchment. The areas of low NAPP simulated for the present climate scenario, *viz.* < 4.0 t.ha^{-1}.season^{-1}, shrink and/or shift northwards in the intermediate future climate scenario. The intermediate future climate scenario's NAPP relative to that of the present climate scenario

(**Appendix B: Figure B.1**) shows increases ranging from < 10 % along the northern border of the Limpopo Catchment, to over 90 %, mainly along the southern border.

A further shift is evident towards the northern border of the Limpopo Catchment in the distant future climate's areas with NAPP < 4.0 $t.ha^{-1}.season^{-1}$, when compared to areas for the present climate scenario, as shown in **Figure 6.7** (top right). The areas with NAPP > 8.0 $t.ha^{-1}.season^{-1}$, which are distributed in patches along the eastern interior to southern border under the present and the intermediate future climate scenarios, expands over the eastern and southern border of the Catchment in the projected distant future climate scenario. The ratio change in NAPP in the distant future relative to that of the present climate scenario (cf. **Appendix B: Figure B.2**) shows an increase of > 20 % from the northern to over 90 % towards the southern periphery of the Limpopo Catchment. A similar relative increase in the NAPP is evident between the distant and the intermediate future climate scenarios, presented in **Appendix B: Figure B.3**.

The relationship between NAPP and MAP, discussed in **Section 6.3**, becomes evident in these projections. For example, the areas of high agricultural production (i.e. > 8.0 $t.ha^{-1}.season^{-1}$) expand over the Catchment with ECHAM5/MPI-OM GCM projected increases in MAP (Schulze and Kunz, 2010a), i.e. from the present to the intermediate future and through to the distant future climate scenarios.

6.4.2 Projected changes in the inter-annual variability of net above-ground primary production

In **Figure 6.8** the maps of inter-annual variability of primary production expressed in absolute terms (standard deviation) shows values across the Catchment from 0.50 to 2.50 $t.ha^{-1}.an^{-1}$ for the present and intermediate future, while in the distant future the standard deviation in yields can exceed 4.00 $t.ha^{-1}.an^{-1}$ in places. The relative year to year variability expressed as the CV (%) shown in **Figure 6.9** decreases in parts of the northern Catchment from the present through to the distant future. This indicates that relative to actual harvestable yields, the year to year variability will decrease, owing to wetter climates projected from ECHAM/MPI-OM GCM outputs (i.e. increases in mean annual rainfall; Schulze and Kunz, 2010c).

The summaries, per Water Management Areas (WMAs) in the Limpopo Catchment, of the CVs in NAPP, shown in **Table 6.1** (top) and **Figure 6.9** indicate that the *relative* variabilities, i.e. expressed by the CVs, under intermediate and distant future climate scenarios to those of the present climate scenario are not significantly different in the Limpopo, Luvuvhu/Letaba and Crocodile (West) and Marico WMAs, but show a marked increase in the Olifants WMA. Conclusions made from further investigations, however, show that the standard deviation, which is an *absolute* statistic of variability, is likely to increase markedly from present to intermediate future through to the distant future climate scenarios, as indicated especially by the ratio changes (I:P, F:I and F:P) in standard deviations in **Table 6.1** (bottom).

The implications of the above results are that the choice of the statistic of variability is crucial in interpreting changes in variability into the future, with a relative statistic sometimes giving very different results to those of an absolute statistic.

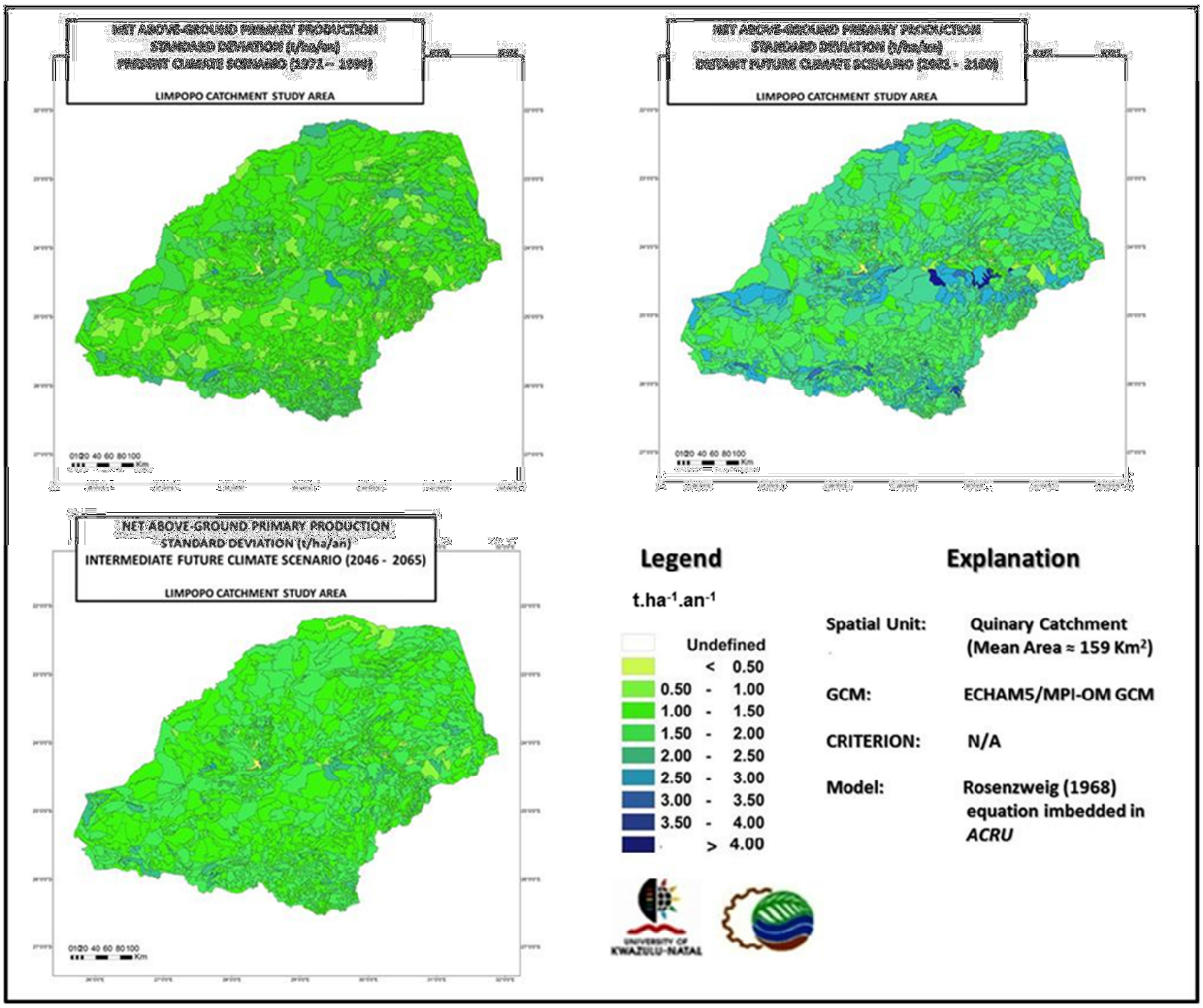

Figure 6.8 Inter-annual variability in net above-ground primary production, expressed by the standard deviation (t.ha^{-1}.an^{-1}), under present (top left), intermediate future (bottom left) and distant future (top right) climate scenarios derived from the ECHAM5/MPI-OM GCM (Source information: BEEH, 2008)

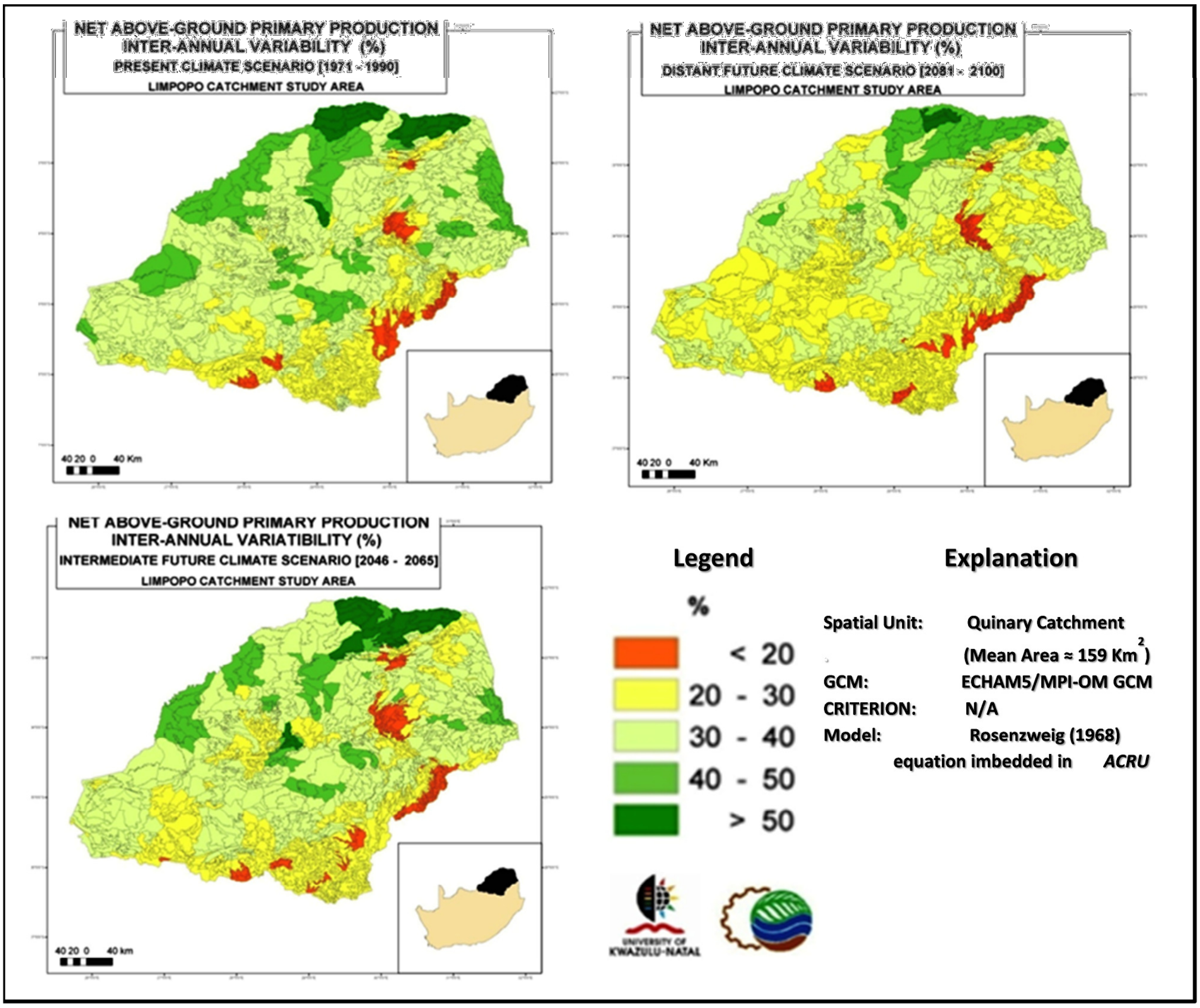

Figure 6.9 Inter-annual variability in net above-ground primary production, expressed by the coefficient of variation CV (%), under present (top left), intermediate future (bottom left) and distant future (top right) climate scenarios derived from the ECHAM5/MPI-OM GCM (Source information: BEEH, 2008)

Table 6.1 Summary of coefficients of variation (top) and standard deviation (bottom) of the net above-ground primary production derived from the ECHAM5/MPI-OM GCM (Source information: BEEH, 2008)

Limpopo Catchment Water Management Area	**Coefficient of Variation (%) of Net Above-ground Primary Production**					
	Present Climate Scenario	**Intermediate Future Climate Scenario**	**Distant Future Climate Scenario**	**I : P**	**F : P**	**F : I**
Limpopo	33.31	33.98	32.71	1.02	0.98	0.96
Luvuvhu and Letaba	29.13	26.55	28.43	0.91	0.98	1.07
Crocodile (West) and Marico	28.71	29.38	28.48	1.02	0.99	0.97
Olifants	18.95	26.20	26.46	1.38	1.40	1.01

Limpopo Catchment Water Management Area	**Standard Deviation ($t.ha^{-1}.season^{-1}$) of Net Above-ground Primary Production**					
	Present Climate Scenario	**Intermediate Future Climate Scenario**	**Distant Future Climate Scenario**	**I : P**	**F : P**	**F : I**
Limpopo	1.26	1.46	1.78	1.16	1.42	1.22
Luvuvhu and Letaba	1.55	1.70	2.22	1.09	1.43	1.31
Crocodile (West) and Marico	1.18	1.45	1.89	1.23	1.60	1.30
Olifants	1.18	1.51	2.10	1.28	1.78	1.39

6.5 Summary

A review of literature indicated that there is a relationship between estimated values of NAPP and observed crop yields. The estimated NAPP distribution patterns correspond broadly with the Savanna, Grassland and Forest biomes over the Limpopo Catchment. The analysis of agricultural production under baseline climate conditions indicated that agricultural production was likely to be higher in parts of the southern periphery and lower along the northern periphery of the Limpopo

Catchment. This distribution in agricultural production was found to correlate with the MAP received over the landscapes.

These areas of potentially high NAPP, mainly in parts of the southern border of the Catchment, have low CVs, i.e. a low relative environmental risk for NAPP, while the high risk environment areas are along the northern border.

The findings from the validation analyses indicated that there was a relatively strong positive linear relationship between NAPP simulated from ECHAM5/MPI-OM GCM's present climate scenario and from baseline climate conditions for the same time period [1971 - 1990]. Therefore, the NAPP derived from the ECHAM5/MPI-OM GCM's present climate scenario is considered representative baseline climate NAPP in the Catchment. The assessment of the correlations between climate variables and NAPP indicated a weak negative linear response in NAPP to rises in temperature, whereas with increases in precipitation a strong positive linear response was observed.

The assessment on the effects of climate change on the NAPP in the Catchment, derived from output of the ECHAM5/MPI-OM GCM climate scenarios, suggests an increase in NAPP, and hence agricultural production, under the intermediate and the distant future climate scenarios. This increase is projected to be experienced more along the southern borders of the Catchment. This increase in the Catchment's agricultural production is likely to be in response to the projected wetter conditions from the ECHAM5/MPI-OM GCM.

The ECHAM5/MPI-OM GCM projected future climate suggests that the Limpopo Catchment is likely to experience decreased relative to actual harvestable yields. This indicates low relative risk of agricultural production into the future, as a result of projected wetter climate conditions from the same GCM output (Schulze and Kunz, 2010c). It should be stressed again, that this research derives from a single GCM and needs to be confirmed using output from more GCMs.

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In this Chapter the climate predictors from the ECHAM5/MPI-OM GCM were used to assess the impacts of climate change on agricultural production in the Limpopo Catchment. In the following chapter the impacts of climate change were assessed in regards to the distribution patterns of the *Chilo partellus* Spotted Stem Borer, using temperature-based techniques for simulating development periods of its various life stages, mortality and number of life cycles per annual, which were then projected for future climates derived from the ECHAM5/MPI-OM GCM climate scenarios.

7. EFFECTS OF PROJECTED FUTURE CLIMATE CHANGE ON THE *Chilo partellus* SPOTTED STEM BORER

Having assessed the impacts of climate change on estimated agricultural production in Limpopo Catchment in **Chapter 6**; in this chapter, a similar impact assessment was conducted using a temperature based technique developed for estimating the development periods in the life cycles of an agricultural yield-*reduction* factor, *viz. Chilo partellus* Spotted Stem Borer, including the average number of its life cycles. The technique developed by the author was then used to estimate the spatial and temporal distribution of *C. partellus* in the Limpopo Catchment under present and projected future climate conditions.

7.1 Distribution of development periods of the *Chilo partellus* life cycle

What follows in this sub-section are maps of the development periods of the entire *C. partellus* life cycle under baseline climate conditions. Similar maps for the egg, larval and pupa stage development periods are presented in **Appendix D** because of length constraints to the main body of this dissertation. **Figure 7.1** illustrates that the distribution of the life cycle development period of *C. partellus* over the Limpopo Catchment ranges from < 40 days, mainly along the northeastern border, to over 100 days in cooler areas of moderate to high relief (cf. **Figure 2.4**) along the southern border and central interior. Undefined quinaries are those experiencing mean daily temperature ranges outside the model's predictive range, i.e. between ≥ 15 and ≤ 35 ^{o}C.

The areas where shorter development periods of the *C. partellus* life cycle occur under baseline climate conditions are associated with higher temperatures found at the lower altitudes, compared with the longer development periods found in the lower temperature high altitude regions. This concurs with Kfir's (2001) findings that in cooler climatic conditions in the Highveld of South Africa the pest entered into an involuntary hibernation (diapauses) which lengthened the development period.

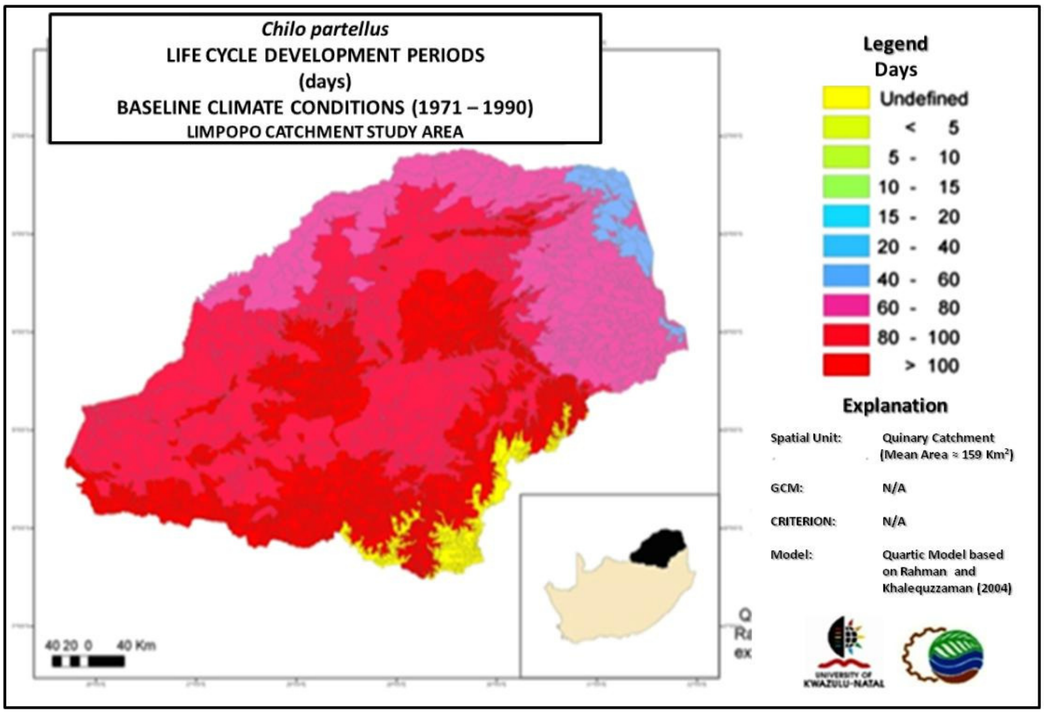

Figure 7.1 Mean period (days) for the development of a *C. partellus* life cycle under the baseline climate conditions

7.2 Validation of the ECHAM5/MPI-OM GCM's Climate Output Against that of Baseline Climate Conditions for the Prediction of Life Cycle Development Periods of *Chilo partellus*

In this section the validation analyses were used to determine the degree of accuracy to which the life cycle development periods of the *C. partellus*, derived from the ECHAM5/MPI-OM GCM's present climate scenario, is representative of that derived from baseline climate conditions (historical data assumed to be valid, cf. **Section 9.5.2**), for same time period from 1971 – 1990. This was tested using relative difference and regression analyses, as discussed in **Section 5.9.2**.

The relative difference is an indicator of the ability of the ECHAM5/MPI-OM GCM's present climate scenario to mimic spatial distributions of baseline climate conditions of the *C. partellus* life cycle development periods. Results of this analysis are shown in **Figure 7.2**, with the map scales indicating the direction and magnitude in the difference between the two simulations, where the range -10 to 10 % is considered to be acceptable. Over most of the Limpopo Catchment the GCM's prediction of the development periods closely correlates with that of the baseline climate conditions. However, small patches of Quinaries in high altitudes (> 800 m) along the southeastern regions indicate under- and over-estimation of the development periods of *C. partellus* life cycle.

These regions of under- and over-estimation in the map produce the outliers in the scatterplot shown in **Figure 7.3** and are likely to be the results of input errors in temperature values (Schulze, 2010; Personal Communication). These outliers (along the y and x axes, as well as at the origin) influence the fit of the equation. The R^2 of 0.30 indicates a relatively strong positive linear relationship between the present climate scenario and baseline climate condition for the simulated *C. partellus* life cycle development period, while the slope of the 0.985 is close to the near perfect.

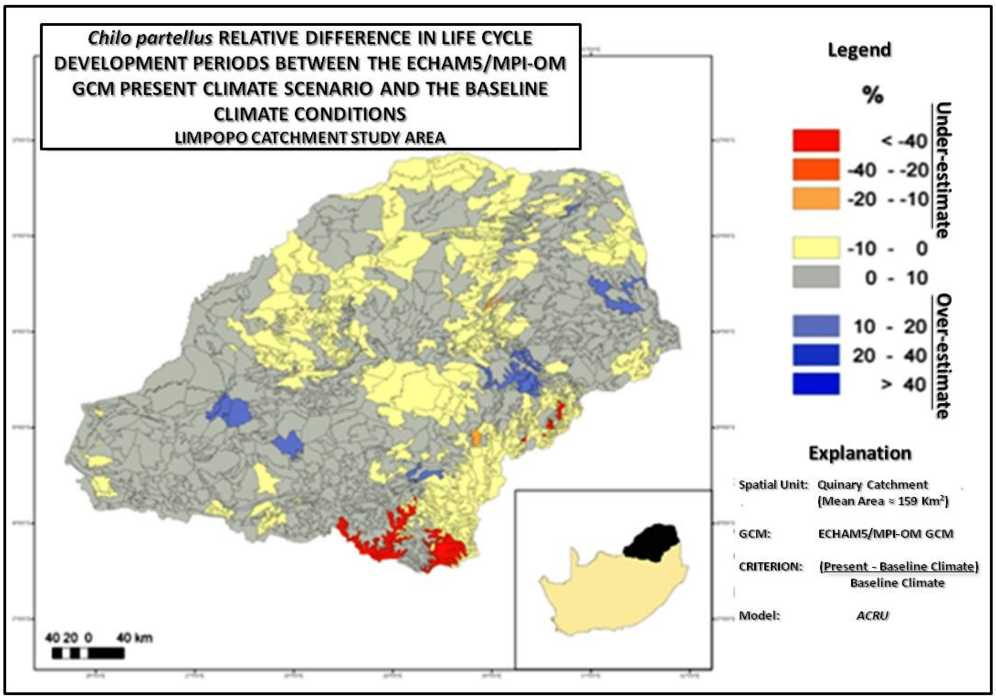

Figure 7.2 Relative difference between predictions of the *C. partellus* life cycle development period generated from the ECAHM5/MPI-OM GCM's present climate scenario vs. those from baseline climate conditions

The relative difference and regression analyses of the development periods indicate that life cycle development periods of *Chilo partellus* derived from the ECHAM5/MPI-OM GCM's present climate scenario are representative of those derived from the baseline climate.

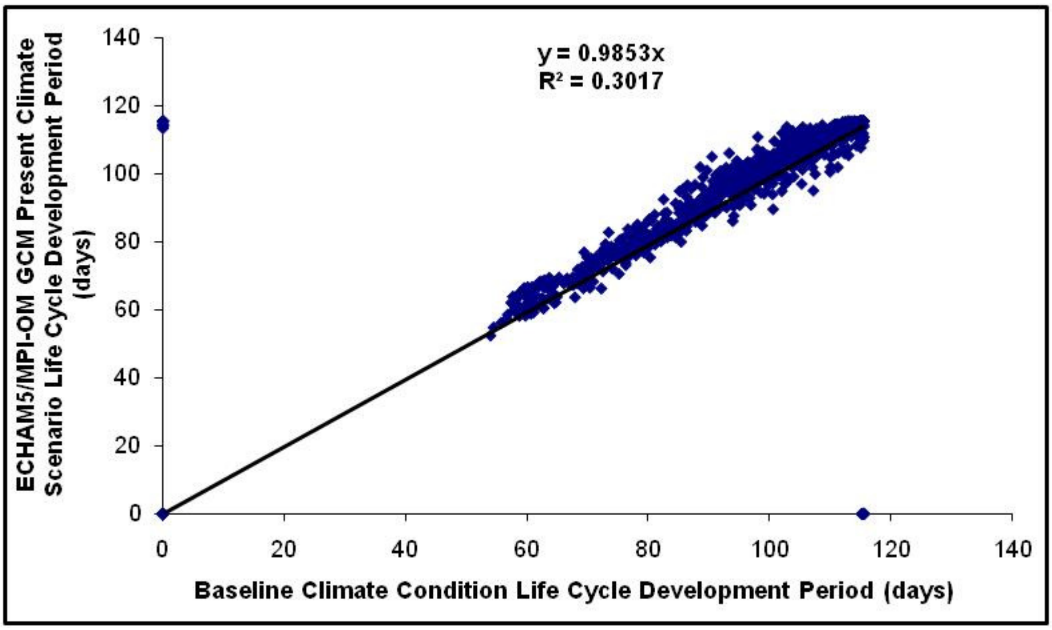

Figure 7.3 Relationship between C. *partellus* life cycle development periods generated from the ECHAM5/MPI-OM GCM's present climate scenario and baseline climate conditions for the same period [1971 – 1990], with each point representing a Quinary Catchment

7.3 Projections of Patterns of Development Periods of *Chilo partellus* Life Cycle under Conditions of Climate Change

If the temperature over the Limpopo Catchment were to increase due to changes in climate, then the *C. partellus* development periods are hypothesised to be shorter than under the baseline climate conditions. To reject or accept the stated hypothesis, the values of daily maximum and minimum temperatures for present [1971 – 1990], intermediate future [2046 – 2065] and distant future [2081 – 2100] climate scenarios derived from the ECHAM5/MPI-OM GCM were used to project the effects of climate change on the development periods of the *C. partellus* life cycle.

The development period of the *C. partellus* life cycle, shown in **Figure 7.4** (top left), is defined as the number days required for completing a life cycle. Development periods under the present climate scenario range from < 60 days, along the northeastern periphery of the Limpopo Catchment, up to 100 days in mainly high lying areas along the southern periphery and the central interior, associated with lower temperatures (cf. **Figure 2.7**).

In the intermediate future climate scenario the development periods, shown in **Figure 7.4** (bottom left), indicate that areas with over 100 days for the *C. partellus* life cycle to be completed might retreat to higher lying areas in the central interior and along the southern border of the Catchment, while those with < 60 days expand southward from the northeastern periphery.

In the distant future climate scenario the development periods < 60 days are projected to expand even further south, as shown in **Figure 7.4** (top right), to occupy the central interior and parts of the southern periphery, while the development periods in areas along the northern border of the Limpopo Catchment under this climate scenario are projected to be reduced further to < 40 days as a result of the projected GCM's increase in temperature. The regions with the longest development periods of *C. partellus* (over 100 days) are projected to continue to retreat to an ever smaller area along the southeastern periphery.

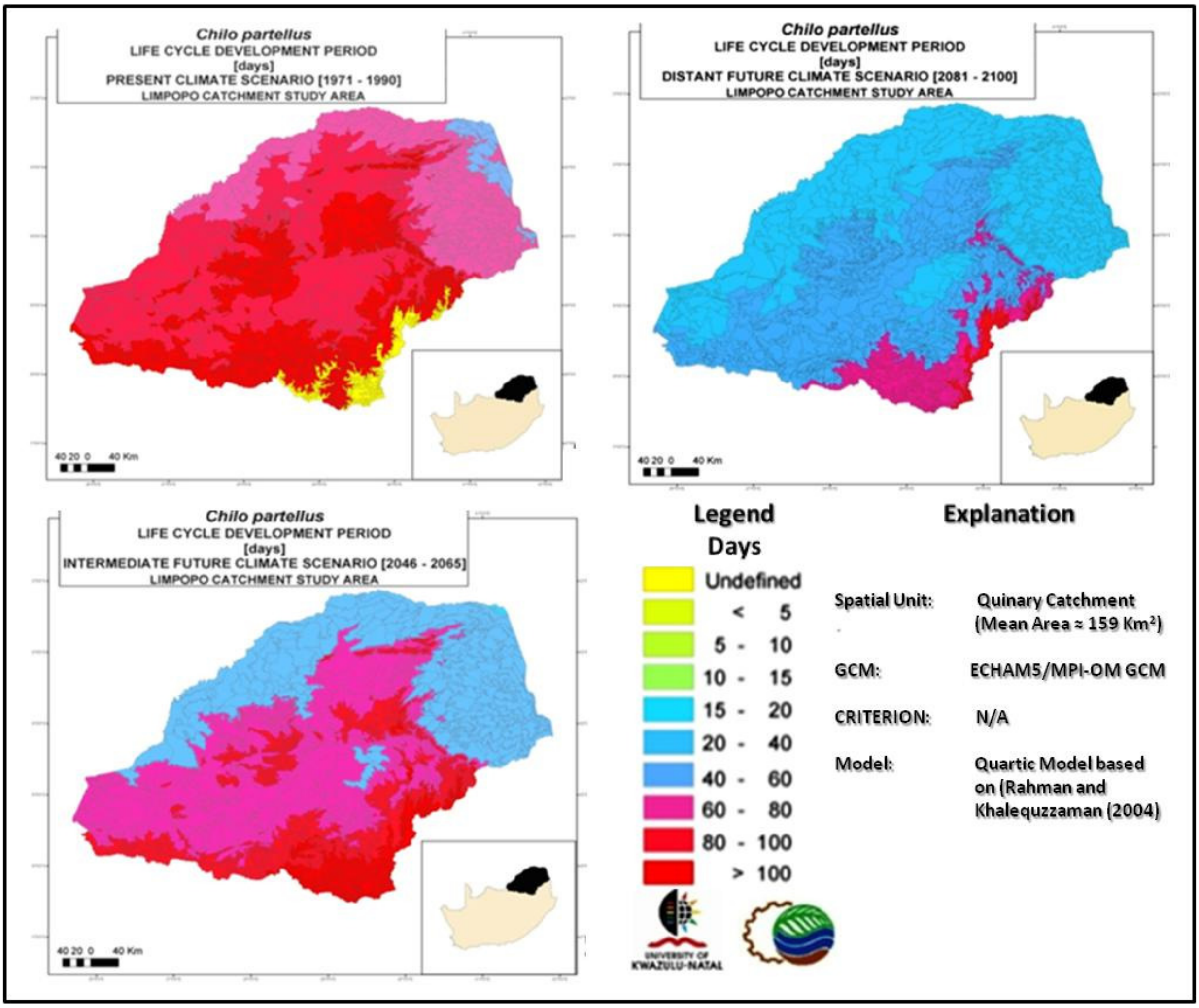

Figure 7.4 Mean period (days) taken for the development of a *C. partellus* life cycle under the present (top left), intermediate future (bottom left) and distant future (top right) climate scenarios of the ECHAM5/MPI-OM GCM

Projections of the development periods of the *C. partellus* life cycle, discussed above, were further analysed to determine the ratio changes between the projected climate change scenarios. The ratio change between the intermediate future and present climate scenarios of the development periods (cf. **Figure 7.5**, top left), suggests a reduction in the development periods varying across Catchment to 0.50 to over 0.90 of the present.

The ratio changes in the development period of *C. partellus* between the distant and intermediate future climate scenarios, in **Figure 7.5** (bottom left), suggests a further decline mainly along the eastern parts of the Catchment. In **Figure 7.5** (top right), the ratio change in the development periods between the distant future and present climate scenarios suggests a reduction in the distant future to > 50 % of that applicable to present climate conditions over 90 % of the Limpopo Catchment.

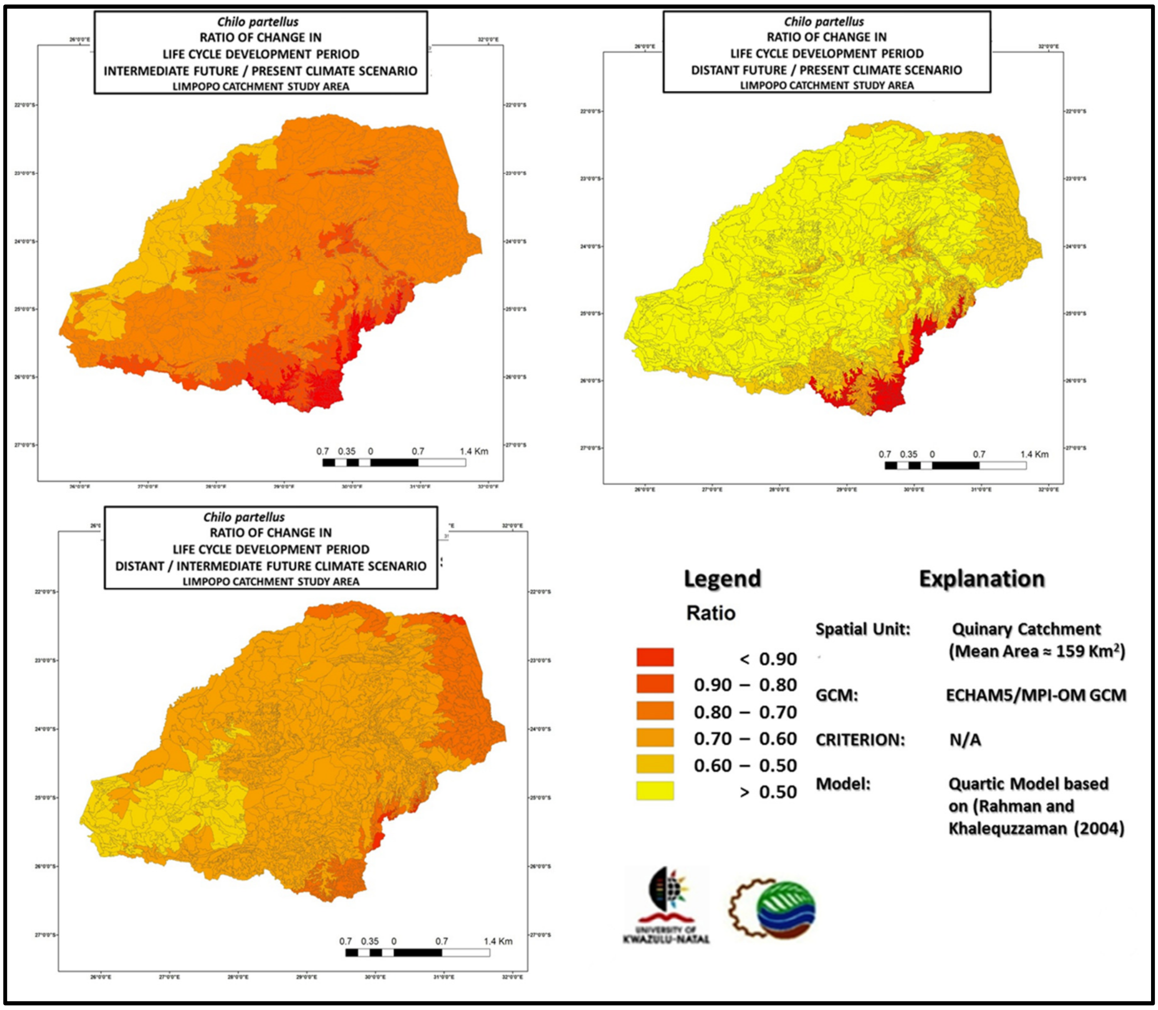

Figure 7.5 Ratio changes in the *C. partellus* life cycle development periods between the intermediate future and present (top left), the distant and intermediate future (bottom left) and the distant future and present (top right) climate scenarios from the ECHAM5/MPI-OM GCM

7.4 Distribution of Life Cycles per Annum of *Chilo partellus*

In **Figure 7.6**, the estimated number of *C. partellus* life cycles per annum under baseline climate conditions are shown to range from < 4 in central interior and along the southern border of Limpopo Catchment (i.e. in high altitude areas associated with lower temperatures; cf. **Figure 2.3**; **Figure 2.7**, respectively), to > 6 life cycles per annum along the northeastern border.

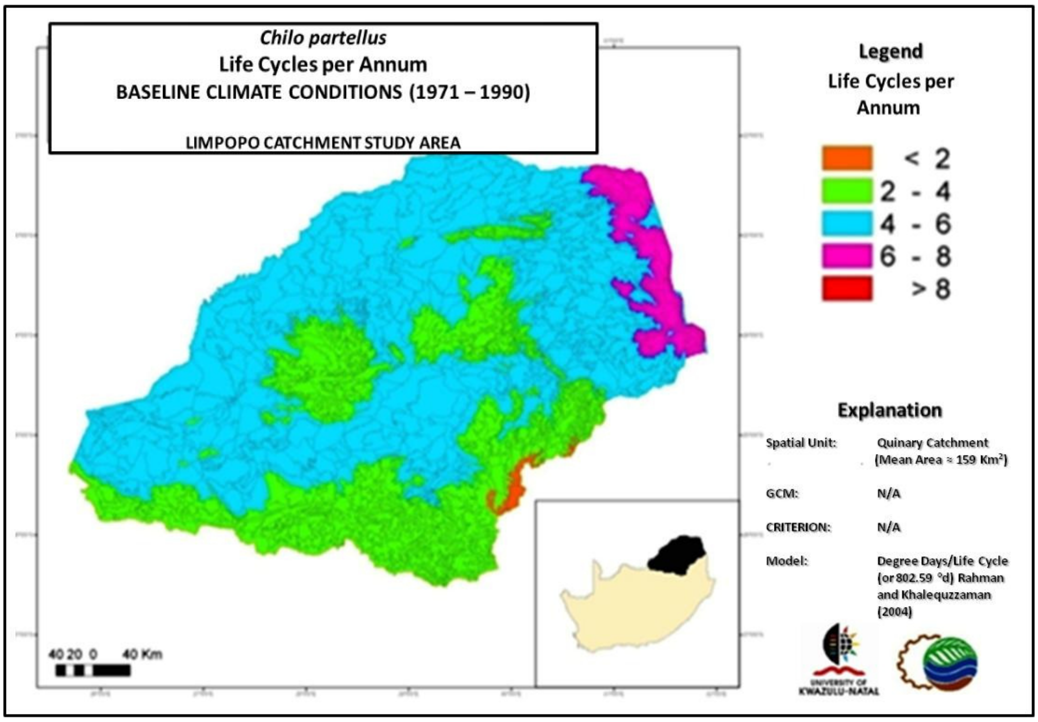

Figure 7.6 Mean number of life cycles per annum of *C. partellus* under baseline climate conditions

7.5 Validation of the ECHAM5/MPI-OM GCM's Output Against that of Baseline Climate Conditions for the Prediction of Annual Life Cycles of *Chilo partellus*

The validation analyses in this section, were undertaken to determine if *Chilo partellus* life cycles per annum derived from the ECHAM5/MPI-OM GCM's present climate scenario are representative of those from baseline climate conditions (i.e. from historical data assumed to be valid, cf. **Section 5.9.2**), for the same time period [1971 – 1990]. As in **Section 7.2**, the relative difference and regression analyses were used. The relative difference map indicates that the mean annual number of life cycles of *C. partellus* derived from the ECHAM5/MPI-OM GCM's present climate scenario closely mimicked those derived from baseline climate conditions. This is shown in **Figure 7.7**, which illustrates that the dominant proportion of the Limpopo Catchment displays differences of less than 10 %, which is within an acceptable range. Furthermore, in **Figure 7.8** the R^2 of 0.95 indicates a strong positive linear correspondence, while the slope of 0.98 is near perfect, confirming the validity of using the ECHAM5/MPI-OM GCM for this specific climate change impact study.

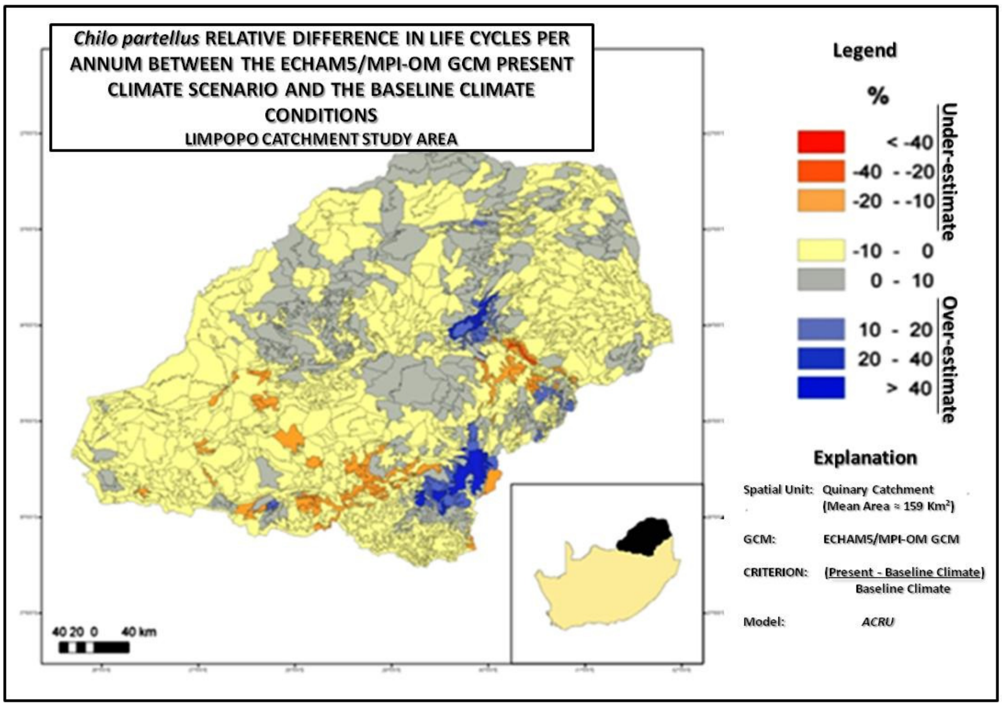

Figure 7.7 Relative difference in the number of *C. partellus* life cycles per annum generated from the ECHAM5/MPI-OM GCM's present climate scenario vs. that from baseline climate conditions

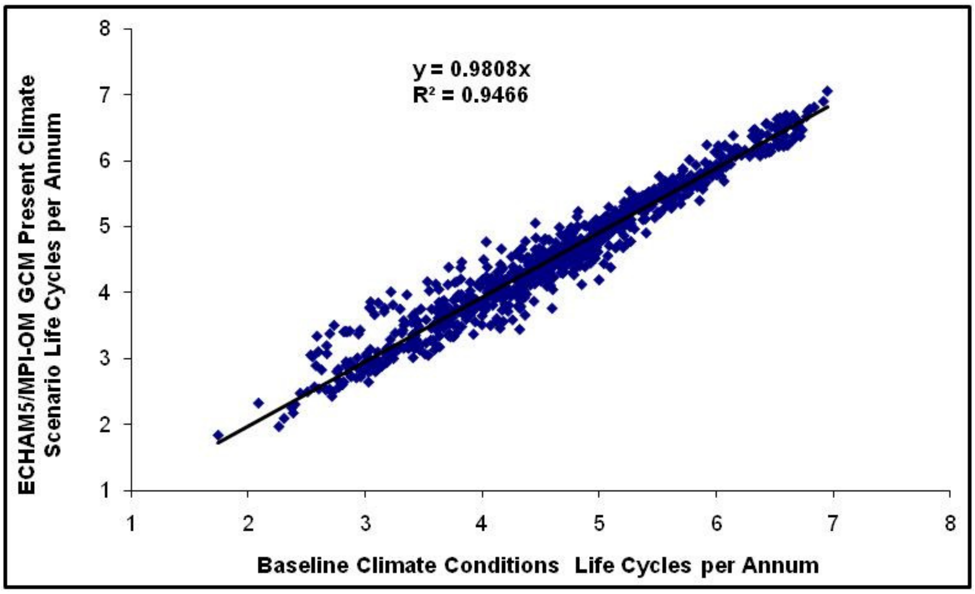

Figure 7.8 Relationship between the number of life cycles/annum of *C. partellus* generated from the ECHAM5/MPI-OM GCM's present climate scenario and baseline climate conditions for the same period [1971 – 1990], with each point representing results from a Quinary Catchment

7.6 Projections of Life Cycles per Annum of the *Chilo partellus* under Climate Change Conditions

If the prevailing temperature conditions were to increase as a result of to climate change, the number of *C. partellus* life cycles per annum should increase in response. This increase in the number of life cycles per annum is likely to be more pronounced where temperature tends to increase more rapidly. This hypothesis was tested by computing the projected number of *C. partellus* life cycles per annum over the Limpopo Catchment under future climate conditions using the ECHAM5/MPI-OM GCM's daily minimum and maximum temperature scenarios.

The life cycles per annum of *C. partellus* derived from the present climate scenario of the ECHAM/MPI-OM GCM (cf. **Figure 7.9**, top left) ranges from < 4 in the central interior and along the southern periphery of the Limpopo Catchment, to > 6 life cycles per annum along the northeastern border.

Projections of *C. partellus* life cycles per annum in the intermediate future (cf. **Figure 7.9**, bottom left) compared to those under the present climate scenario, suggest that areas with < 4 life cycles might shift towards the southeastern border and those with > 6 life cycles per annum expand along the northern border and toward the central interior of Limpopo Catchment. The more distant future climate projections of *C. partellus* life cycles per annum, shown in **Figure 7.9** (top right), indicate that areas with > 6 life cycles per annum in the intermediate future are likely increase to over > 8 life cycles per annum along the northern border, while those with < 4 life cycles along the southeastern border of the Catchment might increase to > 6 life cycle per annum.

The ratio change of life cycles per annum of *C. partellus* between the intermediate future and the present climate scenario (**Appendix D**: **Figure D.40**; not shown here because of length constriants), suggest an increase in the life cycle per annum ranging >10 % in the northeast to > 40 % along the southern border of the Limpopo Catchment. A similar increase in *C. partellus* life cycles is evident in the more distant future relative to the intermediate future climate scenario (**Appendix D**: **Figure D.42**). The ratio change in life cycles per annum in the distant future to present climate scenarios (**Appendix D**: **Figure D.41**) is likely to increase by > 30 % (a ratio of 1.30) along the northeast, to more than 80 % (a ratio of 1.80) along the southern border of the Limpopo Catchment.

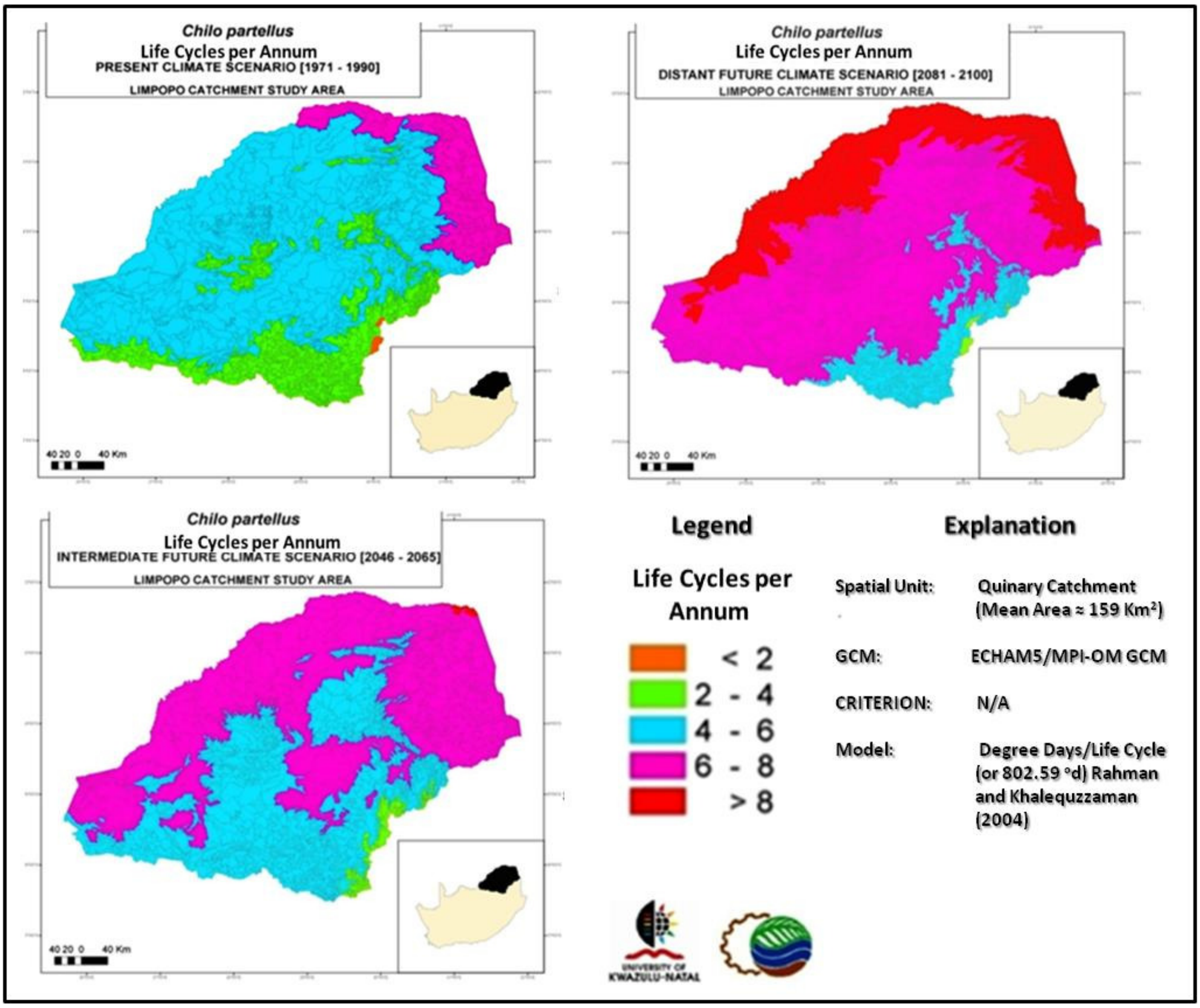

Figure 7.9 Mean number of life cycles per annum of *C. partellus* under present (top left), intermediate future (bottom left) and distant future (top right) climate scenarios of the ECHAM5/MPI-OM GCM

The spatial comparisons of projected *C. partellus* life cycles per annum for the intermediate future to present, the distant future to intermediate and the distant future to present climate scenarios, suggest an increase in the spatial distribution of the number of life cycles per annum. This increase from low to high altitude areas, i.e. from the northern to the southern parts of the Catchment. The analyses suggest a substantial potential increase in the pest's life cycles per annum over the Limpopo Catchment, which is more pronounced along the northern border.

7.7 Summary

A review of literature indicates that there is a relationship between temperature and the development of C. *partellus*. This relationship formed on the basis on which techniques were developed for predicting the distribution of *C. partellus*. The findings from the analysis indicate that *C. partellus* under baseline climate conditions would be more prevalent in the warmer northern periphery of the Limpopo Catchment, compared to the cooler areas in the central interior and the south, whereas under ECHAM5/MPI-OM GCM future climate scenarios the infestation distribution (or proliferation) was shown to expand towards the southern periphery of the Catchment.

An inference which can be drawn from these projections is that agricultural production areas (cf. **Chapter 6**) might be severely impacted by the potential proliferation of *C. partellus*, with overlapping life cycles over a growing season. This information is of importance in pest management.

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Having demonstrated a technique for determining the potential distributions of a yield-*reducing* pest, *viz. Chilo partellus,* in this chapter, a yield-*limitation* factor is discussed in the next chapter, *viz*. agricultural water use and productivity in the Limpopo Catchment, was accomplished using water accounting techniques.

8. EFFECTS OF PROJECTED FUTURE CLIMATE CHANGE ON AGRICULTURAL WATER USE AND PRODUCTIVITY

Having discussed the effects of climate change on an agricultural yield-*reduction* factor in the previous chapter, in this chapter water accounting techniques for analysing agricultural water uses and productivity in the Limpopo Catchment are discussed, with water being viewed as an agricultural-*limiting* factor. These techniques were adopted and used to assess water use and productivity at high spatial and temporal resolution, and for projecting future climate impacts (using ECHAM5/MPI-OM GCM scenarios) in the Limpopo Catchment.

8.1 Agricultural Water Use

The agricultural water use indicator in this study refers to that amount of water which is transpired by crops for production in relation to the total amount of water evaporating into the atmosphere. This definition was adopted from Molden (1997). The map of the agricultural water use (i.e. process fraction) under baseline climate conditions (**Figure 8.1**) indicates water use ratios ranging from < 0.46 to > 0.76, suggesting that up to three quarters of the water depleted from the Catchment is used for crop production (i.e. through the process of transpiration) and the remaining smaller portion is evaporated from the surface (which is considered to be non-beneficial). For the same time period simulations from the ECHAM5/MPI-OM GCM scenario (**Figure 8.2**, top left), i.e. for the present climate scenario [1971 – 1990], indicate similar water use patterns over most of the Catchment, apart from Quinaries mainly along central interior of the Catchment which display lower water use values, implying higher non-productive water depletion.

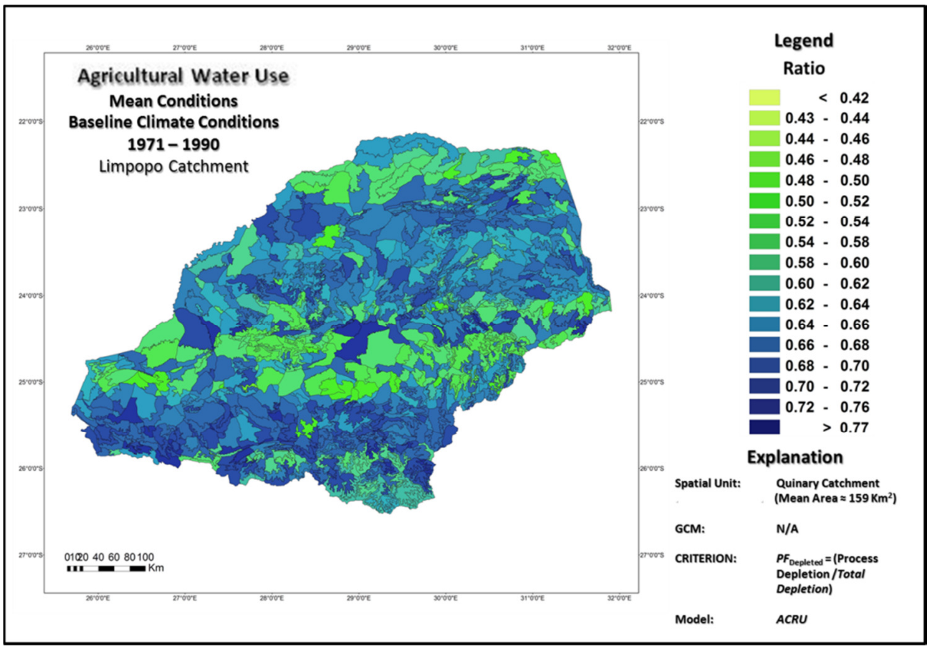

Figure 8.1 Mean annual agricultural water use under baseline climate conditions

The projections from the ECHAM5/MPI-OM GCM for intermediate [2046 – 2065] to distant [2081 – 2100] future climate scenarios (**Figure 8.2**, bottom left and top right, respectively), when compared to values for the present climate, indicate only slight overall changes across the Catchment (cf. **Table 8.1**). **Table 8.1** presents statistics for changes in the agricultural water use for the entire Catchment, and results suggest insignificant maximum increases of 6 % (i.e. a ratio of 1.06) and 8 % (i.e. a ratio of 1.08) for the intermediate and distant future climates, respectively, compared to the present climate scenario. Similarly, maximum reductions of about 12 % (i.e. a ratio of 0.88) are shown between distant future and present climate scenarios. The ratio of change maps in **Figure 8.3** capture this change in agricultural water use better with decreases in water use varying spatially across most the catchment between the time periods, i.e. ratios < 0.97. These analyses indicate the spatially variable responses from Quinary to Quinary which might be due to catchment conditions and the manner in which changes in climate might affect them. Furthermore, the projections from the ECHAM5/MPI-OM GCM suggest the productive water use to decrease over most of the Limpopo Catchment into the distant future.

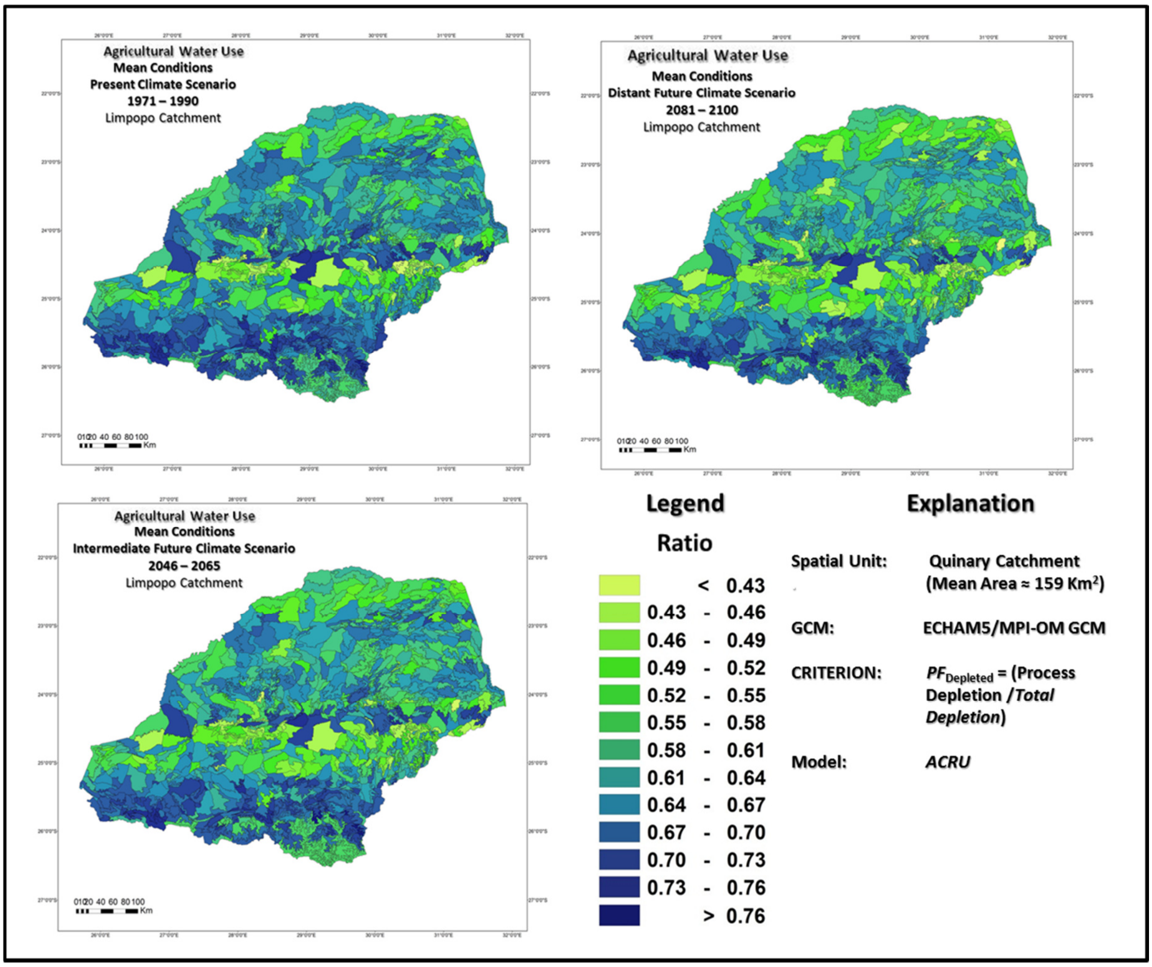

Figure 8.2 Mean annum depletion fraction under present (top left), intermediate future (bottom left) and distant future (top right) climate scenarios of the ECHAM5/MPI-OM GCM

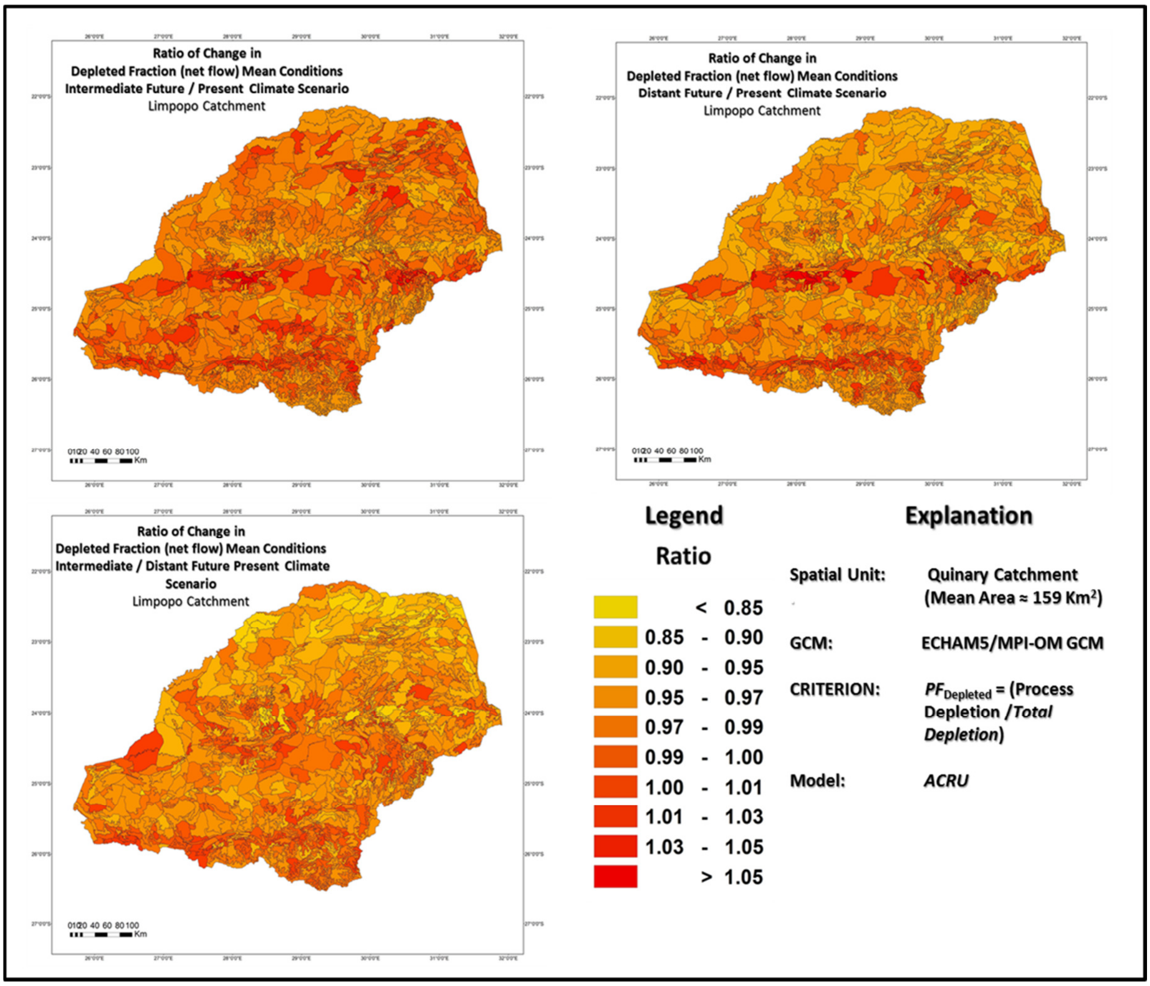

Figure 8.3 Ratio of change in mean annual depletion fraction under intermediate future / present (top left), intermediate / distant future (bottom left) and distant future / present (top right) climate scenarios of the ECHAM5/MPI-OM GCM

Table 8.1 ECHAM5/MPI-OM GCM projected ratio changes in the agricultural water use indicator for intermediate future to present and distant future to present climate scenarios within the Limpopo Catchment

Ratio Changes in Agricultural Water Use	Intermediate Future : Present Climate Scenario	Distant Future : Present Climate Scenario
Maximum	1.06	1.08
Median	0.98	0.97
Minimum	0.91	0.88

8.2 Agricultural Water Productivity

The agricultural water productivity under baseline climate conditions [1971 – 1990], shown in **Figure 8.4**, suggests a general gradient of water productivity from > 0.45 to < 1.20 $kg.m^{-3}$ from north to south within the Catchment. Note that the anomaly of < 0.20 $kg.m^{-3}$ ties in with a similar, anomaly found in **Chapter 6,** which is carried over to this analysis. It is reflective of the limitations in the logarithmic Rosenzweig (1968) equation for estimating NAPP when using lower annual actual evapotranspiration values outside those for which the equation was developed (cf. Rosenzweig, 1968). The ECHAM5/MPI-OM GCM's present climate scenario [1971 – 1990] indicates different spatial distributions and magnitudes of agricultural water productivity (**Figure 8.5**, top left) when compared to the simulation for baseline climate conditions. The GCM's present climate scenario's agricultural productivity of water ranges from a low of < 1.20 $kg.m^{-3}$ in the far northern periphery of the Catchment to > 2.45 $kg.m^{-3}$ along the southern periphery. These values are entirely beyond the range in **Figure 8.4** derived from baseline climate conditions (> 0.45 to < 1.20 $kg.m^{-3}$). This is hypothesised to be the result of higher net above-ground primary production under baseline climate conditions vs. production derived from GCM's present climate scenario (**Chapter 6**).

The future projections for intermediate (**Figure 8.5**, bottom left) and distant (**Figure 8.5**, top right) future climates, suggest increases in the agricultural water productivity, but more so along the southern periphery of the Catchment. The increase relative to the present climate scenario, shown as ratio of change in **Figure 8.6**, is more pronounced in the distant future than in the intermediate future climate projections, with the highest increase within Quinary Catchments being 40 %, i.e. a ratio of 1.40 (**Table 8.2**).

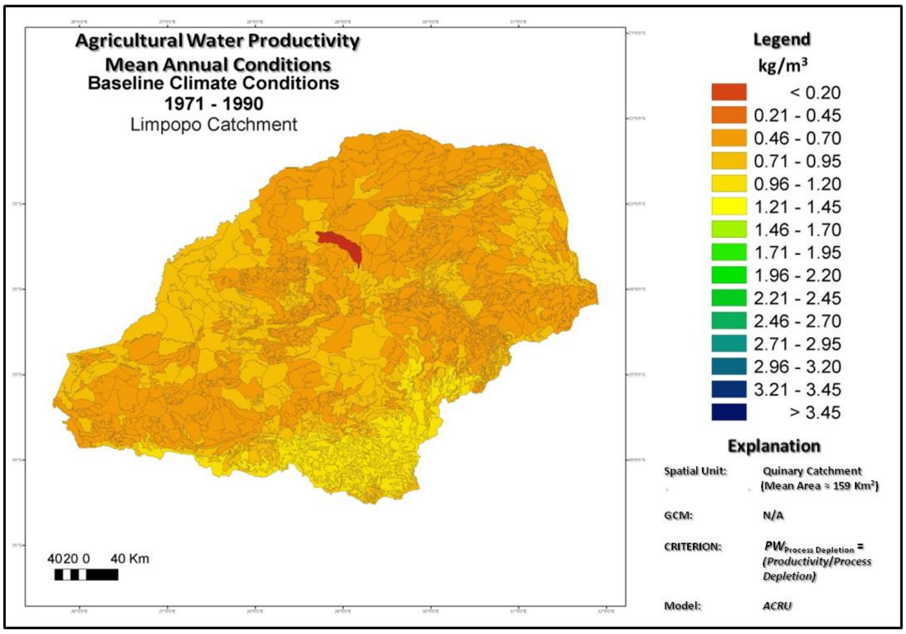

Figure 8.4 Mean annual agricultural water productivity under baseline climate conditions

Table 8.2 ECHAM5/MPI-OM GCM projected ratio changes in the agricultural water productivity for intermediate future to present and distant future to present climate scenarios within the Limpopo Catchment

Ratio Change in Agricultural Water Productivity	Intermediate Future : Present Climate Scenario	Distant Future : Present Climate Scenario
Maximum	1.24	1.47
Median	1.07	1.22
Minimum	0.89	0.92

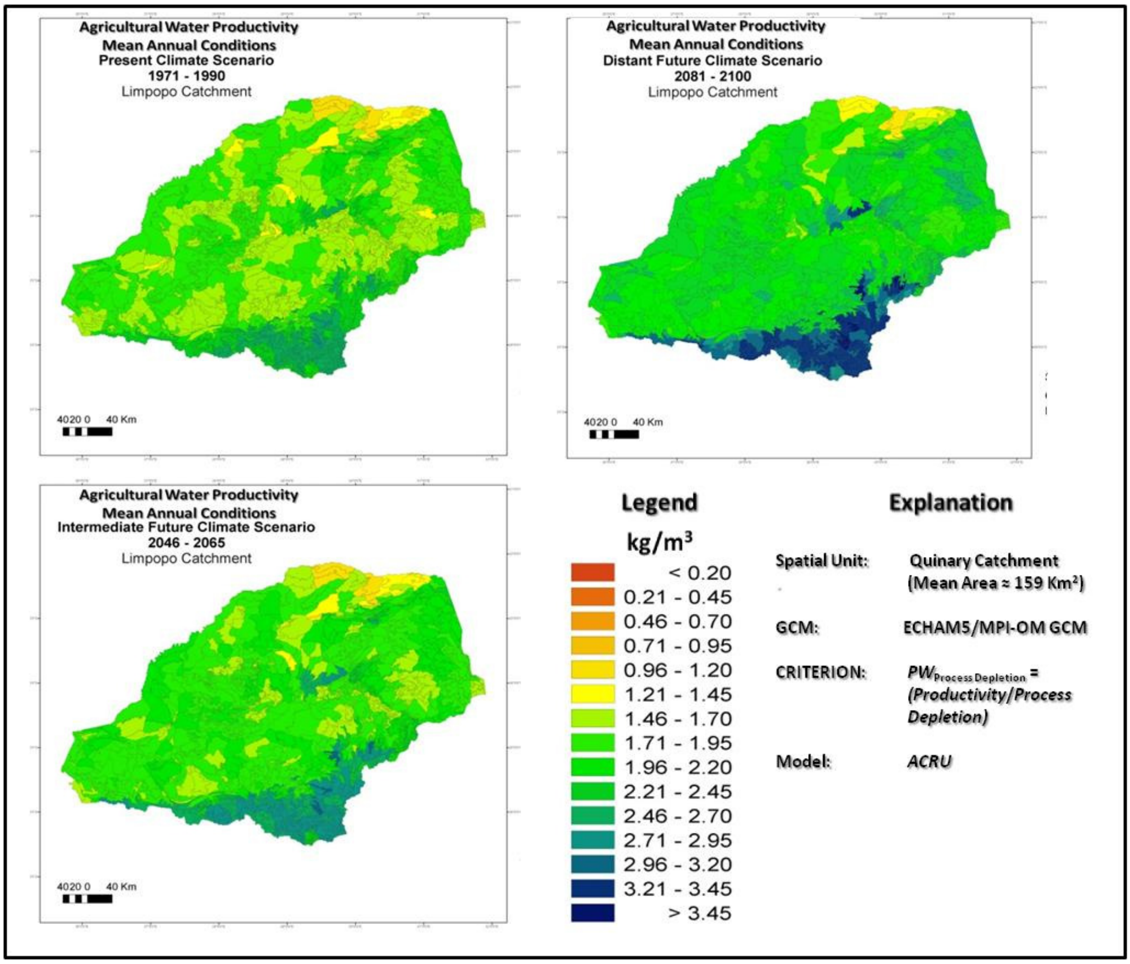

Figure 8.5 Mean annual agricultural water productivity under present (top left), intermediate future (bottom left) and distant future (top right) climate scenarios of the ECHAM5/MPI-OM GCM

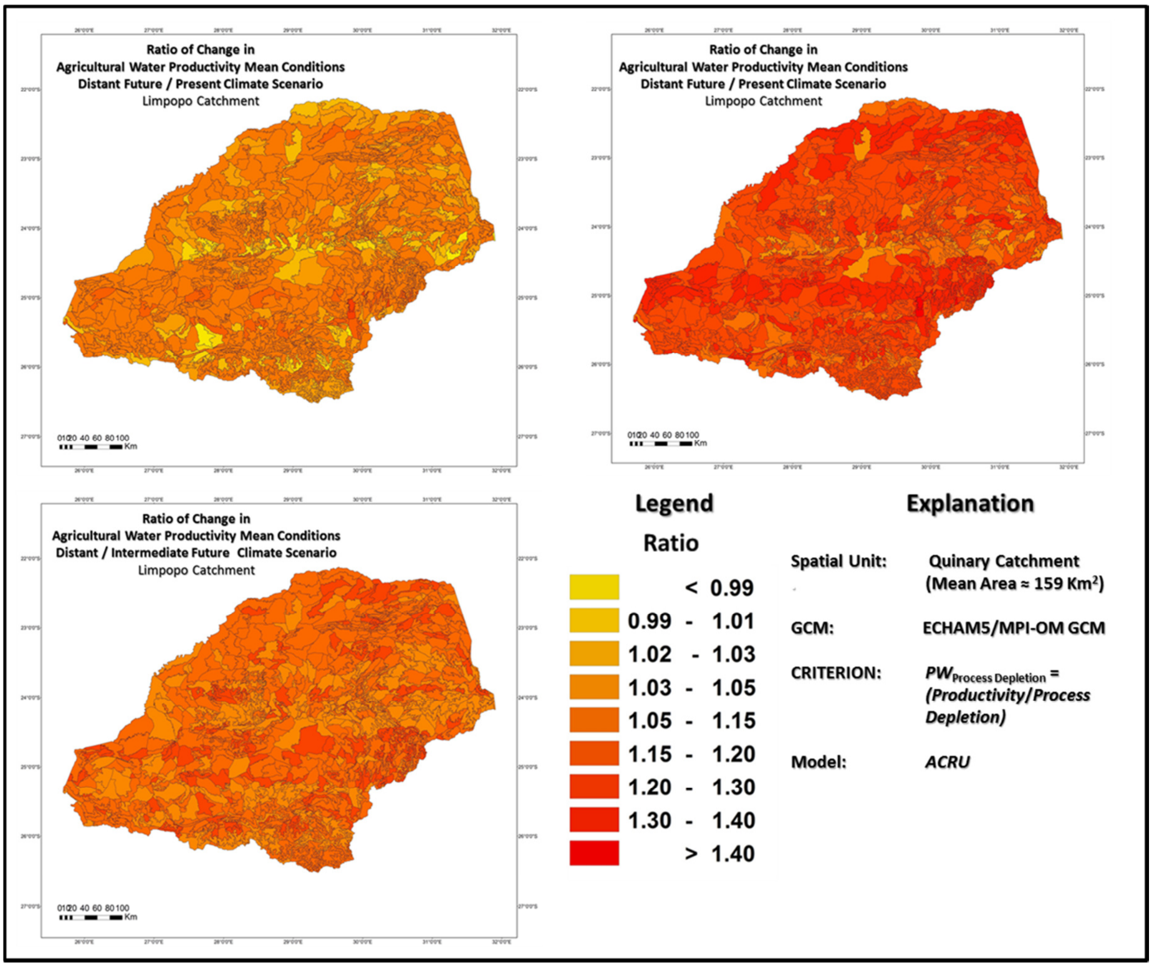

Figure 8.6 Ratio of change in mean annual depletion fraction under intermediate future / present (top left), intermediate / distant future (bottom left) and distant future / present (top right) climate scenarios of the ECHAM5/MPI-OM GCM

8.3 Summary

The findings of the climate projections from the ECHAM5/MPI-OM GCM suggest an increase in the agricultural water productivity for the intermediate future and more so for the distant future climate scenarios (cf. **Figure 8.5**; **Table 8.2**), mainly along the southern periphery of the Catchment. The agricultural water use under ECHAM5/MPI-OM GCM projections will decline generally over most of the Catchment from present through to distant future climate scenarios, with a slightly increases in parts across the Catchment (cf. **Figure 8.2**; **Table 8.1**).

The analysis over time from the intermediate to the distant future suggests an decrease in the agricultural water use and an increase water productivity over the Catchment with the ECHAM5/MPI-OM GCM. What is not known at this stage is whether this is an artifact of this particular GCM or whether it is an overall trend.

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In the **Chapter 9**, which follows, the overall conclusions on the findings from the analyses conducted in this dissertation, and which were set out in the objectives stated in **Chapter 1**, are discussed. Furthermore, the applications of techniques developed from this study and recommendations regarding future research studies on agricultural impact assessment are also discussed.

SECTION FIVE: CONCLUSIONS

9. CONCLUSIONS

Recent climate change detection studies, particularly in the southern African region, indicate a likely increase in surface air temperature and in spatial variations in changes in precipitation characteristics (cf. **Chapter 1**). The increases in global temperature regimes are attributed to increases in anthropogenically induced greenhouse gas emissions of (mainly) carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphurhexafluoride (SF_6). There is high confidence in climate science research that some of the likely effects of climate change on hydrological and terrestrial biological systems are already taking place around the world. These are projected to be further enhanced into the future, as the emission scenarios suggest that greenhouse gas levels are likely to increase significantly, unless mitigation of emissions is successful (**Chapter 1**).

Impact assessment studies suggest that semi-arid regions, such as the Limpopo Catchment, are likely to experience agrohydrological changes when compared to current climate conditions; this is due to the region already being subjected to climate stresses (**Chapter 2**) and poor production systems (**Chapter 3**). The effects of climate change will significantly affect the distribution, condition, composition and productivity of agricultural crops and water for agriculture, including pests, diseases and invasive alien plants. The degree of the impact of climate change on the Limpopo Catchment's agrohydrological responses depends on a number of factors, some of which are its location, climate and present land conditions. In the following section key conclusions of the impact assessments conducted using statistical modelling and analysis techniques are presented.

9.1 Conclusions on the Assessment of the Effects of Projected Future Climate Change on Agricultural Production as well as Agricultural Yield-*Reduction* and Yield-*Limiting* Factors

Estimated agricultural production (AP) in this study was represented by net above-ground primary production (NAPP), the reason for this being that the NAPP values were found, from reviewing international literature, to be closely related to yields of certain crops (**Chapter 3**). Net above-ground primary production was therefore applied as an indicator of agricultural crop and livestock-pasture productivity. NAPP was estimated with the *ACRU* model for dryland production systems assuming Acocks' (1988) Veld Types to represent the baseline land cover (i.e. natural vegetation) over the Limpopo Catchment. It should be kept in mind that present land uses go beyond natural vegetation and include agricultural crops, pastures and plantations, as well as build up areas.

The analyses of estimated AP from baseline climate conditions indicate a relationship with altitude, and hence precipitation, as well as with temperature, especially in the southeastern parts of the Limpopo Catchment. The year to year variability in production is more evident in the dry and wet years, mainly in areas of low production associated with low altitudes and low rainfall, i.e. along the northern and northeastern boundary of the Limpopo Catchment. Inter-annual fluctuations in production shown by the year to year variability of NAPP, generally indicate that the relative to actual harvestable yields are higher in more arid climates, towards northern parts of the Catchment (**Chapter 6**).

Validation analyses indicate that the AP estimated from the ECHAM5/MPI-OM GCM's present climate scenarios represents that derived from the historically observed climate conditions with acceptable accuracy, and hence was considered to adequately represent the prevailing climate conditions.

Temperature and precipitation are important variables because they indicate areas that are conducive to higher or lower estimates AP. The analyses on the effects of average annual temperature and mean annual precipitation on estimated AP displayed associations within the Limpopo Catchment. A strong positive correlation was observed for estimated AP vs. mean annual precipitation, hence implying that estimated AP would increase with an increase in this climate variable. However, the relationship between mean annual temperature and estimated AP was a weak negative correlation, implying that the estimated AP would decrease with increases in temperature, but without high predictive certainty.

The mean annual NAPP in the Limpopo Catchment was projected under the ECHAM5/MPI-OM GCM climate scenarios to increase, mainly in the southern and eastern periphery, from the present to the intermediate future and through to the distant future climate scenario. Ratio change analyses indicate that the NAPP under the intermediate future climate scenario might increase by over 50 % in places, relative to NAPP under the present climate scenario. The results of the impacs assessment of the mean annual Percentage of Potential Production (PPP) indicate a slight increase in the southern portion of the Catchment, with the ratio changes from the distant future climate scenario to the present in this region being above 10 %. For reasons of constraints to the length of the main body of this dissertation, these results are presented in **Appendix C**.

The general positive projections of estimated AP could be attributed to the ECHAM5/MPI-OM GCM's indicating that future climate conditions might be wetter than the prevailing conditions. This, however, may be shown not necessarily to be the case when outputs from multiple GCMs are used.

Distribution patterns of an agricultural *yield reduction* factor, *Chilo partellus* Spotted Stemborer, were assessed using development periods based a 4th order quartic polynomial equation and the number life cycles. The equation was developed to estimate various development periods of the *C. partellus* life cycle (i.e. the time taken by *C. partellus* to emerge or survive each development stage; **Chapter 5**). The limitation of the equation is that it is valid only within the temperature ranges between 15 and 35 ^{o}C. The *C. partellus* life cycle development period under baseline climate conditions over the Limpopo Catchment was predicted to range from 60 days in the northern portion of the Catchment to over 100 days in the southern and middle portions. The longer development periods (> 100 days) were due to lower temperature regimes in high altitude regions.

Validation analyses indicated a strong correlation between the GCM's present climate scenario predictions of the *C. partellus* life cycle development period and those from the historically observed climate conditions. Based on this validation analysis, it was concluded that the ECHAM5/MPI-OM GCM's present climate scenarios were representative of the baseline climate conditions of the *C. partellus* life cycle development period in the Catchment.

The projected development time periods for the *C. partellus* life cycle distributions indicate a reduction in the number of days required to complete development from the northern to the southern borders of the Catchment. The greatest relative decline in the development time periods is projected to be in high altitude regions, mainly along the southern periphery of the Limpopo Catchment. Thus, the ECHAM5/MPI-OM GCM scenarios suggest that the development of *C. partellus*, when based on climatic criteria, will be shortened in response to a warmer human-induced climate change. The projected decrease in *C. partellus* life cycle development periods are in line with the findings by Collier *et al.* (1991) and Fuhrer's (2003) projections of early pest occurrences and expansion and /or shifts in pest infestations in future.

The number of potential *C. partellus* generations expected in a growing season were, in this study, determined from the number of degree days required to complete a generation. The baseline climate condition simulations thereof show that in an average year there were more *C. partellus* generations along the northern portion of the Catchment, compared to those in the moderate to high relief regions along the southern border. The ECHAM5/MPI-OM GCM climate scenarios projected that the number of generations would increase into the future from the northeastern to the southern border of the Catchment.

The projected decrease in the *C. partellus* life cycle development periods and the increase in the number of generations per annum are consistent with expectations (i.e. shorter development periods will result in increased number of generations in a season).

Projections of the mortality index of *C. partellus* (cf. **Appendix D**) using ECHAM5/MPI-OM GCM climate scenarios indicated a reduction in the number of days per annum in the Catchment from north to south. A similar distribution pattern in the mortality indices were evident in the seasonal analyses, also shown in **Appendix D**.

In a study similar in approach to that of *C. partellus*, the author developed a model for, and undertook an assessment of, the *Striga asiatica* witch weed for different present and projected climate conditions in the Limpopo Catchment. For reasons of length constraints of this dissertation, the *S. asiatica* results are not discussed in the main document, but are presented in detail in **Appendix E**.

Projections from ECHAM5/MPI-OM GCM future climate scenarios signal a higher likely prevalence of *C. partellus* and *S. asiatica* than under baseline climate conditions. This might translate to more crop yield losses when compared to losses under present climates, as well as the potential introduction of yield reducing factors to new areas.

Having concluded on the projected effects of an agricultural yield-*reduction* factor, what follows are conclusions on agricultural water use and productivity, with water being viewed as an agricultural-*limiting* factor. The agricultural water use indicator for baseline climate conditions displays a spatial variation of water use across the Limpopo Catchment with over half of the water depleted being for agricultural crop production (transpiration), and the rest for non-productive use (evaporation from the soil surface). This high water use was projected to decline into the future under ECHAM5/MPI-OM GCM climate scenarios, over most of the Catchment. The results therefore suggest that most parts of the Catchment will display less productive water use under projected future climate conditions.

The agricultural water productivity indicator for baseline climate conditions is slightly lower over most of the Limpopo Catchment, compared with that derived from the ECHAM5/MPI-OM GCM's present climate scenario. However, agricultural water productivity displays a similar trend of increase from the northern to the southern periphery of the Limpopo Catchment, under both baseline climate conditions and the ECHAM5/MPI-OM GCM's present climate scenario. The agricultural water productivity is projected under the ECHAM5/MPI-OM GCM's climate scenario to increase in the intermediate future and to be more pronounced in the distant future climate scenario.

Similarly, over time the agricultural water use is projected to decrease over most parts of the Limpopo Catchment. However, the actual quantity of water available for estimated AP in the Catchment is likely to be lower than projected, as water already is allocated to other water users which were not accounted for in this study. Furthermore, even though under the present climate conditions the water resources are simulated to sustain agricultural productivity, in response to projected future climates the productivity could be reduced when the water demand from other in the Catchment increases to the extent that it exceeds the supply.

Ideally a wide range of GCM climate change projections should be used to represent a probability distribution of likely future climatic conditions, because each GCM is based on slightly different process representations in reflecting plausible future climates, and in order to account for the uncertainties in climate projections as a result of human-induced greenhouse gas emissions. Thus, the conclusions drawn above should to be used with caution.

The projected effects of climate change suggest that areas located at higher altitudes with prevailing lower temperature and higher rainfall conditions in the Limpopo Catchment are likely to experience higher estimated AP of host crops, higher water productivity and also more occurrences of infestations of yield-*reduction* factors under the projected ECHAM5/MPI-OM GCM climate conditions.

9.2 Possible Implications of Scenarios of Climate Change on Estimated agricultural production in Limpopo Catchment

Conclusions drawn from the results of this impact assessment were that the potential distribution patterns in estimated AP are sensitive to the projected changes in climate conditions, both spatially and temporally, and more so in the southern and eastern parts of the Limpopo Catchment than eslewhere, and that the threshold of change might be more pronounced in the south as compared to the northern portion of the Catchment.

More incidences of *C. partellus* generations per annum are evident along the hotter northern border of the Catchment than elsewhere under baseline climate conditions, and the number of generations per annum are projected to increase under future climate scenarios. Similarly, the number of generations per annum of *C. partellus* are likely to increase towards the southern border of the Limpopo Catchment. The mortality index and the various development time periods are projected to reduce throughout the Catchment. These results are presented in **Appendix D**. The higher projected estimated AP under the intermediate and distant future climate scenarios might, however, be negated by increased incidences of the agricultural yield-*reduction* factor, considering the likely increase in the number of *C. partellus* generations in a season, the shorter development times of different stages of its life cycle (presented in **Appendix D**) and longer survival periods.

9.3 Applications of the Research Techniques and the Findings

The algorithms developed by the author are applicable in different climatic regions and could therefore be used in other locations across South Africa.

The relationship between NAPP and climate factors established in this study could serve as an indicator of the effects of global change and of variations in climate. Furthermore, the NAPP techniques applied in this dissertation could be used as an indicator of overall estimated AP in an area, particularly in scoping studies.

The techniques developed in this study form a stepping stone in the assessment of agricultural yield *reduction* factors, their distributions patterns and hence their management. For example, the estimation techniques for the distribution of *C. partellus* might be used in policy-making concerning the management of this pest, and might further be applied in improving the efficiency and effectiveness of pesticide applications, as well as biological control methods.

9.4 Recommendations for Future Impact Assessments

The main recommendation emanating from this study on future impact analyses is for the use of climate scenarios from multiple state-of-the-art GCMs. This would better capture the direction of projected future climate impacts resulting from human-induced increases in greenhouse gas emissions. This recommended use of outputs from more GCMs stems from the differences in their projections of future climate conditions. Multiple scenarios provide a range of plausible futures, hence a better estimation range of future climate conditions. The techniques developed and presented in this study should therefore be assessed with outputs from further GCMs as and when they become available at appropriately fine spatial scales. The reason for re-assessment with new and improved GCMs is that the more updated the GCMs are (i.e. with more detailed incorporations of land-sea-atmospheric interactions and other parameters), the smaller the range of uncertainty is likely to be.

Further detailed studies on the relationships between pests and their natural environment and under controlled experiments, could improve the algorithms for simulating the life cycles and their relationship with host plants. The more parameters that are established as a result of further studies, especially in regard to natural environmental interactions, the more accurate the predictions of distribution patterns and development will be.

The techniques developed could, further, be applied to other pests and diseases. In this regard the attention of the reader is drawn to the research undertaken by the author on the development of algorithms for *Striga asiatica*, i.e. witchweed, the results of which are presented for different climate scenarios in the **Appendix E**.

The research in this dissertation has focused on the Limpopo Catchment. However, the techniques developed are of a generic nature and should, in future studies, therefore be applied to the entire South Africa

Finally, in light of the current awareness on climate change, the outcomes of studies such as this one can be used as the scientific basis for adaptation strategies.

9.5 Contributions of this Research

Improvements to modeling, made as part of this research were on the selection of Quinary Catchments rainfall 'driver' stations, specifically in the Limpopo Catchment (cf. **Chapter 5**), which enabled agrohydrological modelling to be performed at high spatial resolution using Quinary level response zones.

The main new contributions emanating from this research are on the techniques for predicting the potential prevalence rates as well as the spatial and temporal distribution patterns of the *C. partellus* Spotted Stemborer, i.e. its development periods and life cycles. The techniques developed have the potential to be used in forecasting short- and long-term (i.e. with projected future climate) impacts of the agricultural yield-*reduction* factor, based on climate information. The parameters used in developing these techniques make them applicable generically, because they are not area-specific.

Furthermore, a new contribution was made on the spatial estimation of the amount of water resources available particularly for agricultural water use and water productivity. These methods of simulating water availability and productivity could be applied in other water use sectors and in other parts of South Africa.

SECTION SIX: REFERENCES

10. REFERENCES

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SECTION SEVEN: APPENDIXES

APPENDIX A: TERRAIN MORPHOLOGY

The following table displays the characteristics of the Limpopo Catchment's terrain morphology.

Table A.1 Terrain morphology attributes found in the Limpopo Catchment (After Kruger, 1983)

Broad Division		**Class**	**Description of Subdivision**	**Slope Form**	**Relief (m)**	**Drainage Density ($km.km^{-2}$)**	**Stream Frequency (streams km^{-2})**	**% Area with Slopes < 5%**
Plains; low relief	A	1	Plains	Straight	0-30	Low-medium, 0-2	Low-medium, 0-6	>80
		2	Plains and pans					
			Slightly undulating plains	concave/ convex				
Plains; moderate relief	B	5	Slightly irregular plains	concave/ straight	30-210			
		7	Extremely irregular plains			High, 2-3.5	High, 6-10.5	
		8	Slightly irregular undulating plains (some hills)	concave/ convex		Low-medium, 0-2	Low-medium, 0-6	
		9	Moderately undulating plains					
		10						
		11						
Lowlands, hills and mountains;	C	12	Lowlands and hills	concave/ straight	30-450			50-80
		13	Lowlands					

moderate and high			and parallel hills					
		16	Lowlands with mountains		450+			
Open hills lowlands, mountains; moderate to high	D	18	Hills and lowlands			Medium, 0.5-2		
		20	Undulating hills and lowlands		130-450			
Closed hills, mountains; moderate and high relief	E	23	Hills					
		27	Low mountains		450-900			
		29	High mountains		900+		Medium-high 1.5-10.5	20-50
Table-lands; moderate and high relief	F	30	Table-lands	concave/ straight	130-900	Medium 0.5-2		<80

APPENDIX B: AGRICULTURAL PRODUCTIVIY

The following maps show of ratio changes in the net above-ground primary production (NAPP) with climate projections in the Limpopo Catchment, and the tables display summarised statistics of the NAPP for each of the four Water Management Areas (WMA; cf. **Figure 2.1**). NAPP is estimated from the Rosenzweig (1968) equation, embedded within the *ACRU* model (cf. **Chapter 6**).

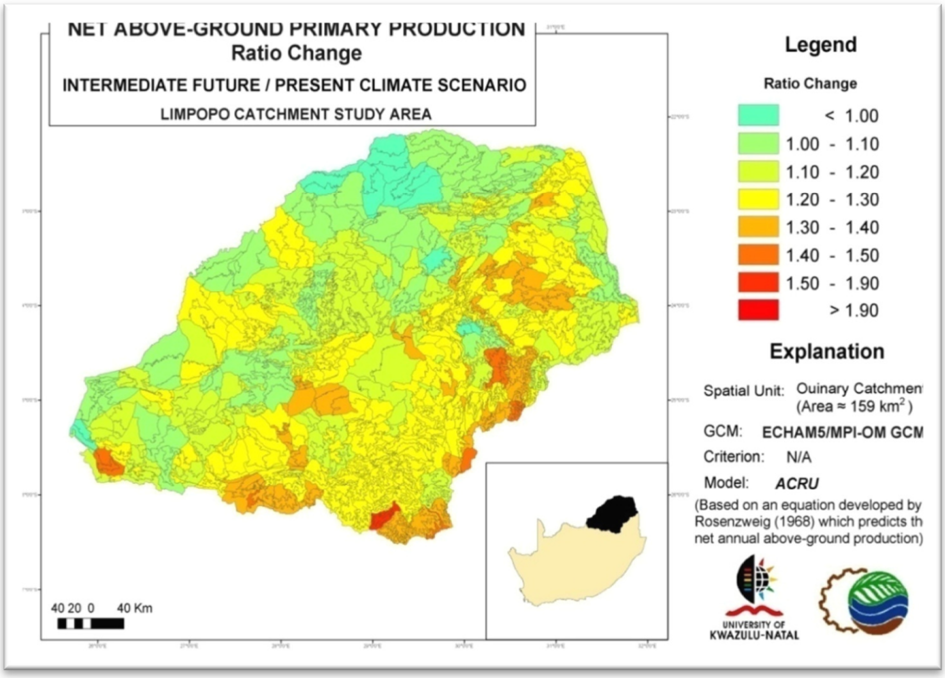


Figure B.1 Ratio changes in net above-ground primary production: ECHAM5/MPI-OM GCM's intermediate future / present climate (Source information: BEEH, 2010)

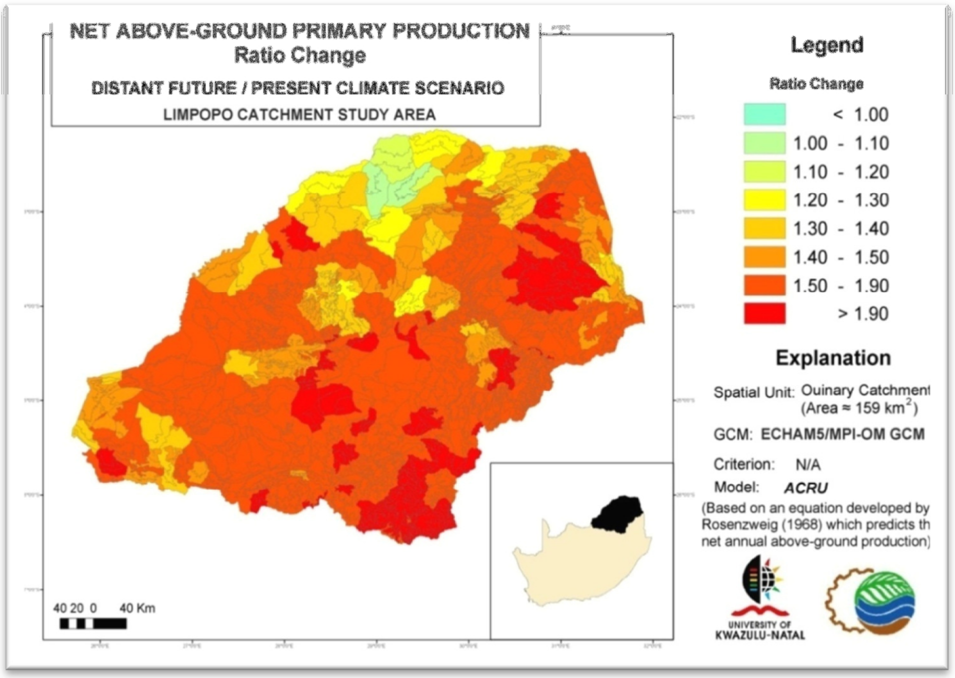


Figure B.2 Ratio changes in net above-ground primary production: ECHAM5/MPI-OM GCM's distant future / present climate (Source information: BEEH, 2010)

Table B.1 Summarised statistics of net above-ground primary production ($t.ha^{-1}.season^{-1}$) for the Water Management Areas in the Limpopo Catchment for baseline climate conditions

Limpopo Catchment Water Management Areas	**Net Above-Ground Primary Production Baseline climate condition [1971 – 1990]**							
	Mean Value	**Standard Deviation**	**Coefficient of Variation (%)**	**Maximum Value**	**Minimum Value**	**Exceedence Probability**		
						10%	**50%**	**90%**
Limpopo	3.87	1.46	37.70	7.64	1.10	2.02	3.76	5.97
Luvuvhu and Letaba	4.87	1.92	39.32	9.02	1.20	2.59	4.76	7.35
Crocodile (West) and Marico	4.67	1.74	37.18	8.49	1.42	2.58	4.55	6.94
Olifants	5.22	1.59	30.44	8.67	1.86	3.22	5.19	7.27

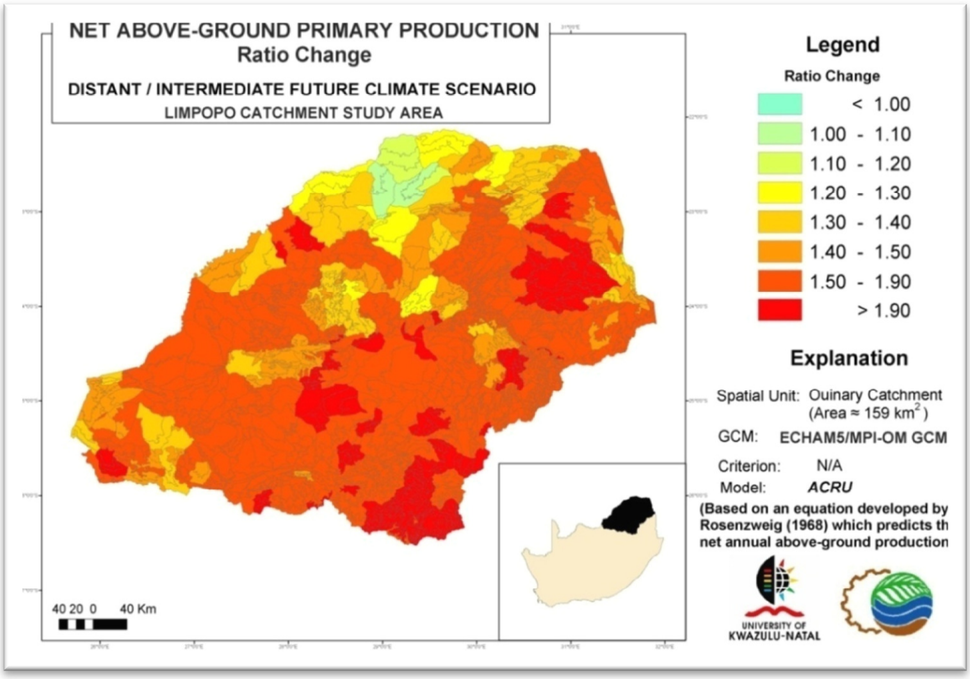


Figure B.3 Ratio changes in net above-ground primary production: ECHAM5/MPI-OM GCM's distant / intermediate future climate (Source information: BEEH, 2010)

Table B.2 Summarised statistics of net above-ground primary production ($t.ha^{-1}.season^{-1}$) for the water management areas in the Limpopo Catchment for the ECHAM5/MPI-OM GCM's present climate scenario

Limpopo Catchment Water Management Areas	**Net Above-Ground Primary Production Present Climate Scenario [1971 – 1990]**							
	Mean Value	**Standard Deviation**	**Coefficient of Variation (%)**	**Maximum Value**	**Minimum Value**	**Exceedence Probability**		
						10%	**50%**	**90%**
Limpopo	3.77	1.26	33.31	6.69	2.00	2.35	3.53	5.87
Luvuvhu and Letaba	5.32	1.55	29.13	8.91	3.07	3.61	5.13	7.62
Crocodile (West) and Marico	4.11	1.18	28.71	7.22	2.21	2.73	3.89	6.03
Olifants	4.57	1.18	25.77	7.61	2.73	3.15	4.39	6.49

Table B.3 Summarised statistics of net above-ground primary production ($t.ha^{-1}.season^{-1}$) for the Water Management Areas in the Limpopo Catchment for the ECHAM5/MPI-OM GCM's intermediate future climate scenario

Limpopo Catchment Water Management Areas	Net Above-Ground Primary Production Intermediate Future Climate Scenario [2046 – 2065]							
	Mean Value	Standard Deviation	Coefficient of Variation (%)	Maximum Value	Minimum Value	Exceedence Probability		
						10%	50%	90%
Limpopo	4.30	1.46	33.98	7.44	2.00	2.50	4.27	6.30
Luvuvhu and Letaba	6.39	1.70	26.55	9.63	3.58	4.27	6.25	8.55
Crocodile (West) and Marico	4.93	1.45	29.38	8.16	2.48	3.22	4.73	7.00
Olifants	5.75	1.51	26.20	8.97	3.13	3.97	5.58	7.84

Table B.4 Summarised statistics of net above-ground primary production ($t.ha^{-1}.season^{-1}$) for the Water Management Areas in the Limpopo Catchment for ECHAM5/MPI-OM GCM's distant future climate scenario

Limpopo Catchment Water Management Area	Net Above-Ground Primary Production Distant Future Climate Scenario [2081 – 2100]							
	Mean Value	Standard Deviation	Coefficient of Variation (%)	Maximum Value	Minimum Value	Exceedence Probability		
						10%	50%	90%
Limpopo	5.74	1.78	32.71	9.76	3.16	3.63	5.56	8.11
Luvuvhu and Letaba	8.66	2.22	28.43	13.24	5.06	5.70	8.61	11.56
Crocodile (West) and Marico	6.75	1.89	28.48	11.33	3.87	4.57	6.58	9.23
Olifants	8.22	2.10	26.46	12.55	4.71	5.70	8.13	10.90

APPENDIX C: PERCENTAGE OF POTENTIAL PRODUCTION

This section on percentage of potential production (PPP) is an addition to **Chapter 6** on agricultural production over the Limpopo Catchment. This PPP was used to estimate yields relative to potential production.

C.1 Estimation of Percentage of Potential Production

The Albrecht equation of annual estimating PPP, "relates soil water supply to soil water demand of crops to predict the yields, this assumption is based on numerous tested indices from detailed study in USA of agricultural production and potential" (Schulze, 2007: 2). The equation best estimates crop yields in relation to the potential production (Schulze, 1995), is expressed by

$$P_{pp} = \left(\frac{E_{\mathrm{se}}}{E_{mse}}\right) - 100 \quad \text{(C.1)}$$

Where, $P_{pp} = percentage\ of\ potential\ production\ in\ a\ growing\ season;$

$E_{\mathrm{se}} = total\ evaportion\ for\ a\ growing\ season\ (mm); and$

$E_{mse} = maximum\ evaporation\ (mm) for\ the\ growing\ season\ (mm).$

The Albrecht (1971) equation is a ratio of supply to demand, with the low PPP values being due to soil water deficiencies, which would mean long periods of plant stress. For this reason, the Albrecht (1971) equation could be used to identify climatic regions experiencing dry spell(s) that might be harsh for crop production (Schulze, 1995).

C.2 Distribution of the Percentage of Potential Production Patterns over the Limpopo Catchment

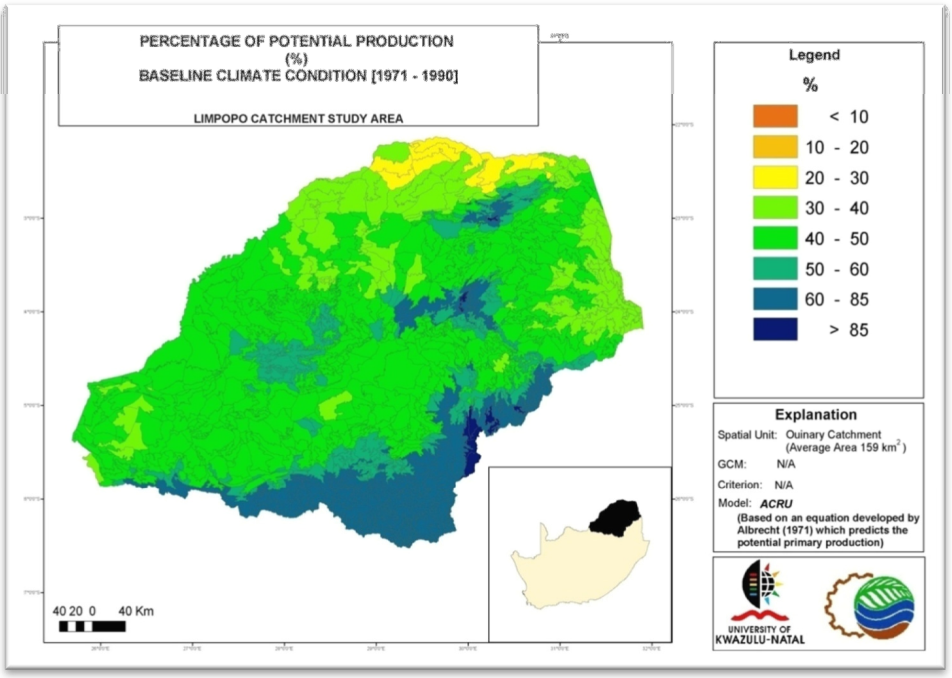


Figure C.1 Mean of the percentage of potential production per annum for baseline climate conditions (Source information: BEEH, 2008)

Table C.1 Summarised statistics of the percentage of potential production (%) for Water Management Areas in the Limpopo Catchment for baseline climate conditions

Limpopo Catchment Water Management Area	Percentage of Potential Production Present Climate Scenario [1971 – 1990]							
	Mean Value	Standard Deviation	Coefficient of Variation (%)	Maximum Value	Minimum Value	Exceedence Probability		
						10%	50%	90%
Limpopo	44.61	9.51	21.31	6.6940	30.33	33.53	43.34	57.90
Luvuvhu and Letaba	52.32	9.25	17.68	8.9101	37.33	40.91	52.17	61.21
Crocodile (West) and Marico	47.57	9.66	20.31	7.2237	32.58	36.82	46.11	61.31
Olifants	55.29	9.94	17.99	7.6136	39.60	43.64	54.27	68.11

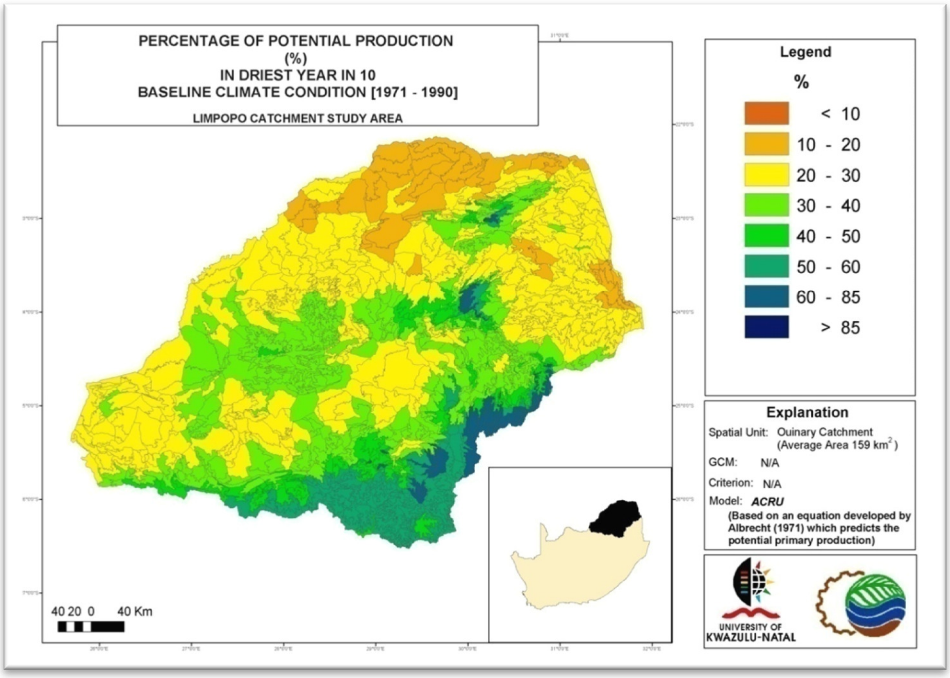


Figure C.2 Mean of the percentage of potential production in the driest year in 10 for baseline climate conditions (Source information: BEEH, 2008)

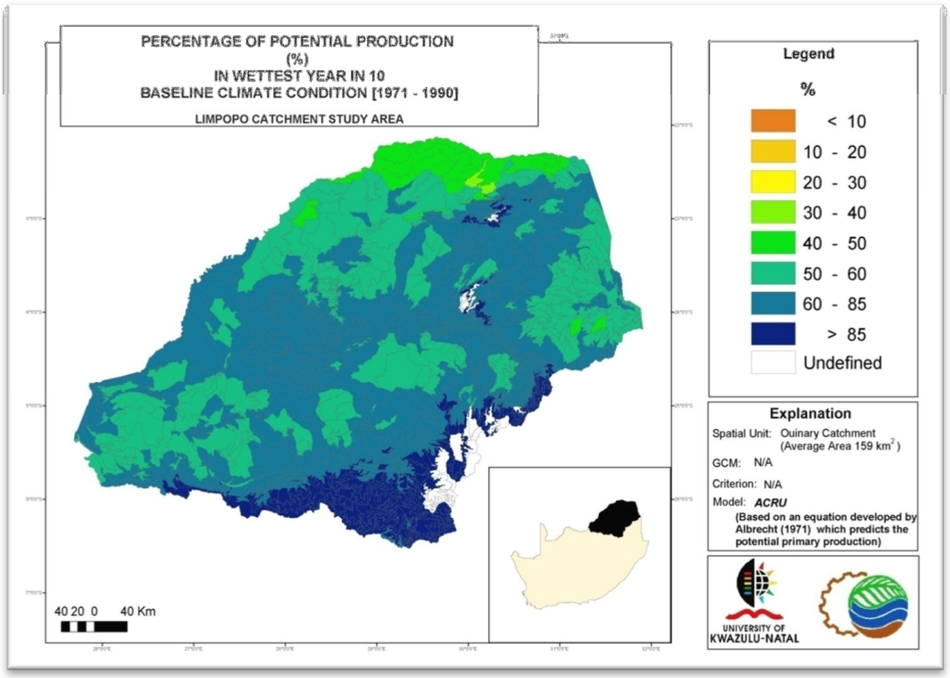


Figure C.3 Mean of the percentage of potential production in the wettest year in 10 for baseline climate conditions (Source information: BEEH, 2008)

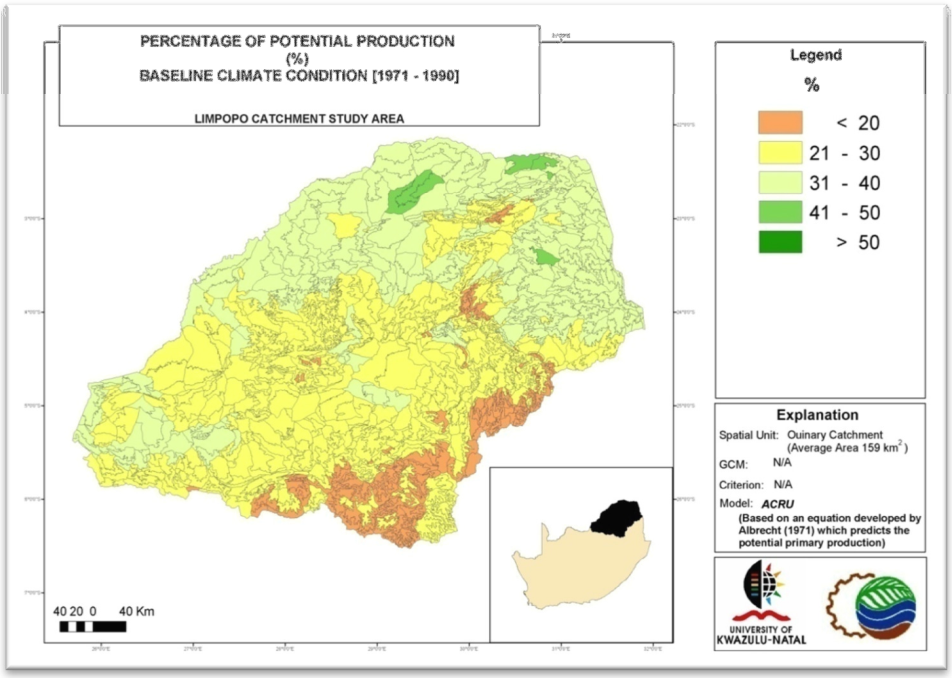


Figure C.4 Inter-annual variability (%) of the percentage of potential production for baseline climate conditions (Source information: BEEH, 2008)

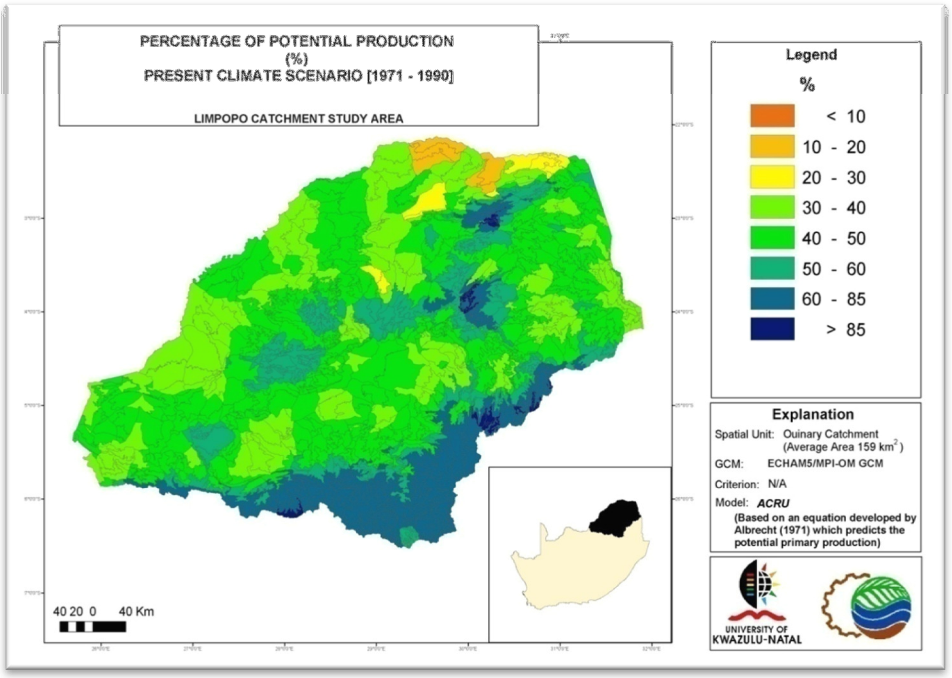


Figure C.5 Mean of the percentage of potential production per annum: ECHAM5/MPI-OM GCM's present climate (Source information: BEEH, 2008)

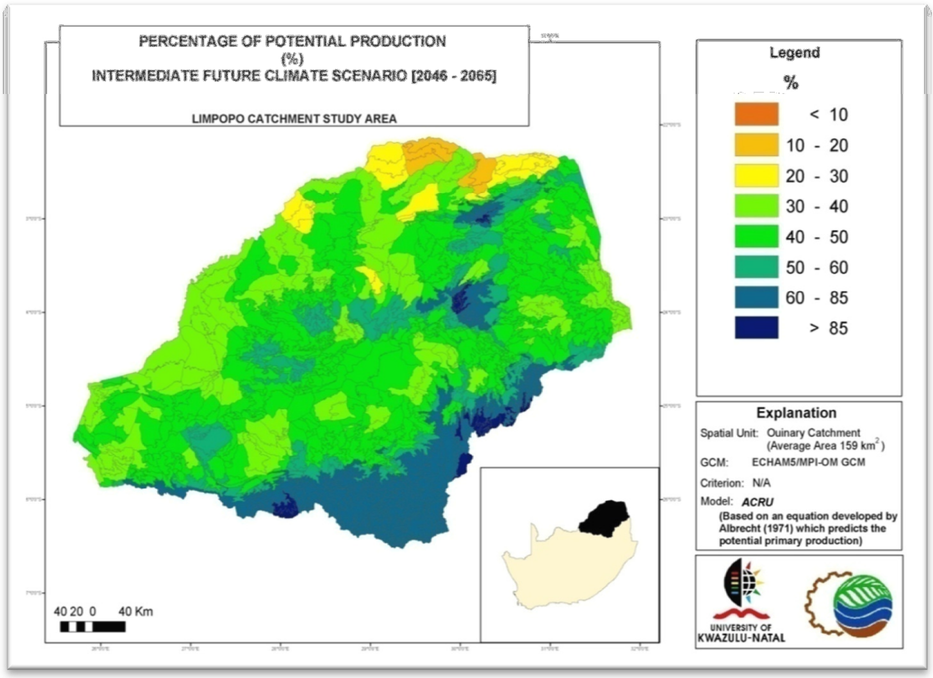


Figure C.6 Mean of the percentage of potential production per annum: ECHAM5/MPI-OM GCM’s intermediate future climate (Source information: BEEH, 2008)

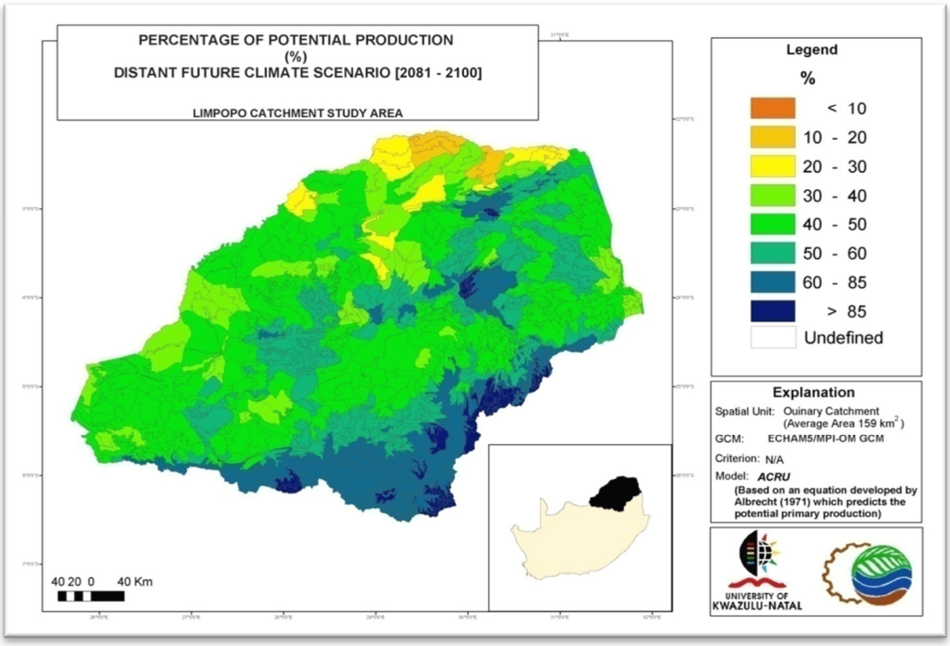


Figure C.7 Mean of the percentage of potential production per annum: ECHAM5/MPI-OM GCM’s distant future climate (Source information: BEEH, 2008)

Table C.2 Summarised statistics of the percentage of potential production (%) for the Water Management Areas in the Limpopo Catchment for the ECHAM5/MPI-OM GCM's present climate scenario

Limpopo Catchment Water Management Area	**Percentage of Potential Production Present Climate Scenario [1971 – 1990]**							
	Mean Value	**Standard Deviation**	**Coefficient of Variation (%)**	**Maximum Value**	**Minimum Value**	**Exceedence Probability**		
						10%	**50%**	**90%**
Limpopo	44.61	9.51	21.31	6.6940	30.33	33.53	43.34	57.90
Luvuvhu and Letaba	52.32	9.25	17.68	8.9101	37.33	40.91	52.17	61.21
Crocodile (West) and Marico	47.57	9.66	20.31	7.2237	32.58	36.82	46.11	61.31
Olifants	55.29	9.94	17.99	7.6136	39.60	43.64	54.27	68.11

Table C.3 Summarised statistics of the percentage of potential production (%) for the Water Management Areas in the Limpopo Catchment for the ECAHM5/MPI-OM GCM's intermediate future climate scenario

Limpopo Catchment Water Management Area	**Percentage of Potential Production Intermediate Future Climate Scenario [2046 – 2065]**							
	Mean Value	**Standard Deviation**	**Coefficient of Variation (%)**	**Maximum Value**	**Minimum Value**	**Exceedence Probability**		
						10%	**50%**	**90%**
Limpopo	43.45	8.96	20.62	60.99	27.72	31.53	43.56	54.99
Luvuvhu and Letaba	52.65	8.46	16.06	67.96	37.33	41.76	52.71	62.78
Crocodile (West) and Marico	47.47	8.54	17.98	63.49	31.89	37.09	46.84	58.00
Olifants	57.18	9.14	15.98	75.34	39.73	46.34	56.76	66.02

Table C.4 Summarised statistics of the percentage of potential production (%) for the Water Management Areas in the Limpopo Catchment for the ECHAM5/MPI-OM GCM's distant future climate scenario

Limpopo Catchment Water Management Area	**Percentage of Potential Production Distant Future Climate Scenario [2081 – 2100]**							
	Mean Value	**Standard Deviation**	**Coefficient of Variation (%)**	**Maximum Value**	**Minimum Value**	**Exceedence Probability**		
						10%	**50%**	**90%**
Limpopo	45.48	9.77	21.48	70.88	31.31	34.76	44.41	57.27
Luvuvhu and Letaba	55.30	10.06	18.18	80.33	39.94	43.17	55.02	62.28
Crocodile (West) and Marico	50.24	9.20	18.31	77.30	35.91	40.39	49.40	57.93
Olifants	62.02	10.32	16.64	89.02	45.37	49.97	60.74	66.50

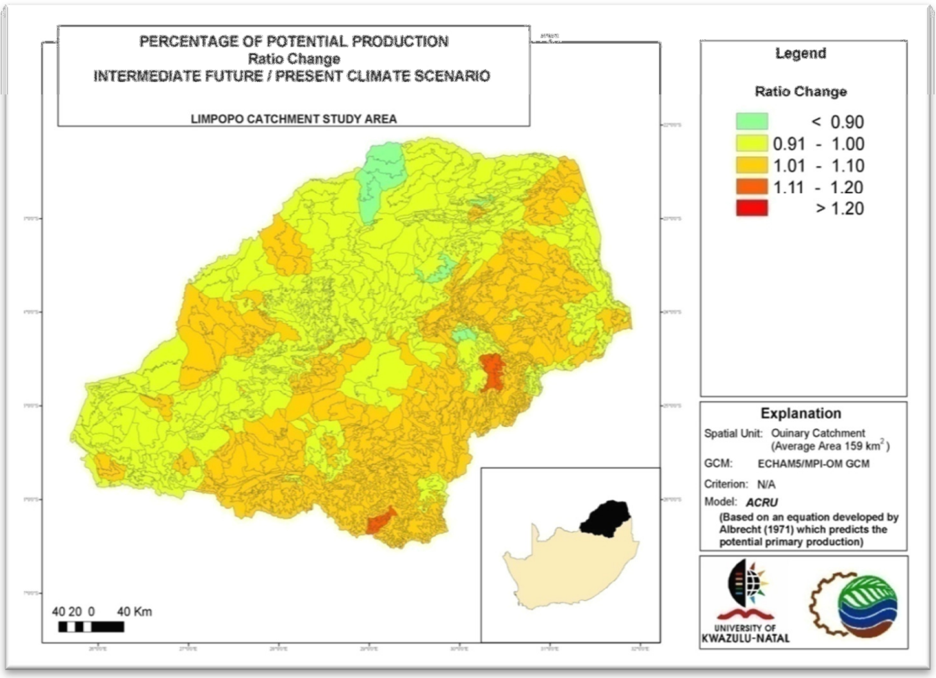


Figure C.8 Ratio changes in the percentage of potential production: ECHAM5/MPI-OM GCM's intermediate future / present climate (Source information: BEEH, 2008)

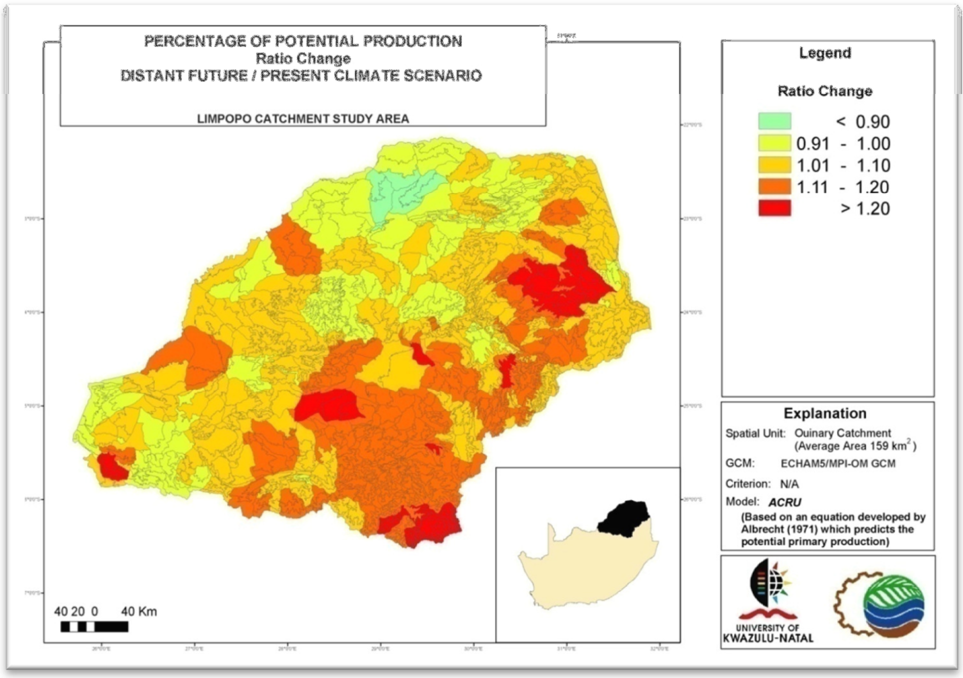


Figure C.9 Ratio changes in the percentage of potential production: ECHAM5/MPI-OM GCM's distant future / present climate (Source information: BEEH, 2008)

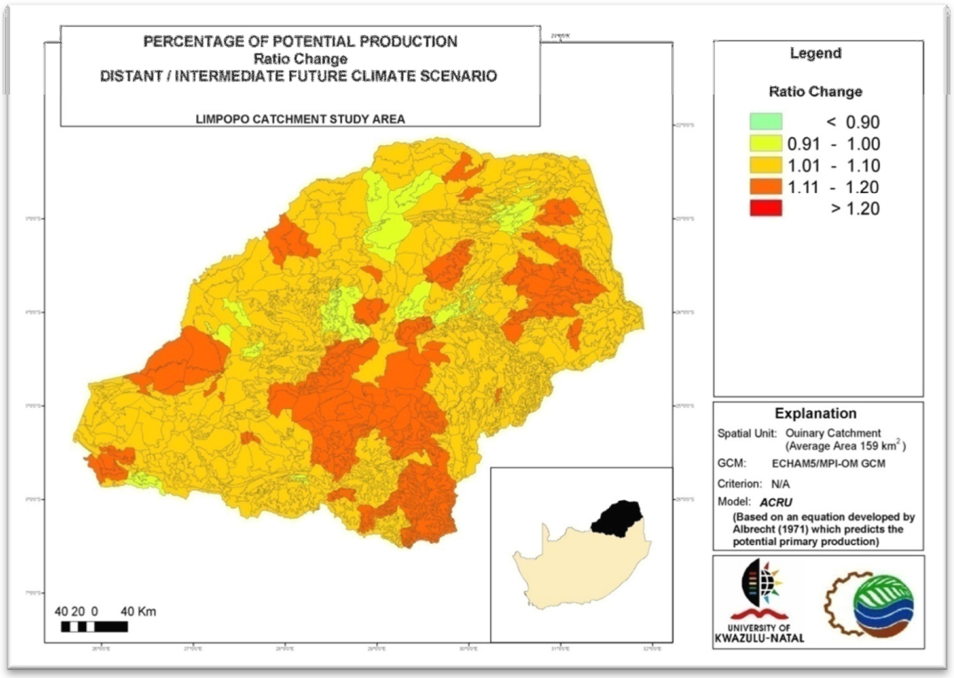


Figure C.10 Ratio changes in the percentage of potential production: ECHAM5/MPI-OM GCM's distant / intermediate future climate (Source information: BEEH, 2008)

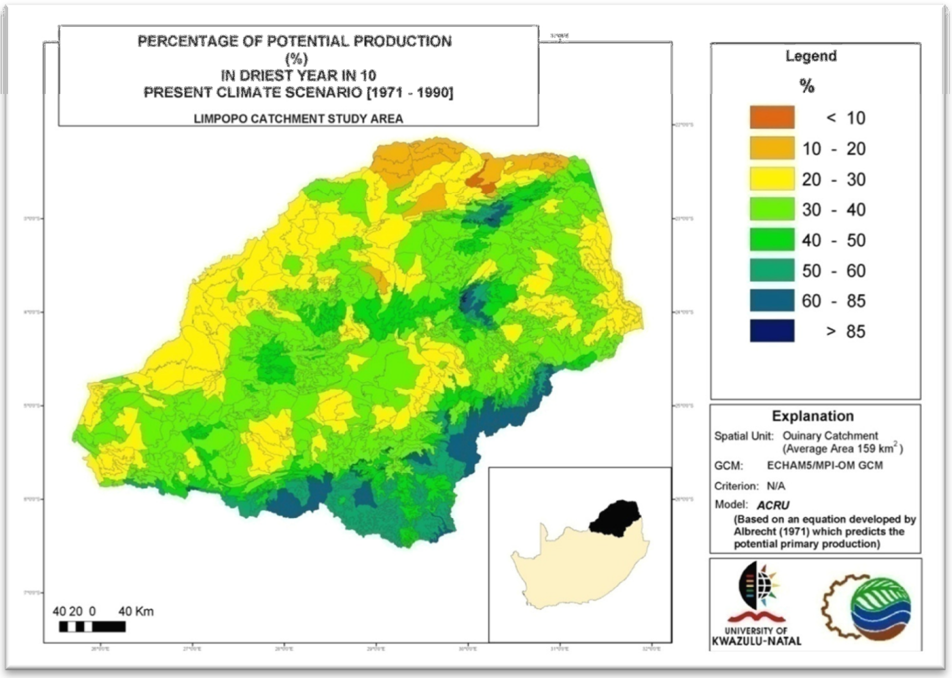


Figure C.11 Mean of the percentage of potential production in the driest year in 10: ECHAM5/MPI-OM GCM's present climate (Source information: BEEH, 2008)

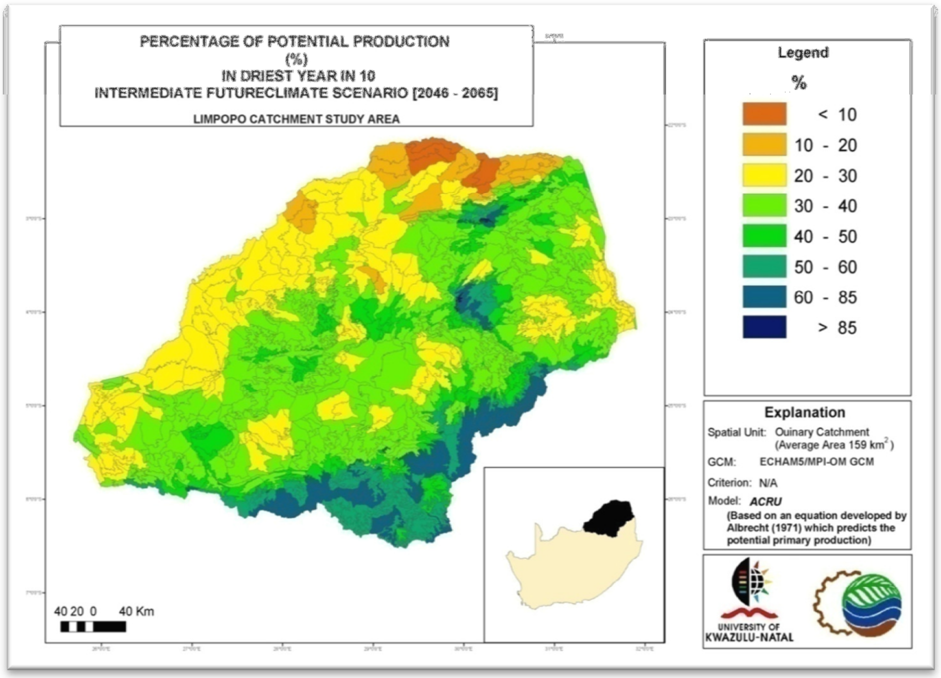


Figure C.12 Mean of the percentage of potential production in the driest year in 10: ECHAM5/MPI-OM GCM's intermediate future climate (Source information: BEEH, 2008)

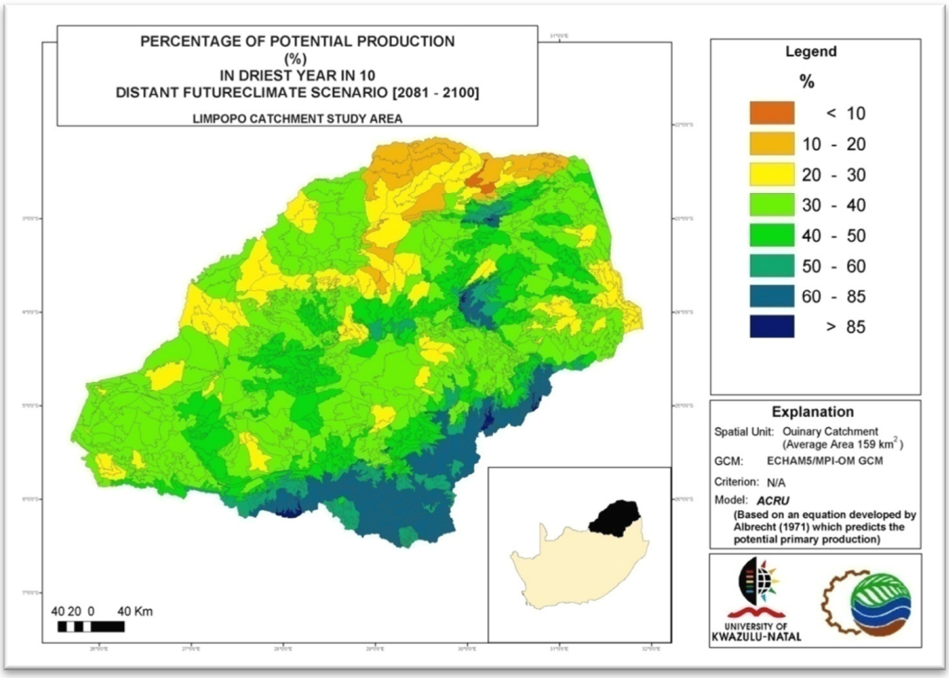


Figure C.13 Mean of the percentage of potential production in the driest year in 10: ECHAM5/MPI-OM GCM's distant future climate (Source information: BEEH, 2008)

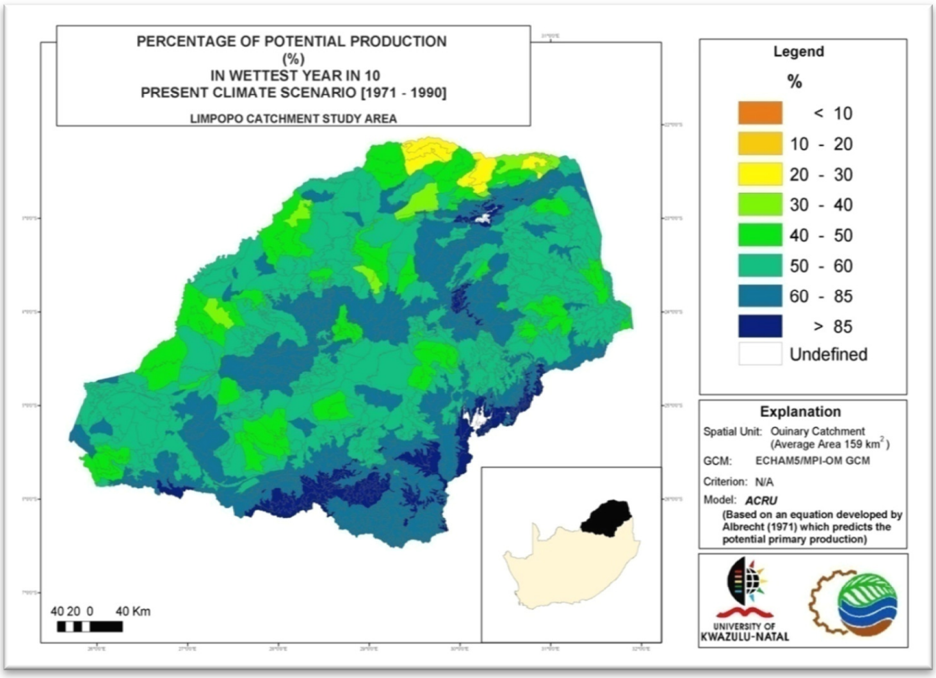


Figure C.14 Mean of the percentage of potential production in the wettest year in 10: ECHAM5/MPI-OM GCM's present climate (Source information: BEEH, 2008)

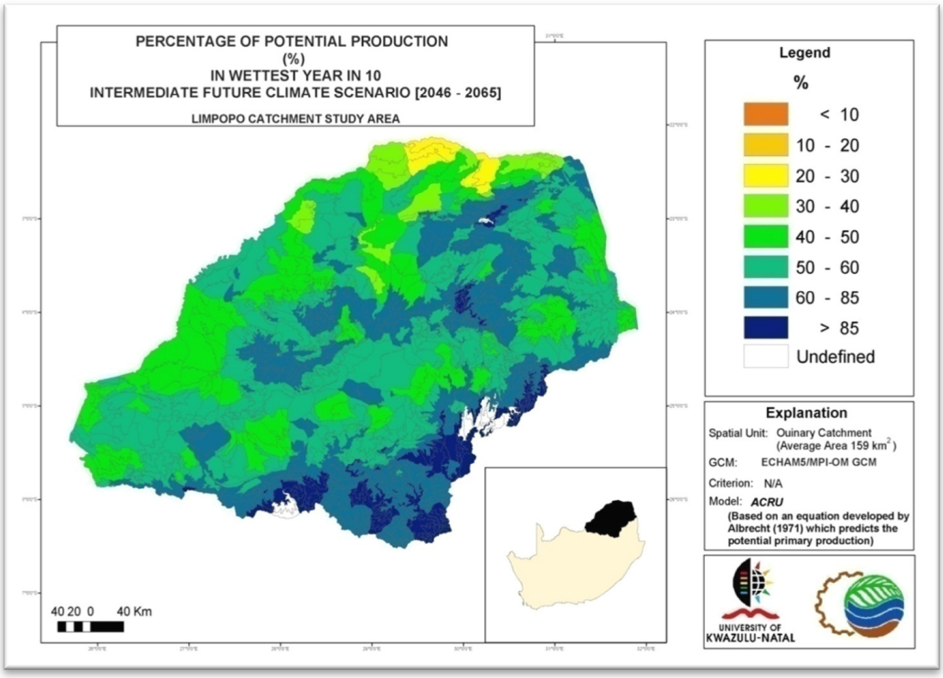


Figure C.15 Mean of the percentage of potential production in the wettest year in 10: ECHAM5/MPI-OM GCM's intermediate future climate (Source information: BEEH, 2008)

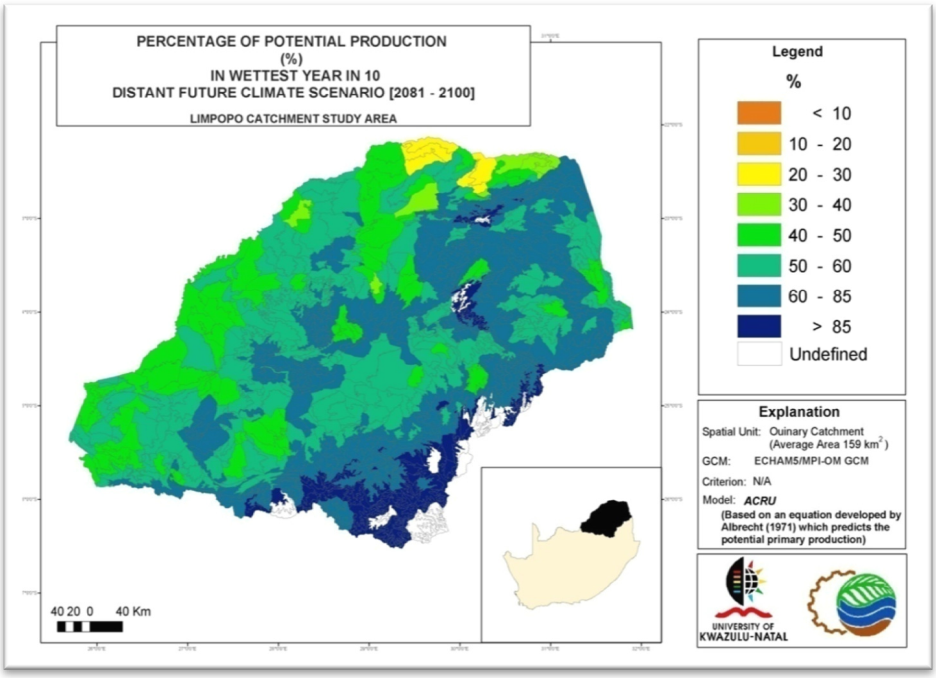


Figure C.16 Mean of the percentage of potential production in the wettest year in 10: ECHAM5/MPI-OM GCM's distant future climate (Source information: BEEH, 2008)

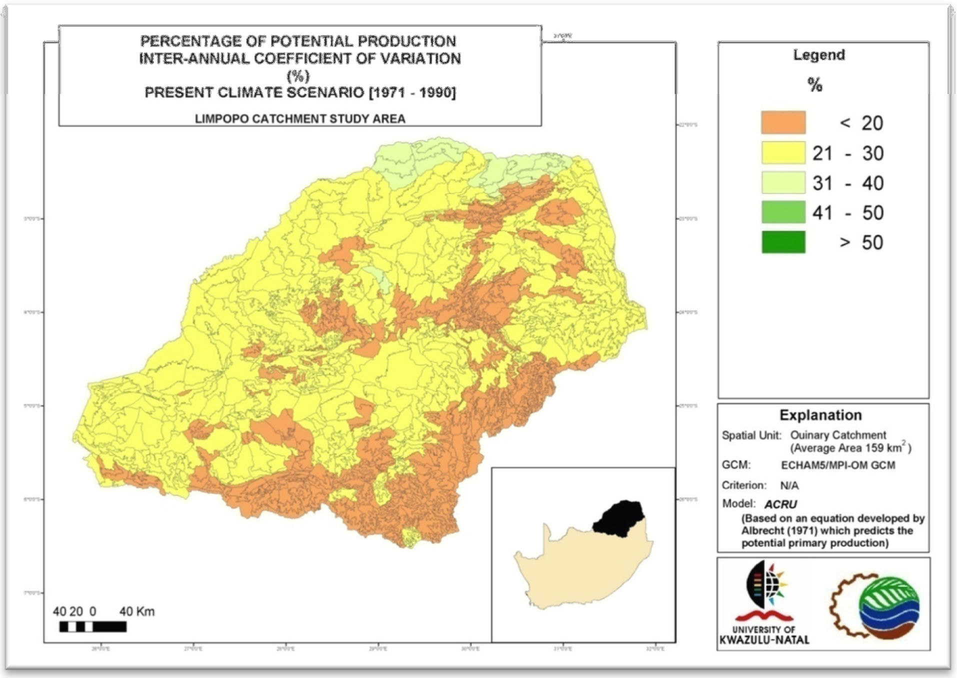


Figure C.17 Inter-annual variation (%) of the percentage of potential production: ECHAM5/MPI-OM GCM's present climate (Source information: BEEH, 2008)

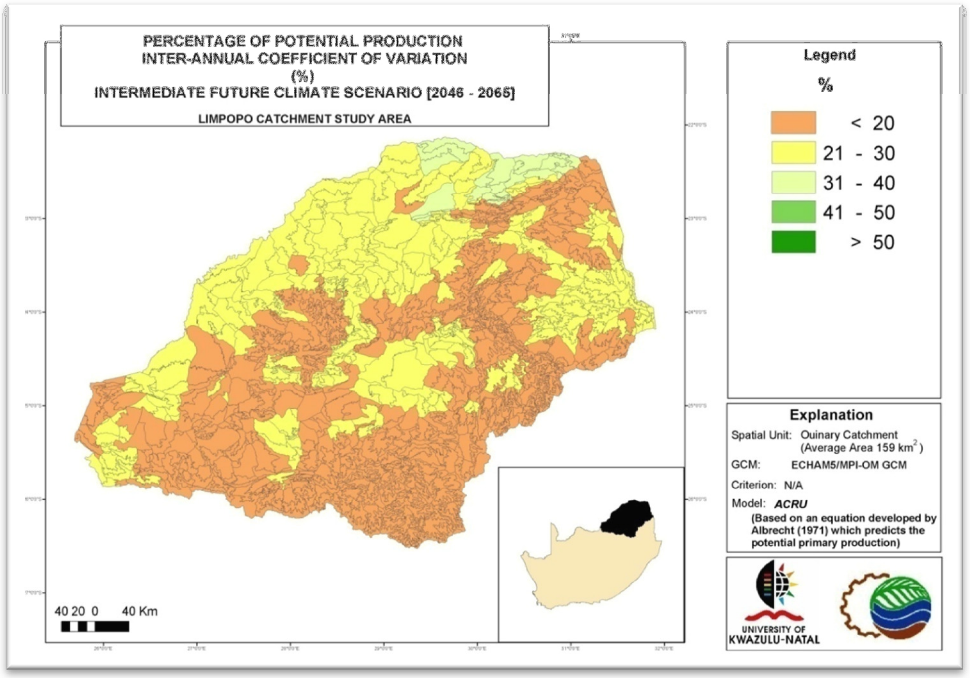


Figure C.18 Inter-annual variation (%) of the percentage of potential production: ECHAM5/MPI-OM GCM's intermediate future climate (Source information: BEEH, 2008)

Table C.5 Summarised inter-annual coefficients of the variation of percentage of potential production for the Water Management Areas in the Limpopo Catchment for the ECHAM5/MPI-OM GCM's scenarios

Limpopo Catchment Water Management Area	Percentage of Potential Production Coefficient of Variation (%)						
	Baseline Climate Condition	**Present Climate Scenario**	**Intermediate Future Climate Scenario**	**Distant Future Climate Scenario**	**I : P**	**F : P**	**F : I**
Limpopo	29.43	21.31	20.62	21.48	0.97	1.01	1.04
Luvuvhu and Letaba	30.26	17.68	16.06	18.18	0.91	1.03	1.13
Crocodile (West) and Marico	26.56	20.31	17.98	18.31	0.89	0.90	1.02
Olifants	22.89	17.99	15.98	16.64	0.89	0.93	1.04

Table C.6 Summarised standard deviation of the percentage of potential production for the Water Management Areas in Limpopo Catchment for the ECHAM5/MPI-OM GCM's scenarios

Limpopo Catchment Water Management Areas	Percentage of Potential Production Standard Deviation						
	Baseline Climate Condition	**Present Climate Scenario**	**Intermediate Future Climate Scenario**	**Distant Future Climate Scenario**	**I : P**	**F : P**	**F : I**
Limpopo	12.89	9.51	8.96	9.77	0.94	1.03	1.09
Luvuvhu and Letaba	14.14	9.25	8.46	10.06	0.91	1.09	1.19
Crocodile (West) and Marico	12.69	9.66	8.54	9.20	0.88	0.95	1.08
Olifants	12.82	9.94	9.14	10.32	0.92	1.04	1.13

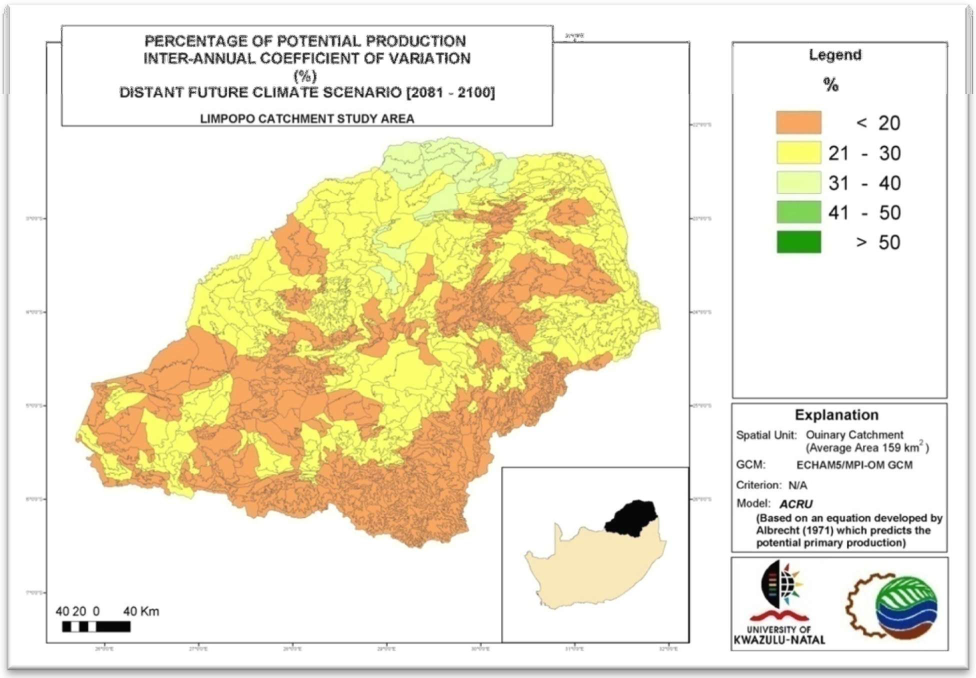


Figure C.19 Inter-annual of variation (%) of the percentage of potential production: ECHAM5/MPI-OM GCM's distant future climate (Source Information: BEEH, 2008)

APPENDIX D: *Chilo partellus*

D.1 Algorithms for the Development Periods of *C. partellus* Life Stage

The following graphs and equations (models) refer to three development periods of the *C. partellus* life stages, i.e. the egg stage (**Equation 11.1**; **Figure D**.1), the larval stage (**Equation 11.2**; **Figure D.2**) and the pupal stage (**Equation 11.3**; **Figure D**.3), with the development stage time period expressed as a function of temperature (in ^{o}C).

The *Chilo partellus* life cycle models developed by the author are given as

Egg stage

$$y_i = 422.72 + (-65.3605 \times t) + (3.88632 \times t^2) + (-0.10174 \times t^3) + (0.000979333 \times t^4) + \varepsilon_i \qquad \text{(D.1)}$$

where, y_i = egg development period (in days),

t = mean daily temperature (^{o}C) for days of the season.

Larval stage

$$y_i = -1410.33 + (266.774 \times t) + (-17.0727 \times t^2) + (0.45973 \times t^3) + (0.00446733 \times t^4) + \varepsilon_i \qquad \text{(D.2)}$$

where, y_i = larval development period (in days),

t = mean daily temperature (^{o}C) for days of the season.

Pupal stage

$$y_i = -59.26 + (13.1712 \times t) + (-0.77205 \times t^2) + (0.0177933 \times t^3) + (0.00142 \times t^4) + \varepsilon_i \qquad \text{(D.3)}$$

where, y_i = pupal development period (in days),

t = mean daily temperature (^{o}C) for days of the season.

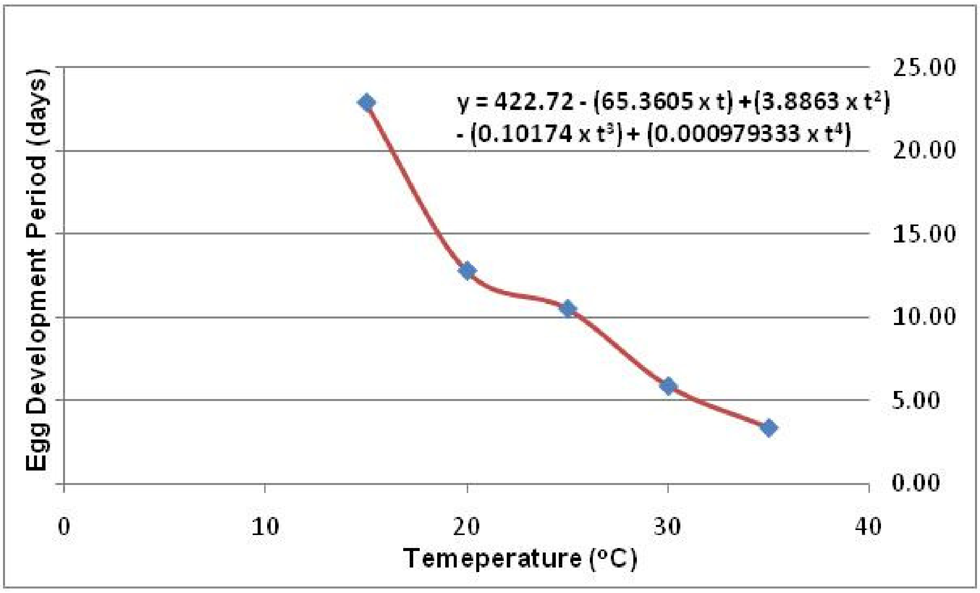


Figure D.1 Modelled egg stage development period of *Chilo partellus* based on temperature (—— Simulated (Quartic polynomial Model); ◆ Means of observations at specified temperatures)

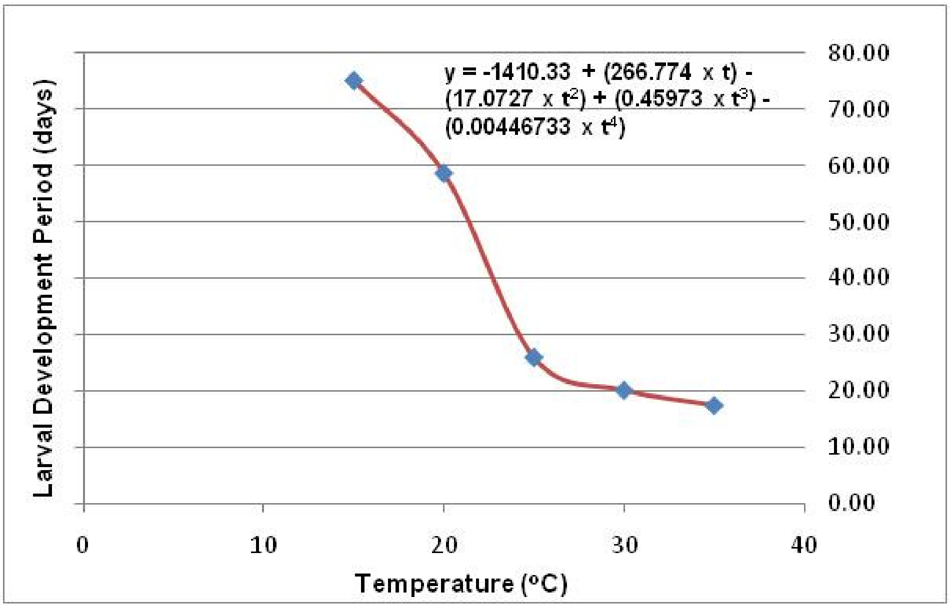


Figure D.2 Modelled larval stage development period of *Chilo partellus* based on temperature (—— Simulated (Quartic polynomial Model); ◆ Means of observations at specified temperatures)

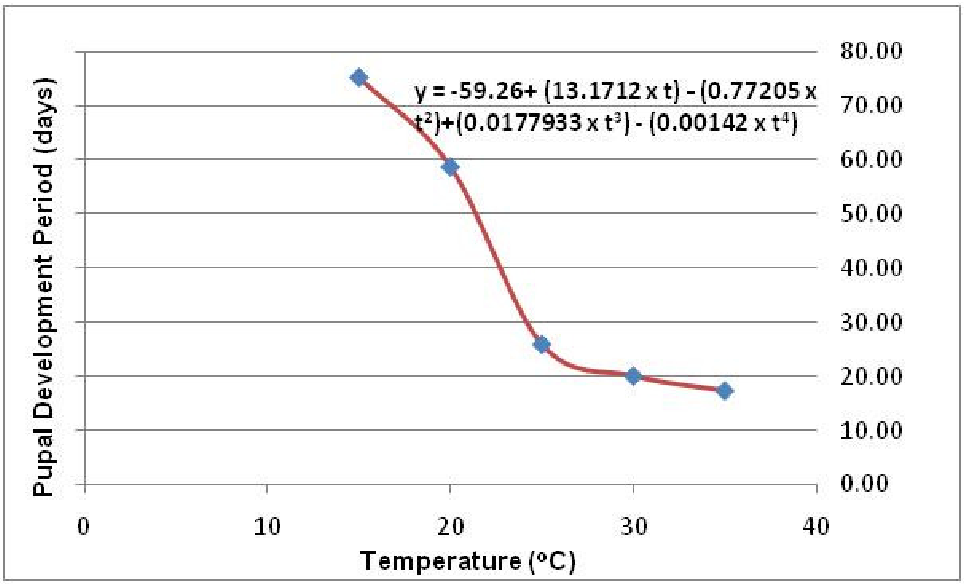


Figure D.3 Modelled pupal stage development period of *Chilo partellus* based temperature (—— Simulated (Quartic polynomial Model); ◆ Means of observations at specified temperatures)

D.2 *Chilo partellus* Development Period and Mortality

The following maps display the mean number of days per annum that are optimal of the egg, larval and pupal stages of the predicted and projected *C. partellus* development periods over the Limpopo Catchment.

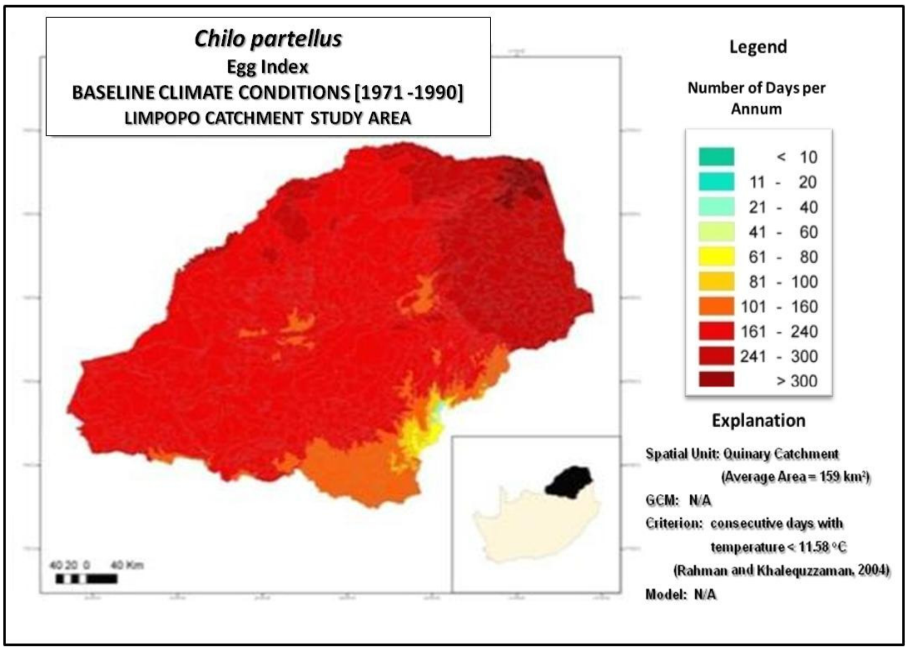


Figure D.4 Mean number of days per annum which are optimal for the *C. partellus* egg stage: baseline climate conditions

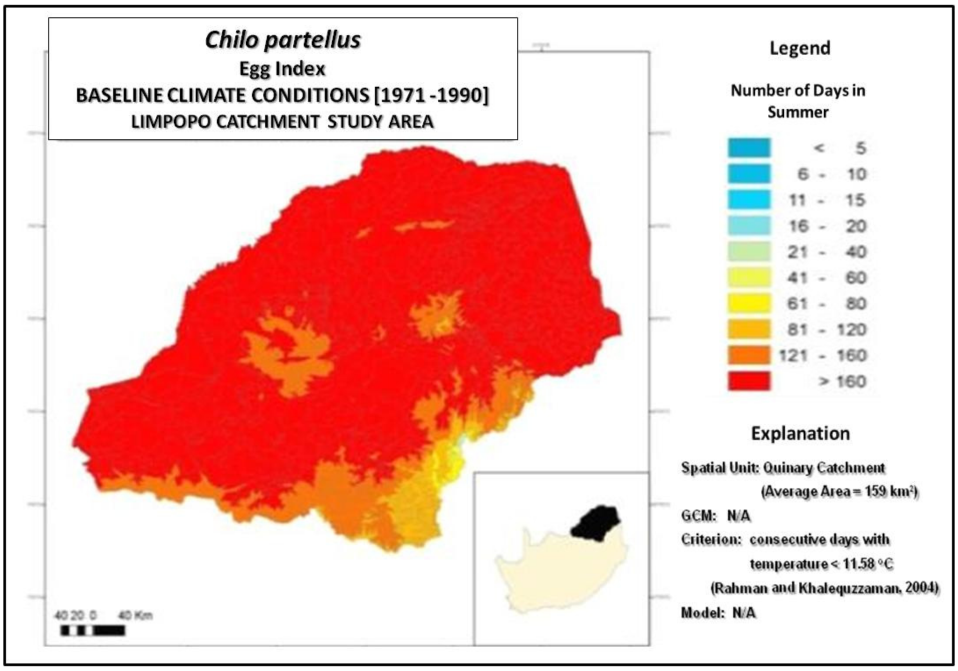


Figure D.5 Mean number of days per annum which are optimal for the *C. partellus* egg stage in summer season [October – March]: baseline climate conditions

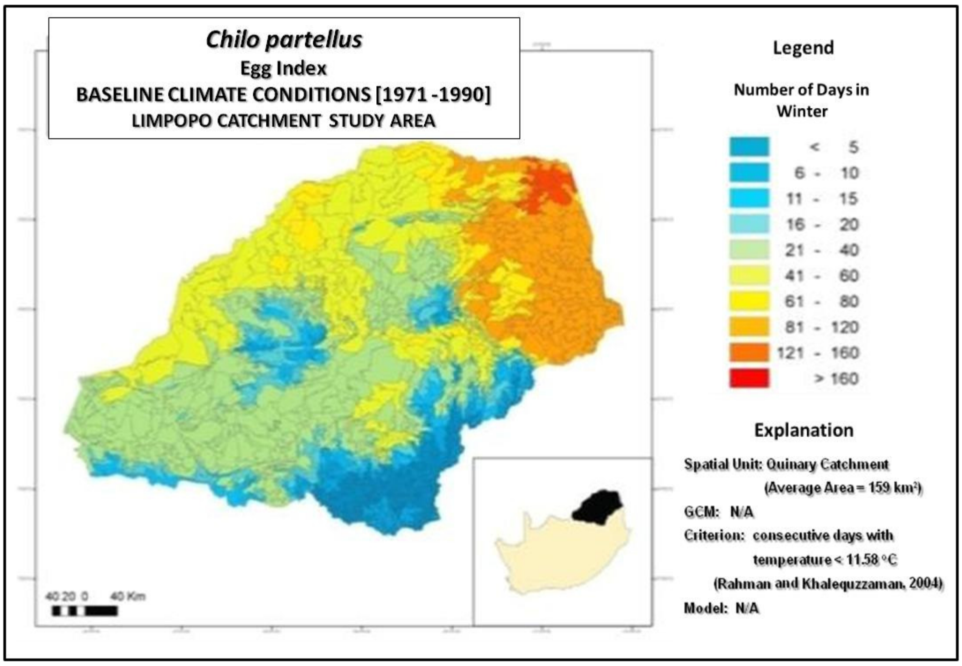


Figure D.6 Mean number of days per annum which are optimal for the *C. partellus* egg stage in winter season [April – September]: baseline climate conditions

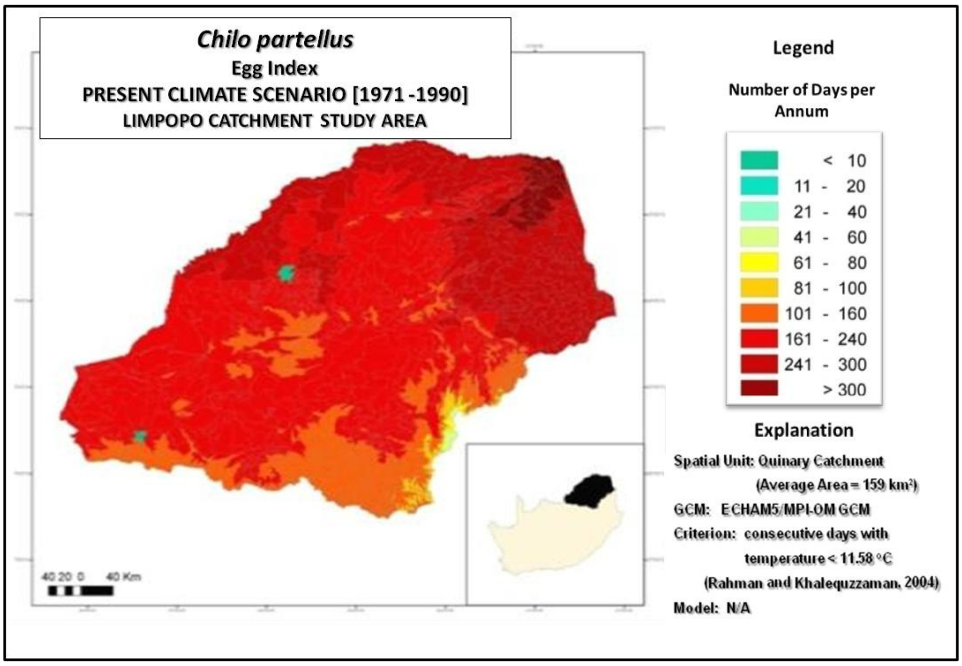


Figure D.7 Mean number of days per annum which are optimal for the *C. partellus* egg stage: ECHAM5/MPI-OM GCM's present climate

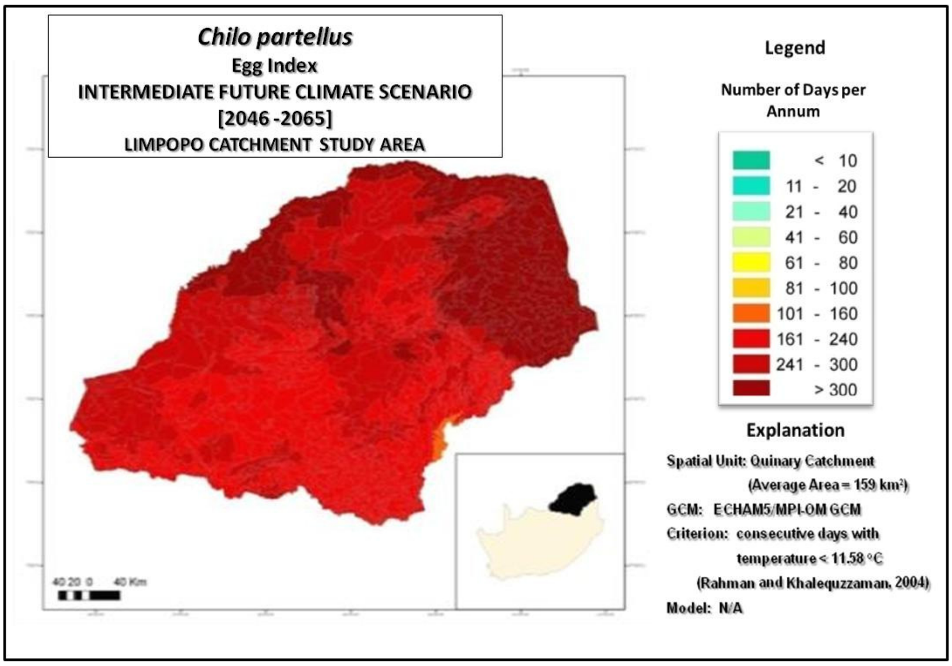


Figure D.8 Mean number of days per annum which are optimal for the *C. partellus* egg stage: ECHAM5/MPI-OM GCM's intermediate future climate

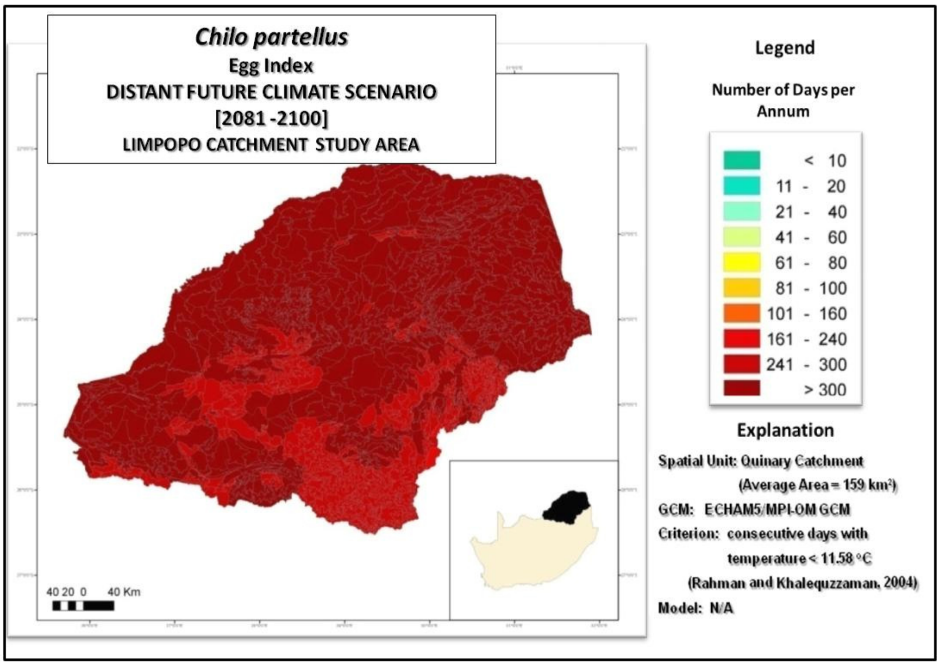


Figure D.9 Mean number of days per annum which are optimal for the *C. partellus* egg stage: ECHAM5/MPI-OM GCM's distant future climate

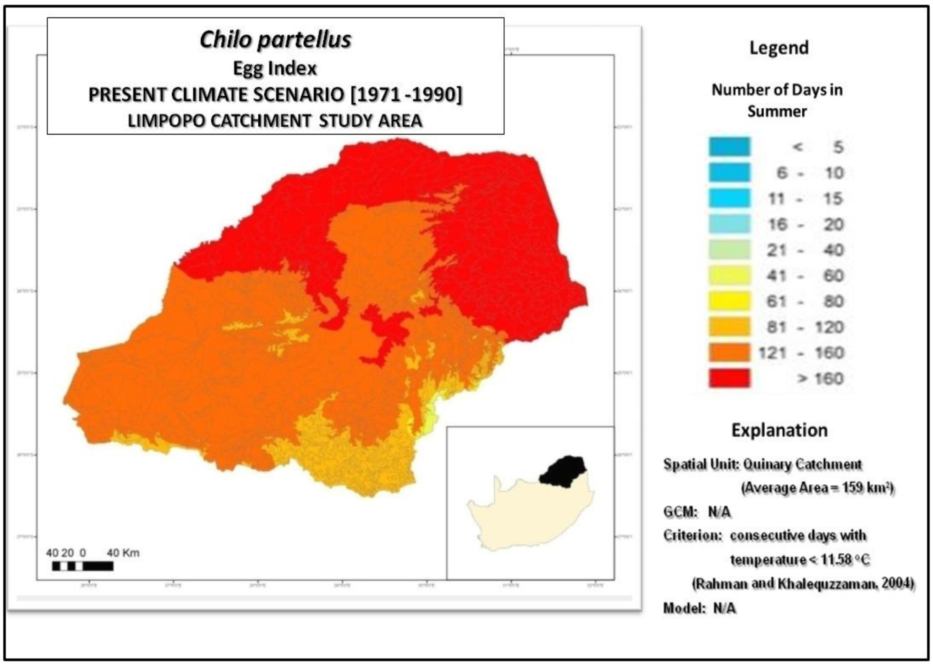


Figure D.10 Mean number of days per annum which are optimal for the *C. partellus* egg stage in summer season [October – March]: ECHAM5/MPI-OM GCM's present climate

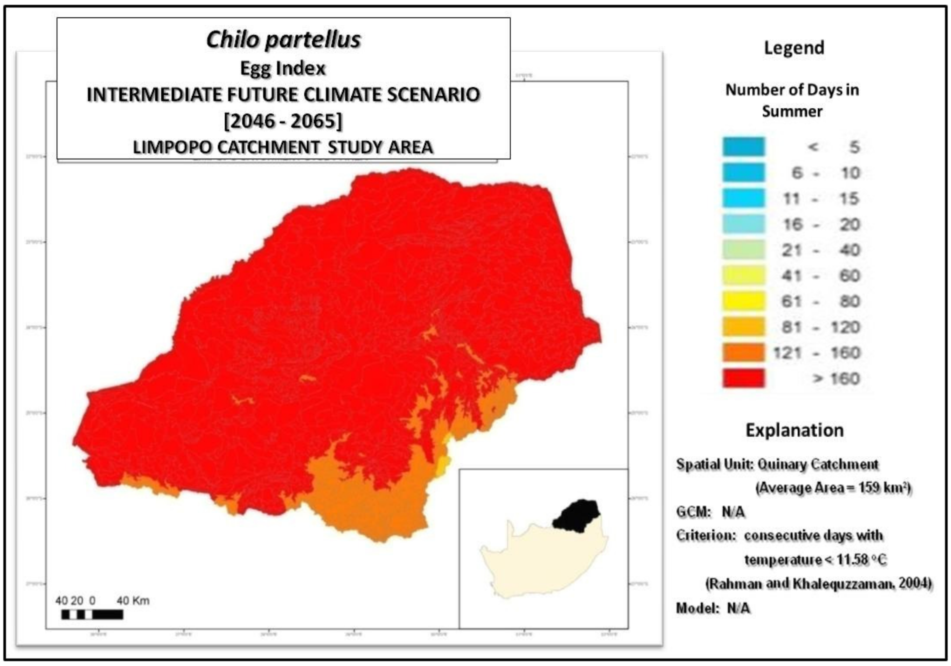


Figure D.11 Mean number of days per annum which are optimal for the *C. partellus* egg stage in summer season [October – March]: ECHAM5/MPI-OM GCM's intermediate future climate

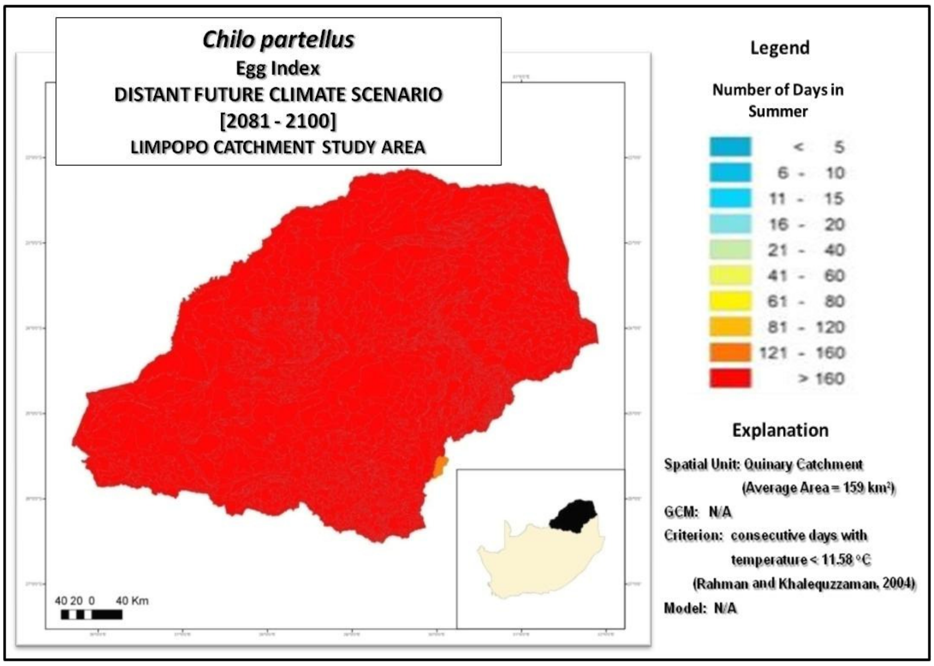


Figure D.12 Mean number of days per annum which are optimal for the *C. partellus* egg stage in summer season [October – March]: ECHAM5/MPI-OM GCM's distant future climate

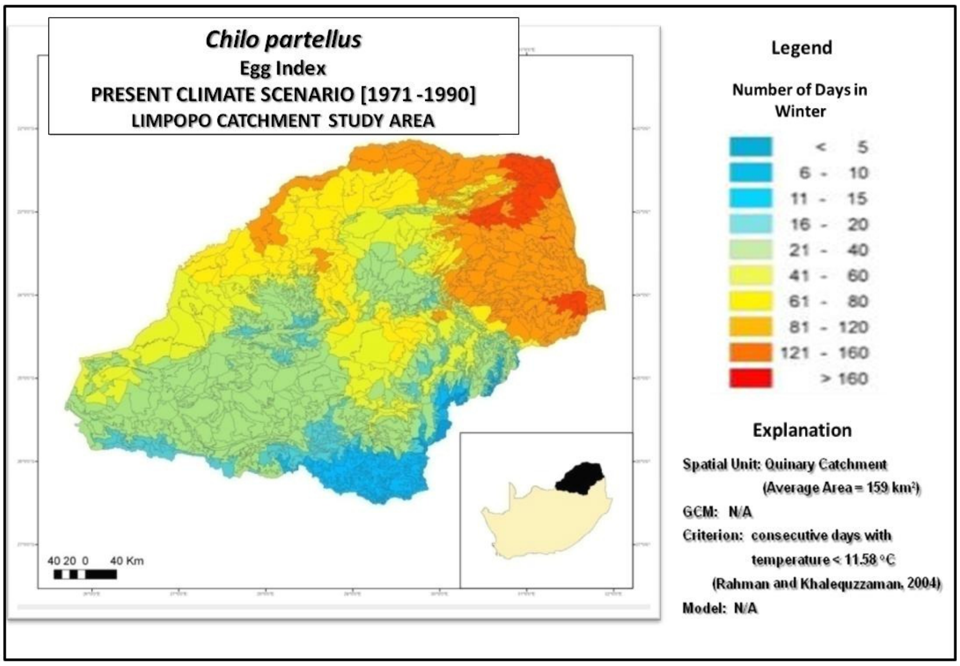


Figure D.13 Mean number of days per annum which are optimal for the *C. partellus* egg stage in winter season [April – September]: ECHAM5/MPI-OM GCM's present climate

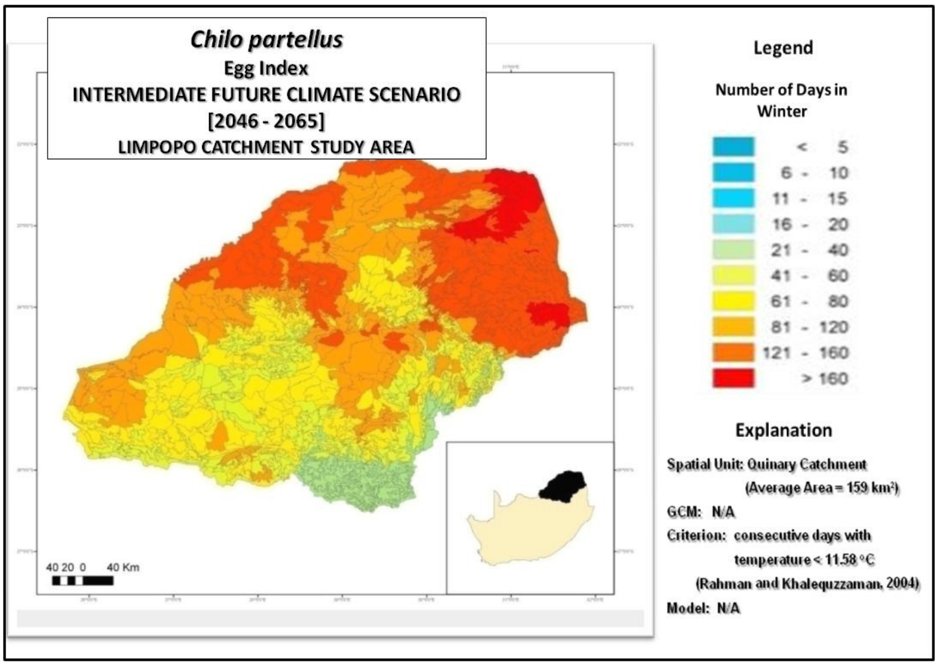


Figure D.14 Mean number of days per annum which are optimal for the *C. partellus* egg stage in winter season [April – September]: ECHAM5/MPI-OM GCM's intermediate future climate

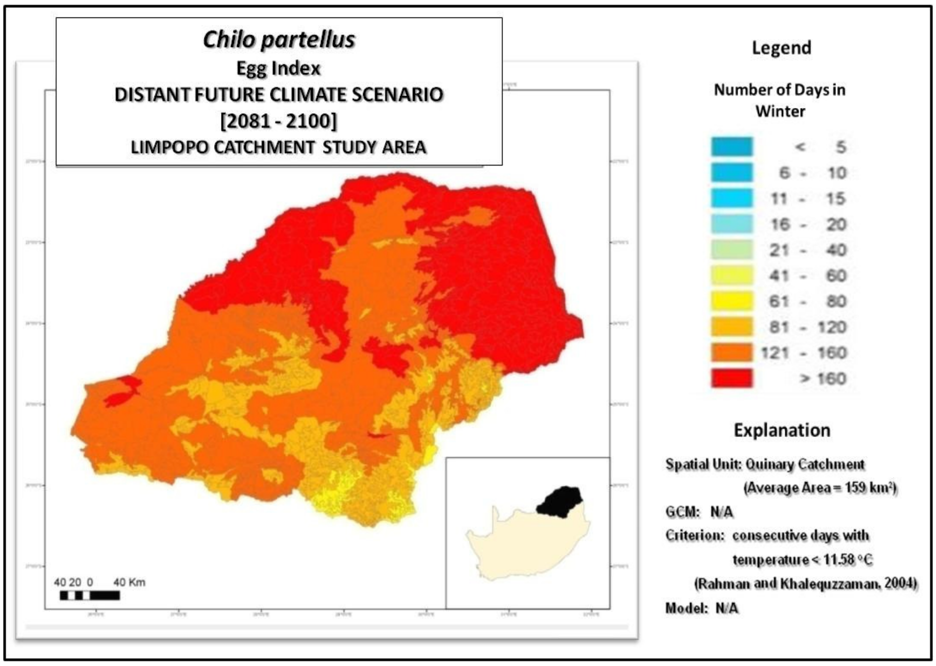


Figure D.15 Mean number of days per annum which are optimal for the *C. partellus* egg stage in winter season [April – September]: ECHAM5/MPI-OM GCM's distant future climate

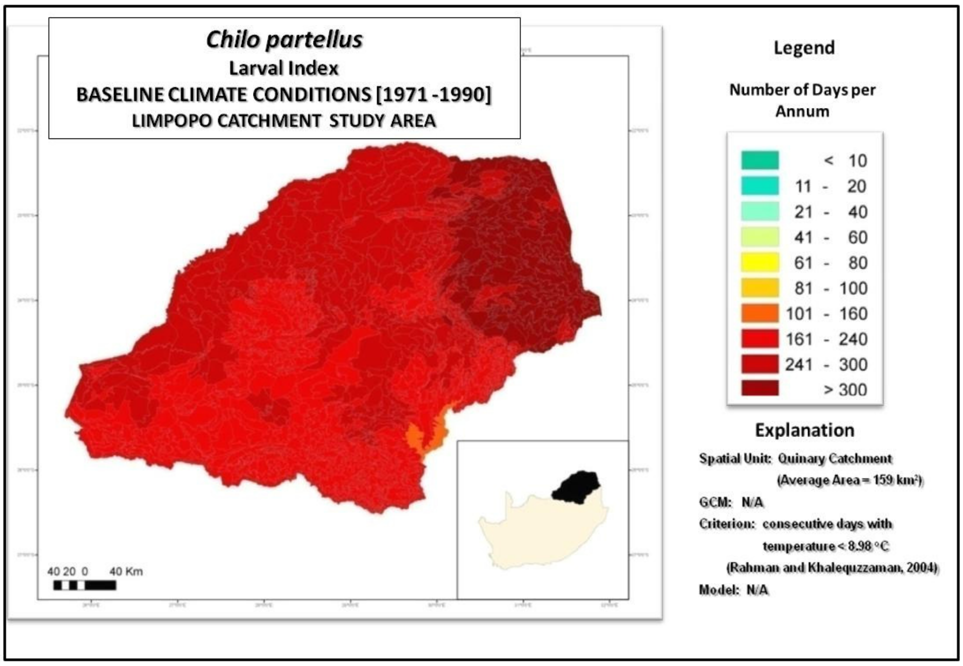


Figure D.16 Mean number of days per annum which are optimal for the *C. partellus* larval stage: baseline climate conditions

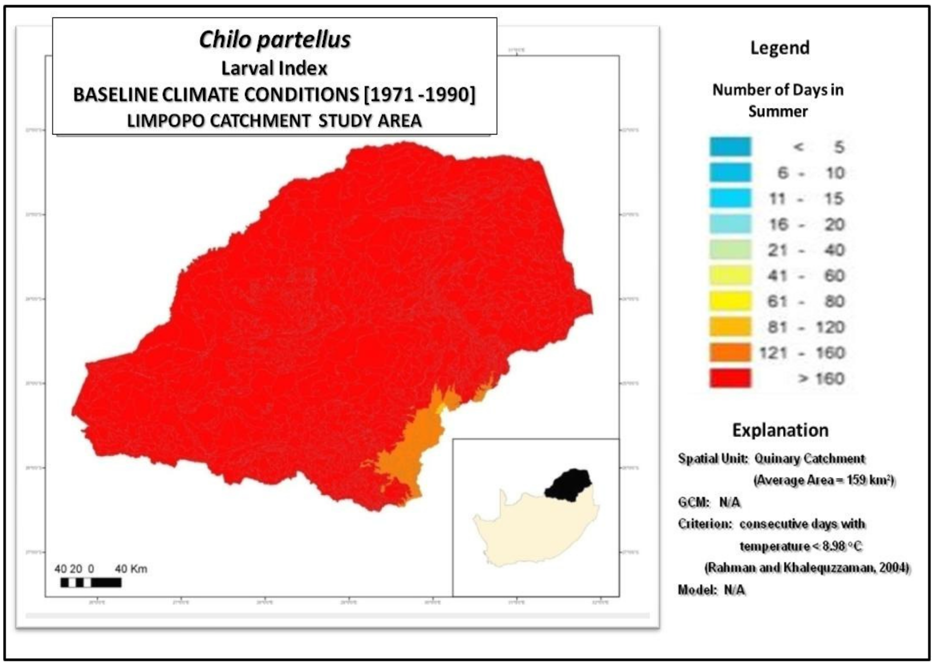


Figure D.17 Mean number of days per annum which are optimal for the *C. partellus* larval stage in summer season [October – March]: baseline climate conditions

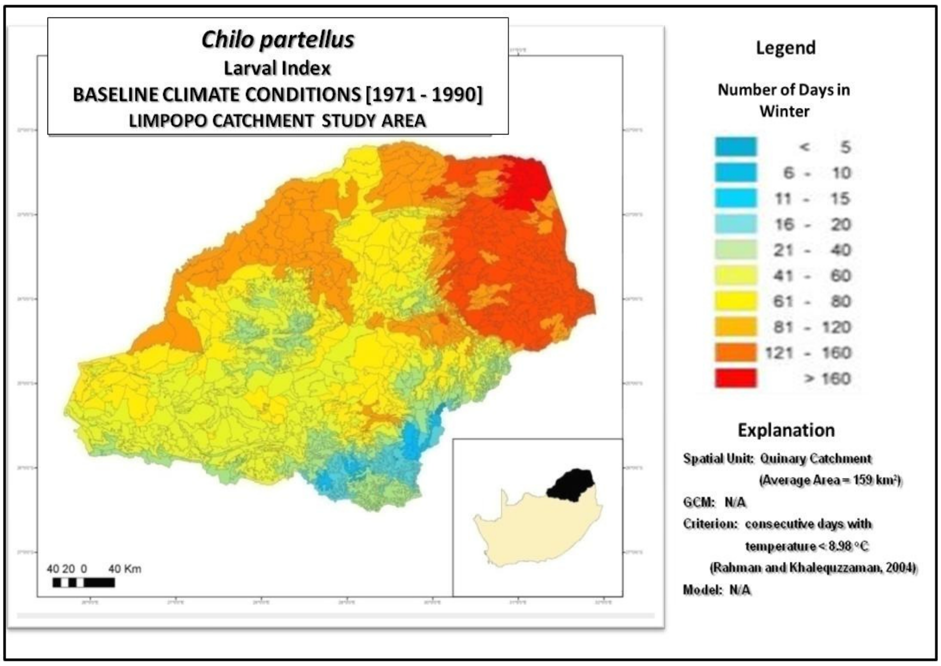


Figure D.18 Mean number of days per annum which are optimal for the *C. partellus* larval days in the winter season [October – March]: baseline climate conditions

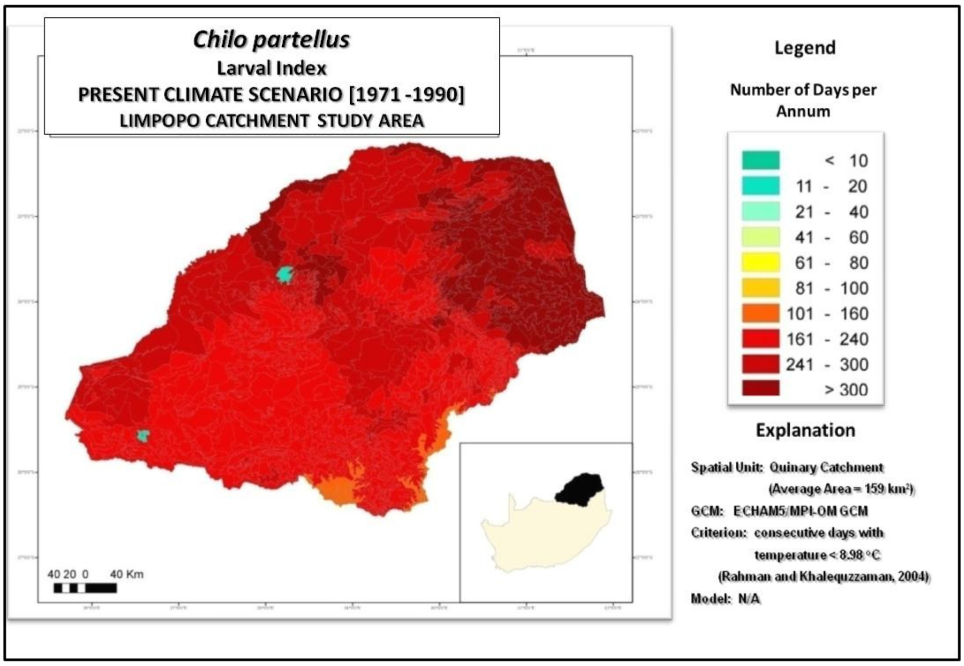


Figure D.19 Mean number of days per annum which are optimal for the *C. partellus* larval stage: ECHAM5/MPI-OM GCM's present climate

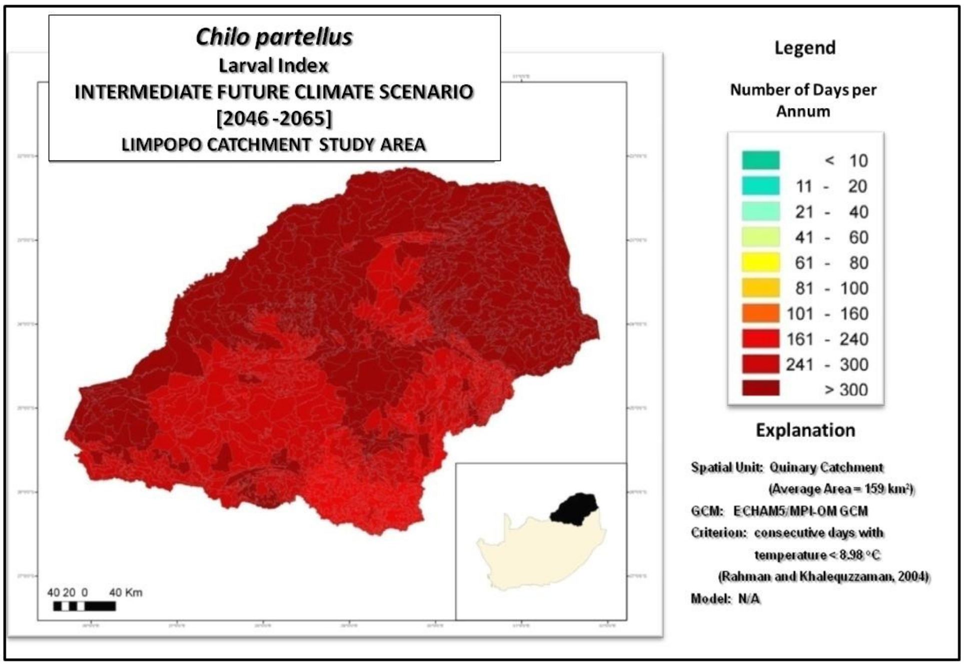


Figure D.20 Mean number of days per annum which are optimal for the *C. partellus* larval stage: ECHAM5/MPI-OM GCM's intermediate future climate

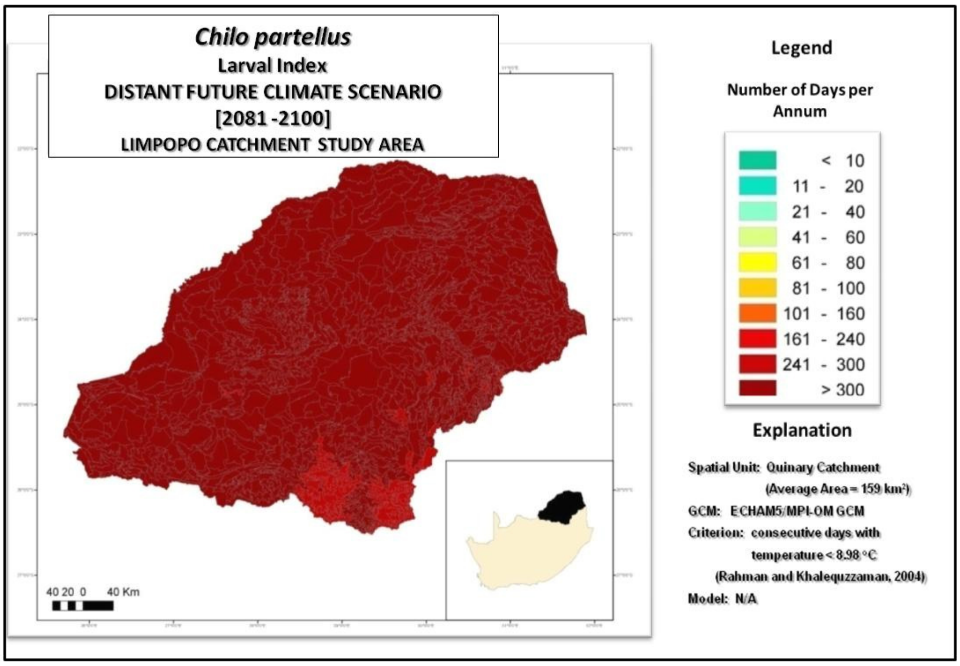


Figure D.21 Mean number of days per annum which are optimal for the *C. partellus* larval stage: ECHAM5/MPI-OM GCM's distant future climate

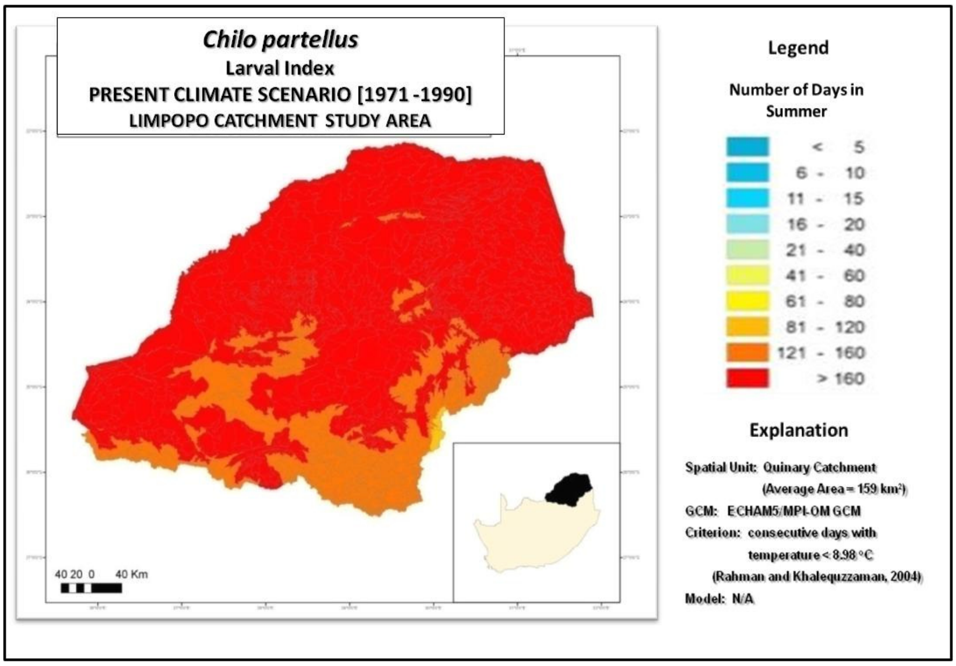


Figure D.22 Mean number of days per annum which are optimal for the *C. partellus* larval stage in summer season [October – March]: ECHAM5/MPI-OM GCM's present climate

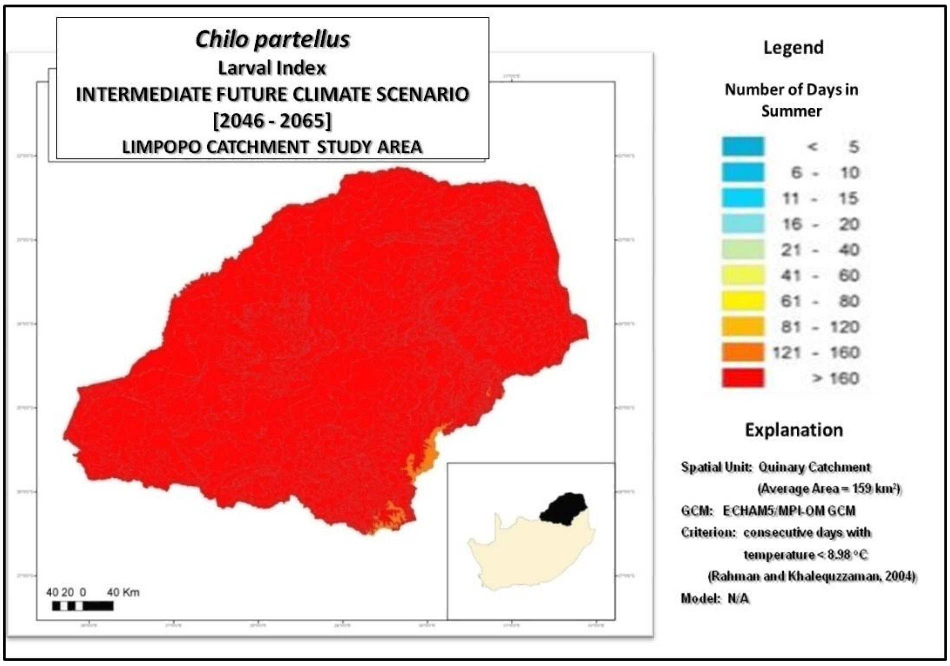


Figure D.23 Mean number of days per annum which are optimal for the *C. partellus* larval stage in summer season [October – March]: ECHAM5/MPI-OM GCM's intermediate future climate

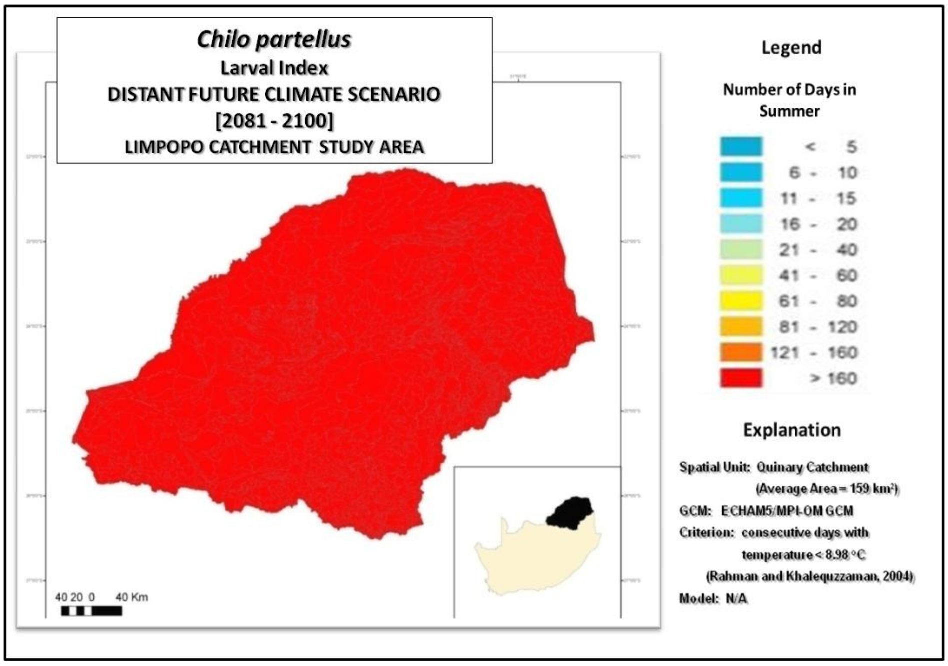


Figure D.24 Mean number of days per annum which are optimal for the *C. partellus* larval stage in summer season [October – March]: ECHAM5/MPI-OM GCM's distant future climate

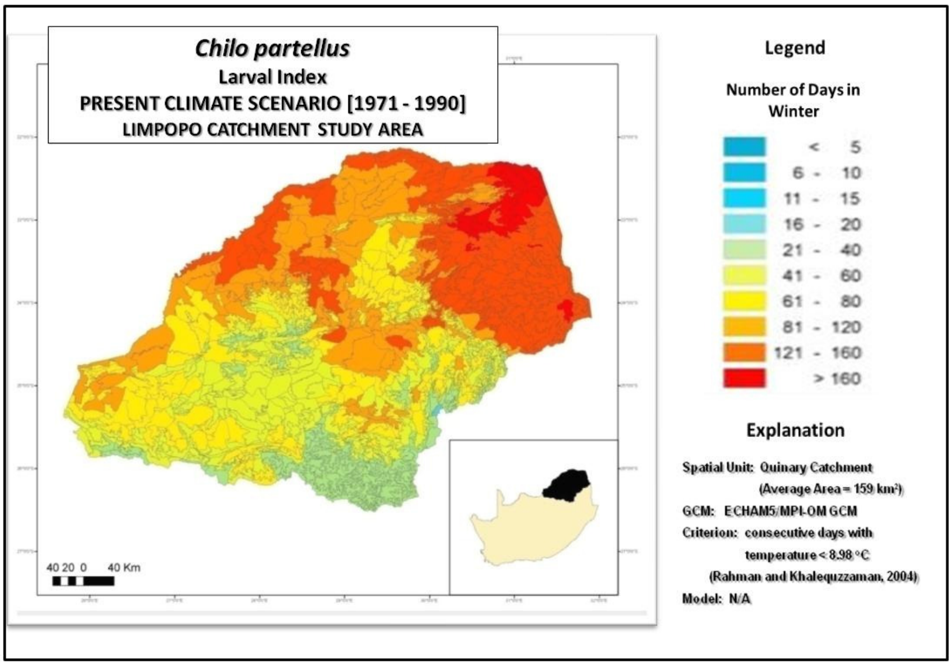


Figure D.25 Mean number of days per annum which are optimal for the *C. partellus* larval stage in winter season [October – March]: ECHAM5/MPI-OM GCM's present climate

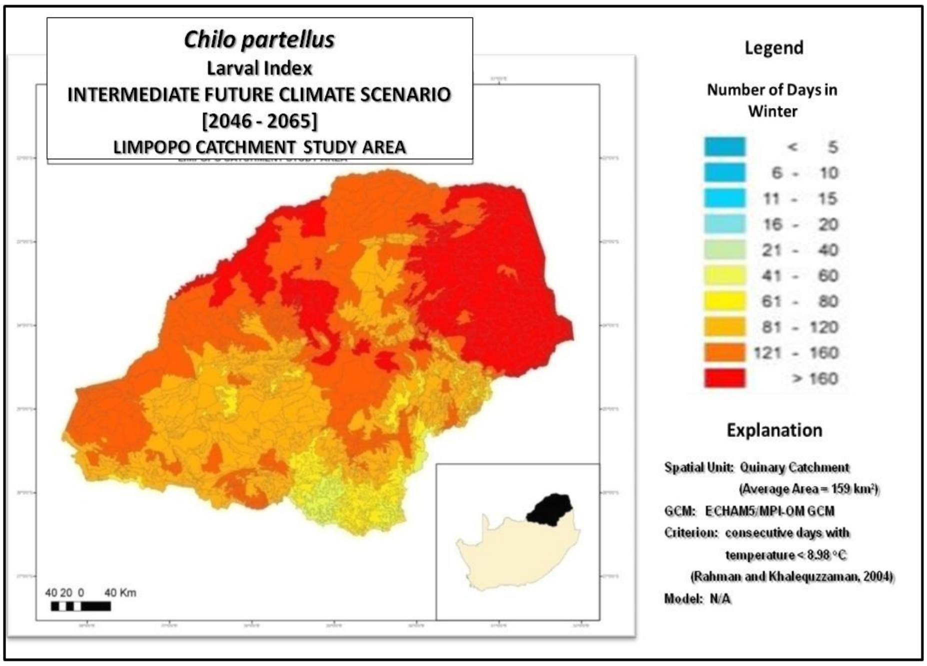


Figure D.26 Mean number of days per annum which are optimal for the *C. partellus* larval stage in winter season [October – March]: ECHAM5/MPI-OM GCM's intermediate future climate

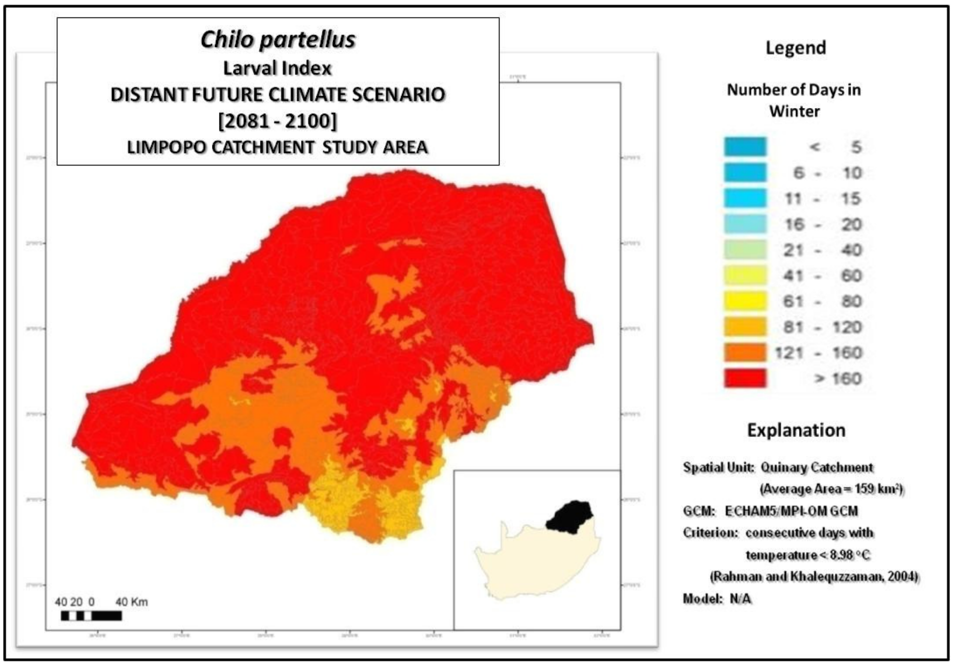


Figure D.27 Mean period (days) of *C. partellus* larval stage in winter season [October – March]: ECHAM5/MPI-OM GCM's distant future

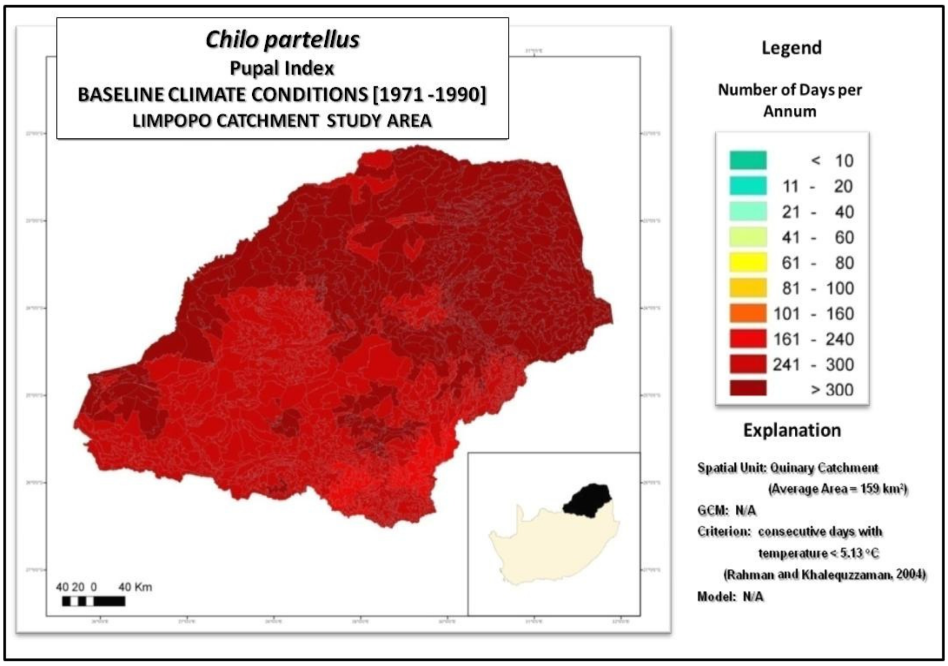


Figure D.28 Mean number of days per annum which are optimal for the *C. partellus* pupal stage: baseline climate conditions

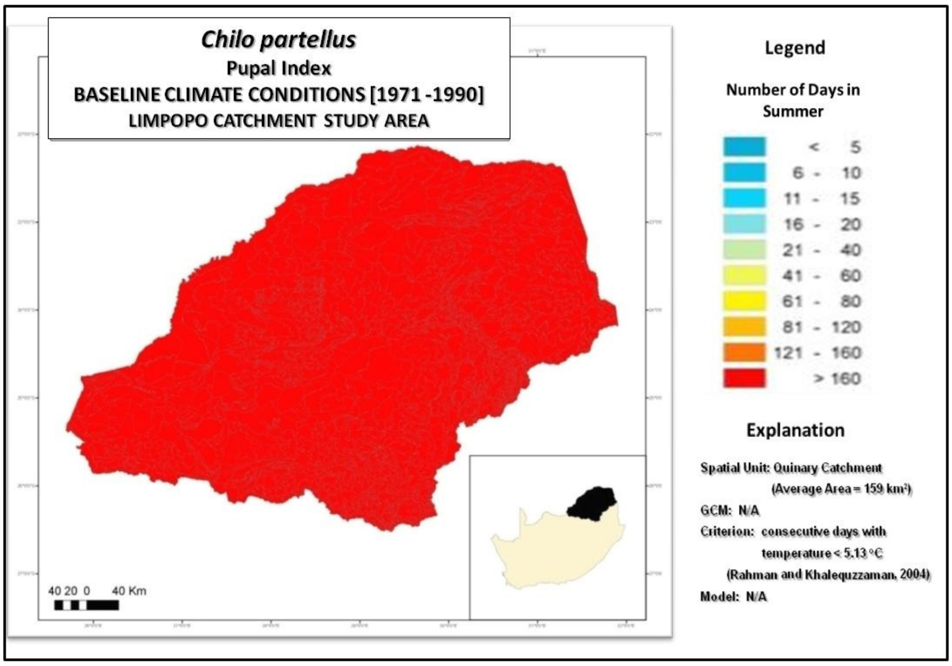


Figure D.29 Mean period (days) of *C. partellus* pupal stage in summer season [October – March]: baseline climate conditions

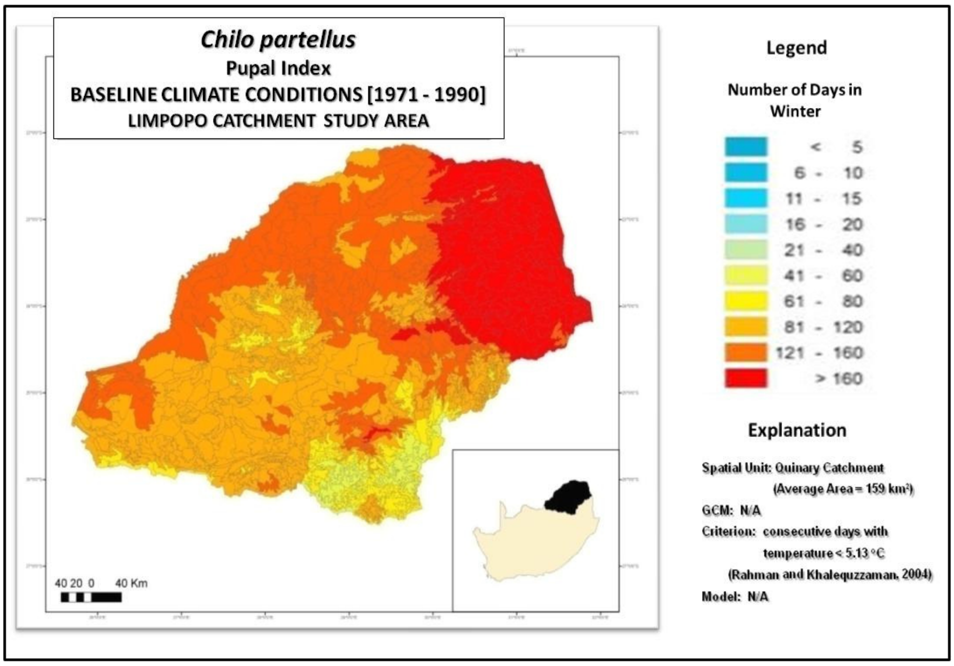


Figure D.30 Mean number of days per annum which are optimal for the *C. partellus* pupal stage in winter season [April – September]: baseline climate conditions

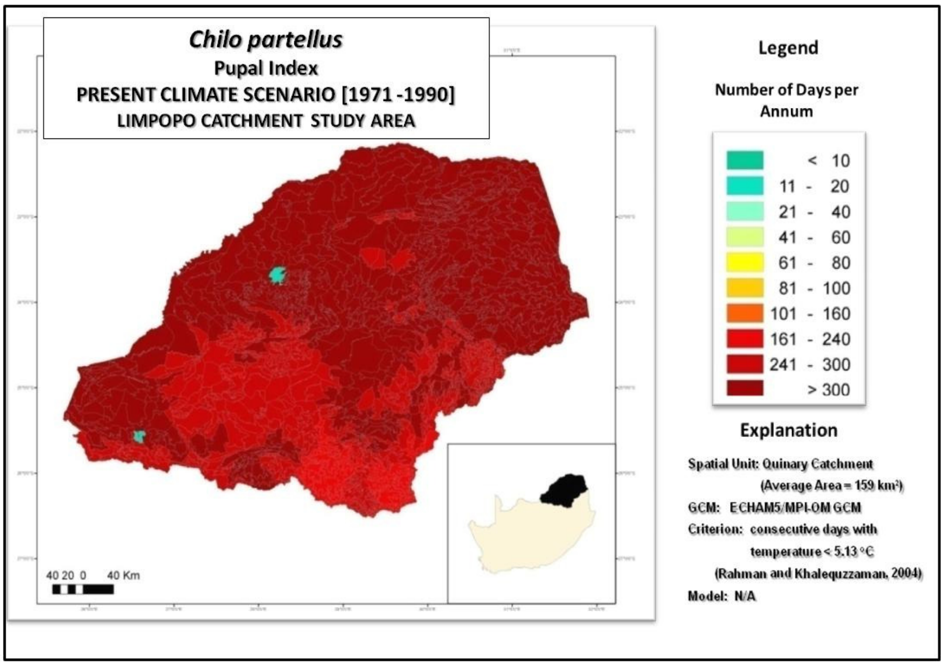


Figure D.31 Mean number of days per annum which are optimal for the *C. partellus* pupal stage: ECHAM5/MPI-OM GCM's present climate

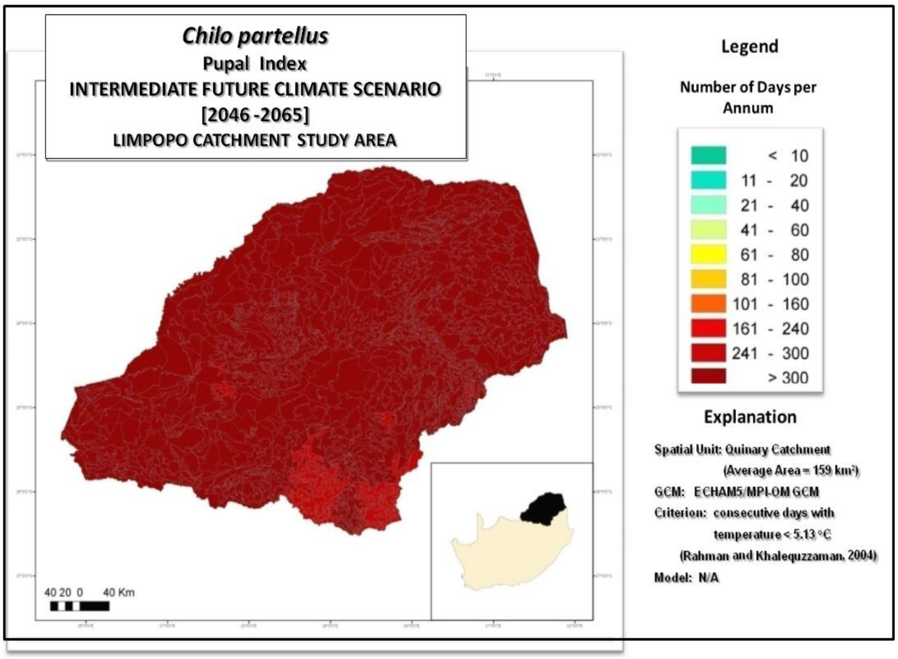


Figure D.32 Mean number of days per annum which are optimal for the *C. partellus* pupal stage: ECHAM5/MPI-OM GCM's intermediate future climate

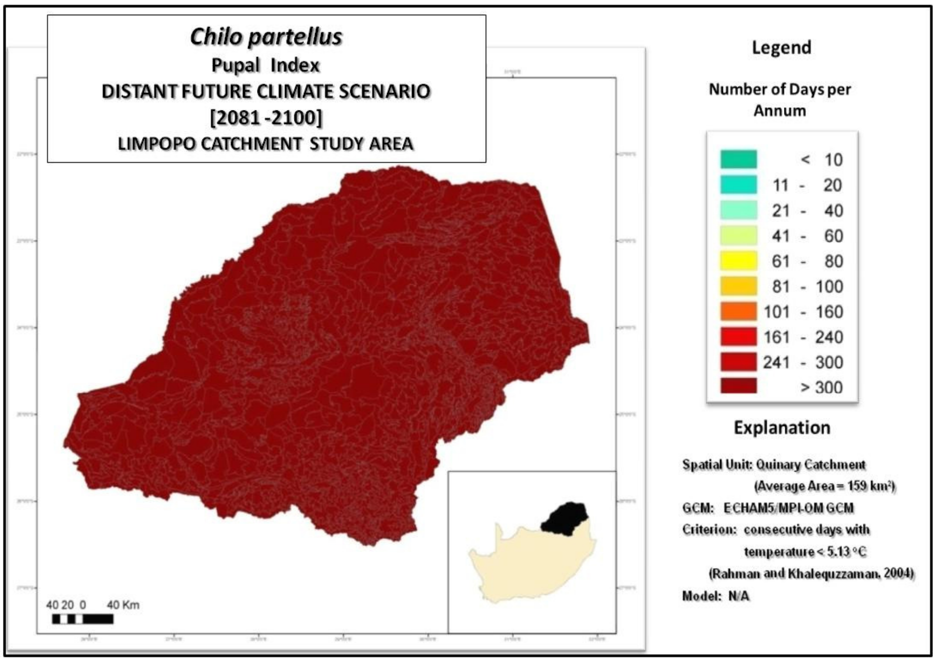


Figure D.33 Mean number of days per annum which are optimal for the *C. partellus* pupal stage: ECHAM5/MPI-OM GCM's distant future climate

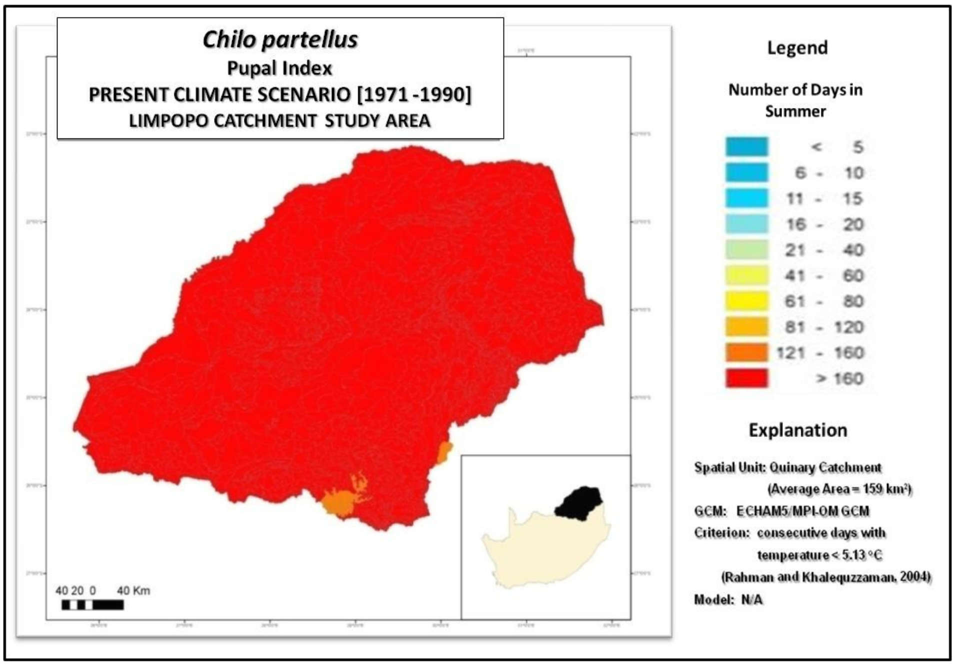


Figure D.34 Mean number of days per annum which are optimal for the *C. partellus* pupal stage in summer season [October – March]: ECHAM5/MPI-OM GCM's present climate

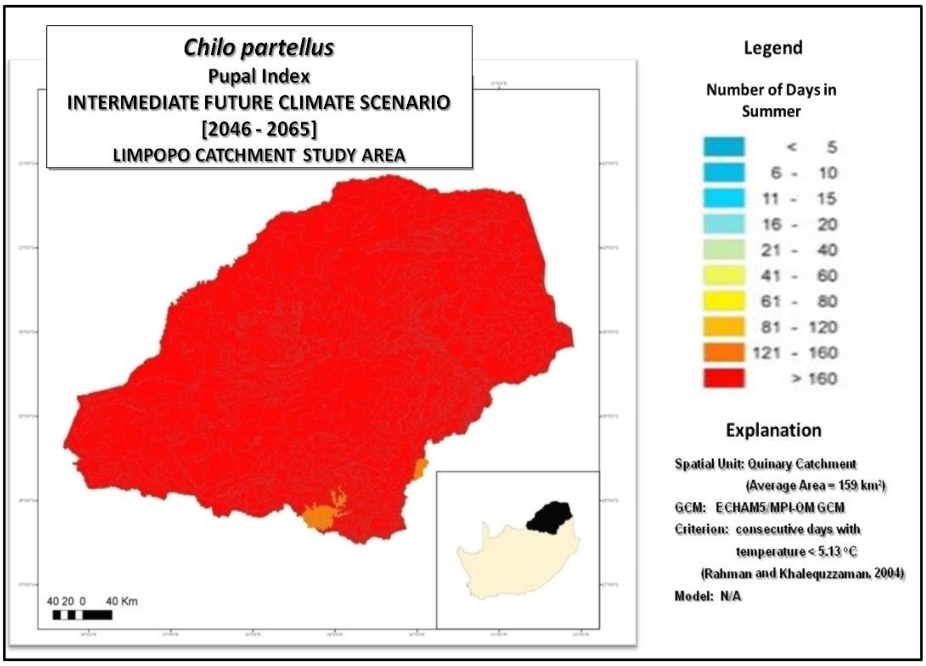


Figure D.35 Mean number of days per annum which are optimal for the *C. partellus* pupal stage in summer season [October – March]: ECHAM5/MPI-OM GCM's intermediate future climate

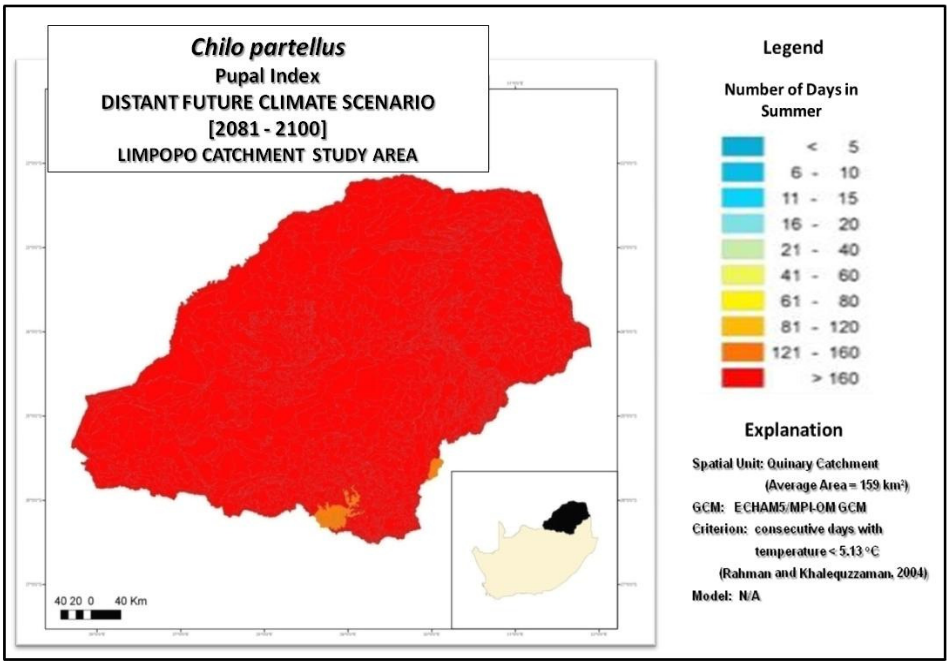


Figure D.36 Mean number of days per annum which are optimal for the *C. partellus* pupal stage in summer season [October – March]: ECHAM5/MPI-OM GCM's distant future climate

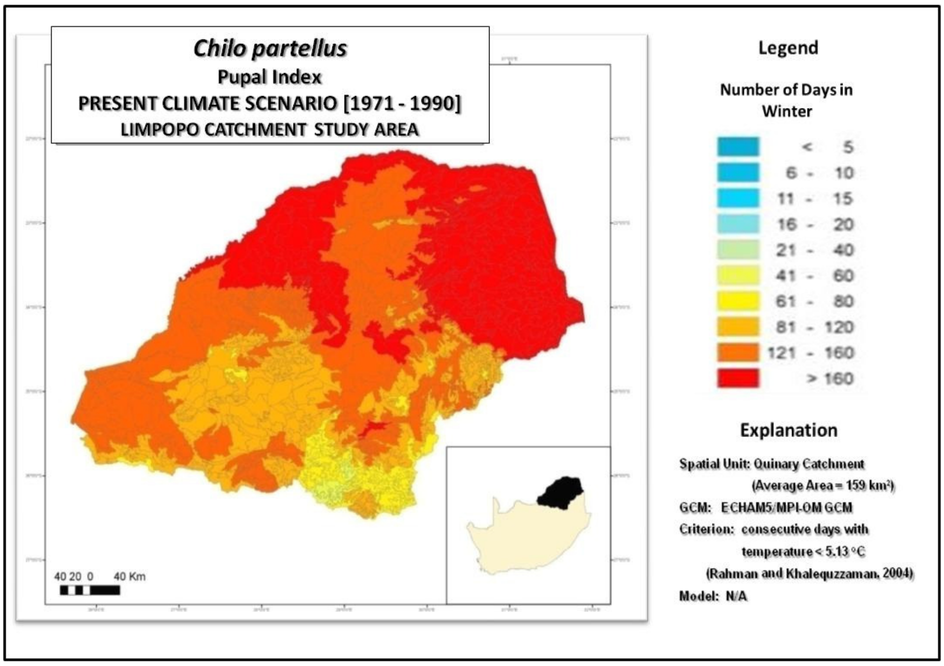


Figure D.37 Mean period (days) of *C. partellus* pupal stage in winter [April – September]: ECHAM5/MPI-OM GCM's present climate

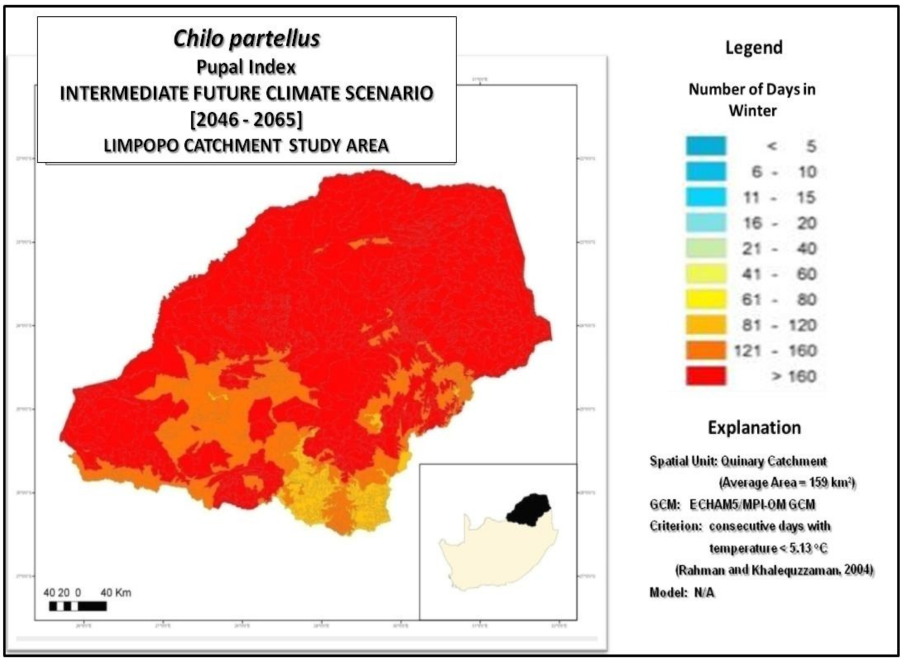


Figure D.38 Mean number of days per annum which are optimal for the *C. partellus* pupal stage in winter season [April – September]: ECHAM5/MPI-OM GCM's intermediate future climate

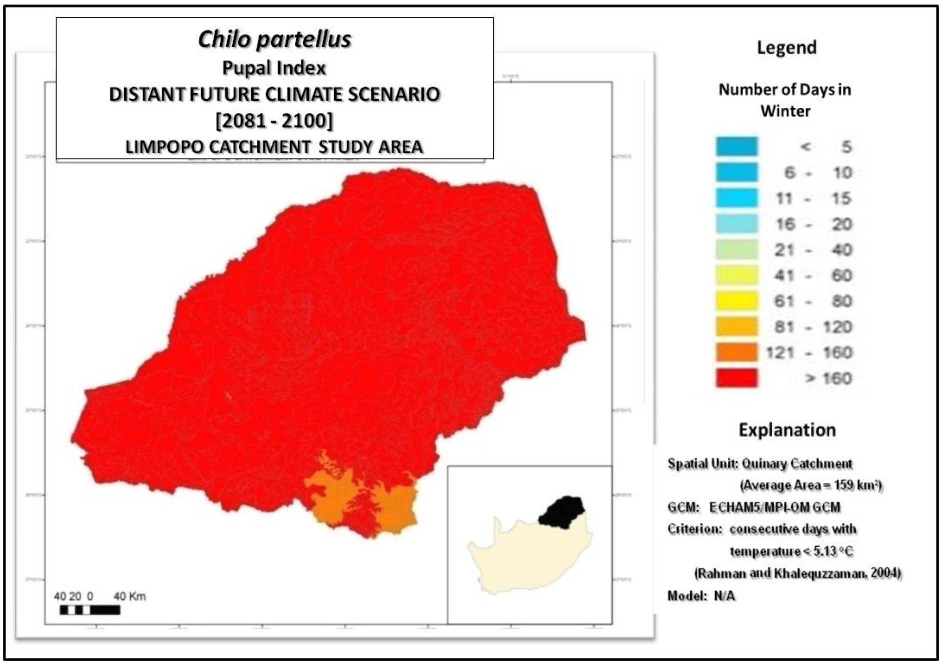


Figure D.39 Mean number of days per annum which are optimal for the *C. partellus* pupal stage in winter season [April – September]: ECHAM5/MPI-OM GCM's distant future climate

D.3 Ratio Changes in *Chilo partellus* Life Cycles

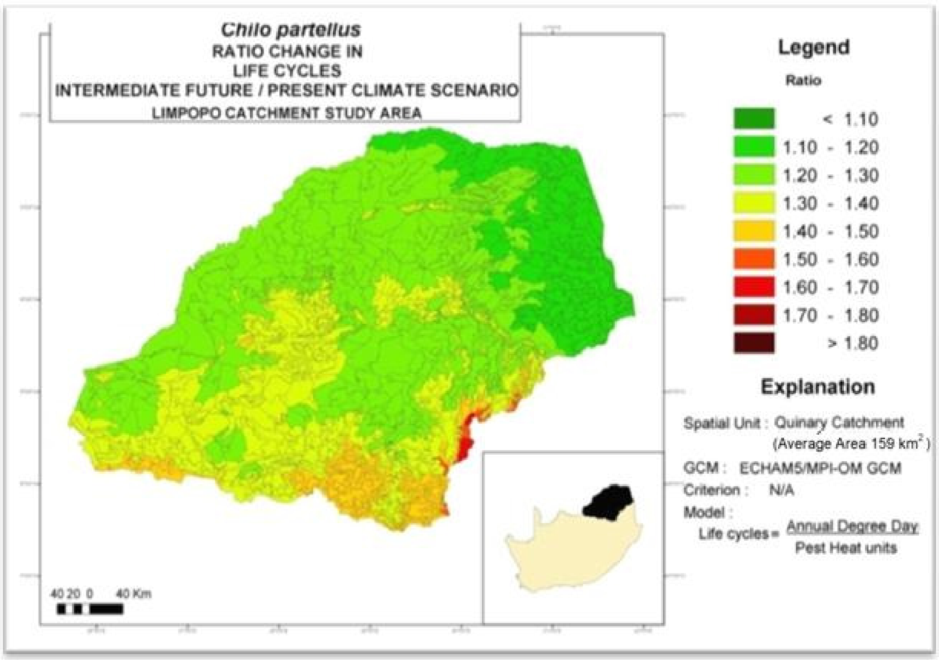


Figure D.40 Ratio changes in the number of days per annum which are optimal for the *C. partellus* life cycles: ECHAM5/MPI-OM GCM's intermediate future / present climate

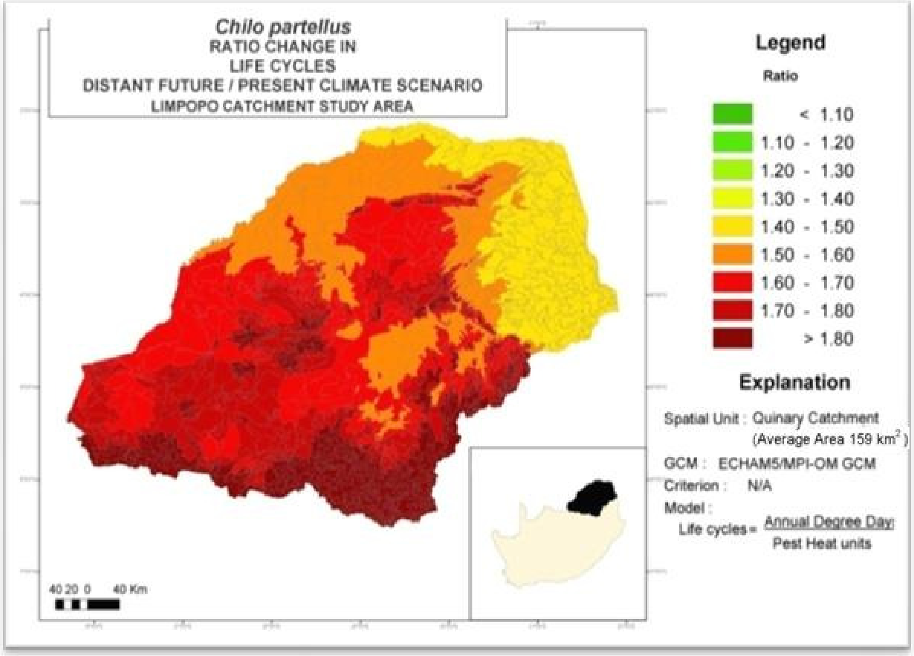


Figure D.41 Ratio changes in the number of days per annum which are optimal for the *C. partellus* life cycles: ECHAM5/MPI-OM GCM's distant future / present climate

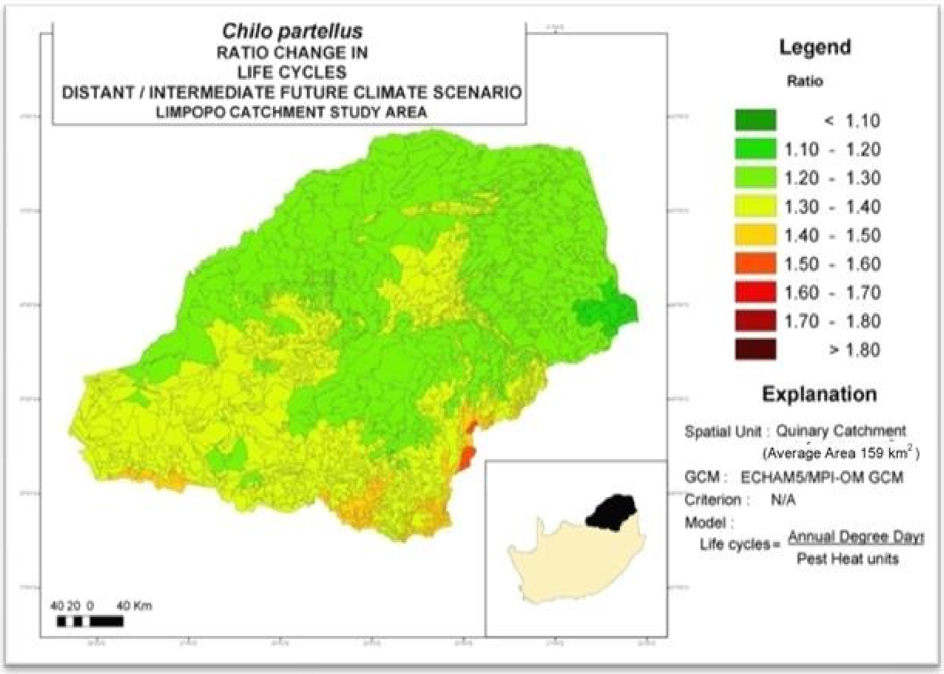


Figure D.42 Ratio changes in the number of days per annum which are optimal for the *C. partellus* life cycles: ECHAM5/MPI-OM GCM's distant future/intermediate climate

D.4 Determination of the *Chilo partellus* Mortality Index Patterns over the Limpopo Catchment

Mortality index is another method used for predicting the potential distribution of insect pests potential establishment, in this dissertation the *C. partellus*. The *C. partellus* development temperature thresholds, discussed in **Chapter 7**, are the temperatures below which the eggs were observed to not hatch and hence resulting in no pest development (Rahman and Khalequzzaman, 2003). The mortality index is the number of days per annum with a minimum daily temperature below a certain threshold in degrees celsius (^{o}C). The mortality index represents non conducive climatic conditions for a particular developmental life stage of *C. partellus*.

The climate index (cf. **Equation D.4)** adopted from a study by Bezuidenhout *et al*. (2008) was used to determine the *C. partellus* mortality index. The mortality index was computed for daily baseline climate conditions [1971 – 1990]. The computed mortality indices were mapped to display the spatial distribution likely *C. partellus* mortality (days per annum or season), over the Limpopo Catchment at a Quinary level.

The climate index is expressed as

$$MI = (\sum (\text{If } T_{min} > \beta, 1, 0)/n) \quad (D.4)$$

where CI = mortality index (number of days per annum not conducive for development),

β = threshold daily growth temperature (^{o}C),

T_{min} = minimum daily temperature (^{o}C), while

N = time period.

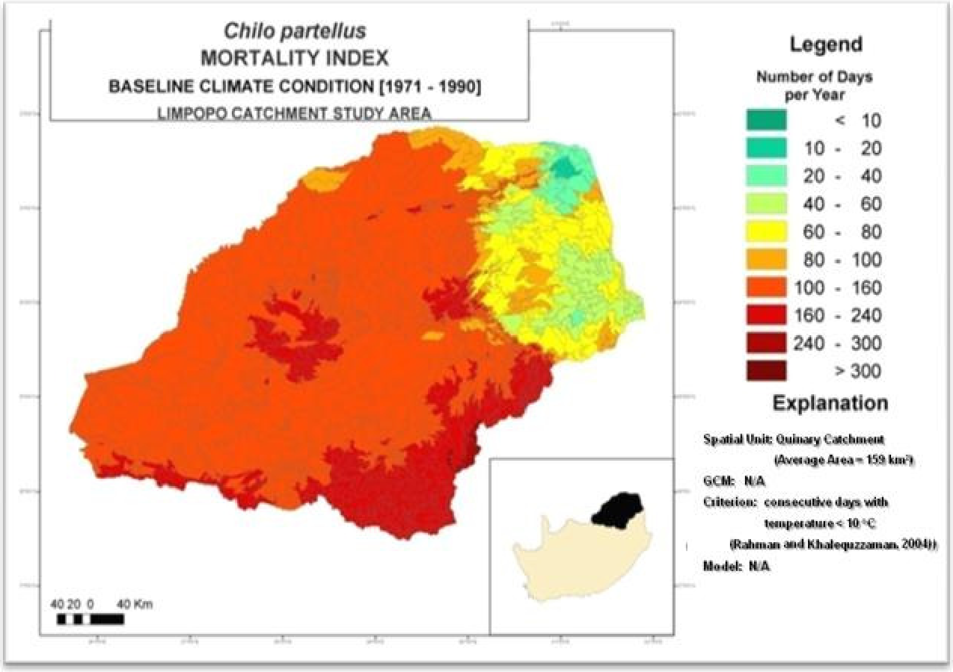


Figure D.43 Mean period (days) of *C. partellus* mortality per annum: baseline climate conditions

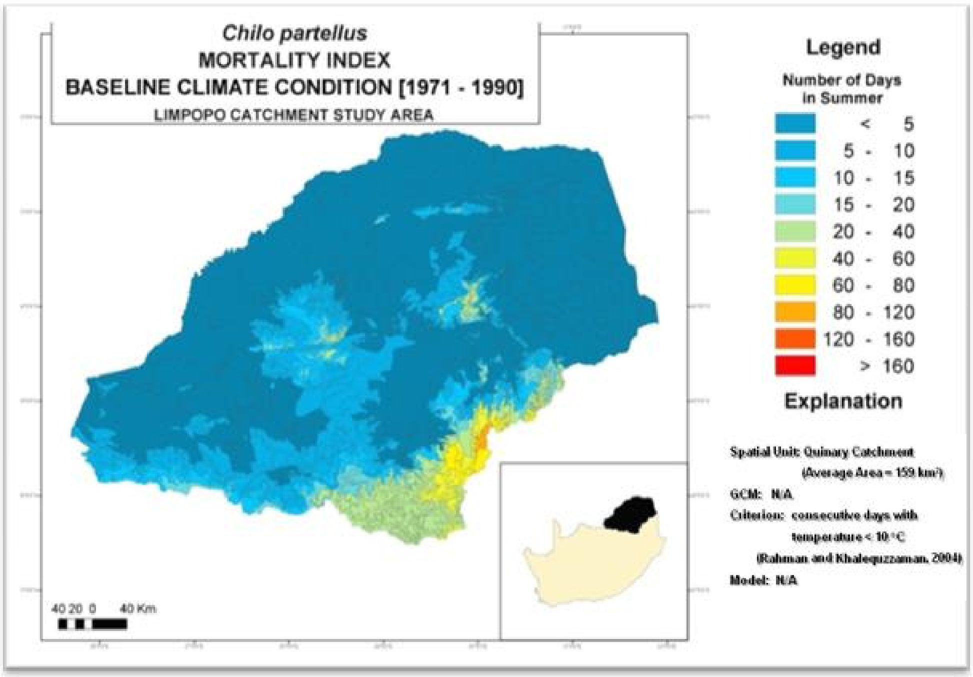


Figure D.44 Mean period (days) of *C. partellus* mortality index in summer season [October – March]: baseline climate conditions

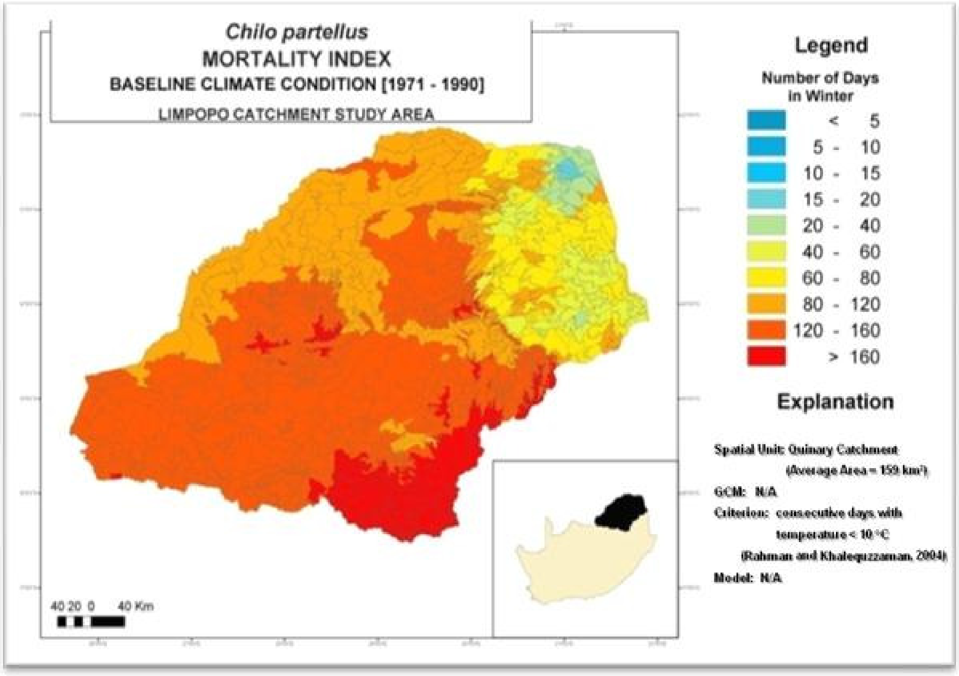


Figure D.45 Mean period (days) of *C. partellus* mortality in winter season [April – September]: baseline climate conditions

D.5 Validation of the ECHAM5/MPI-OM GCM's Output Against that of Baseline Climate Conditions for the Prediction of the *C. partellus* Mortality Index

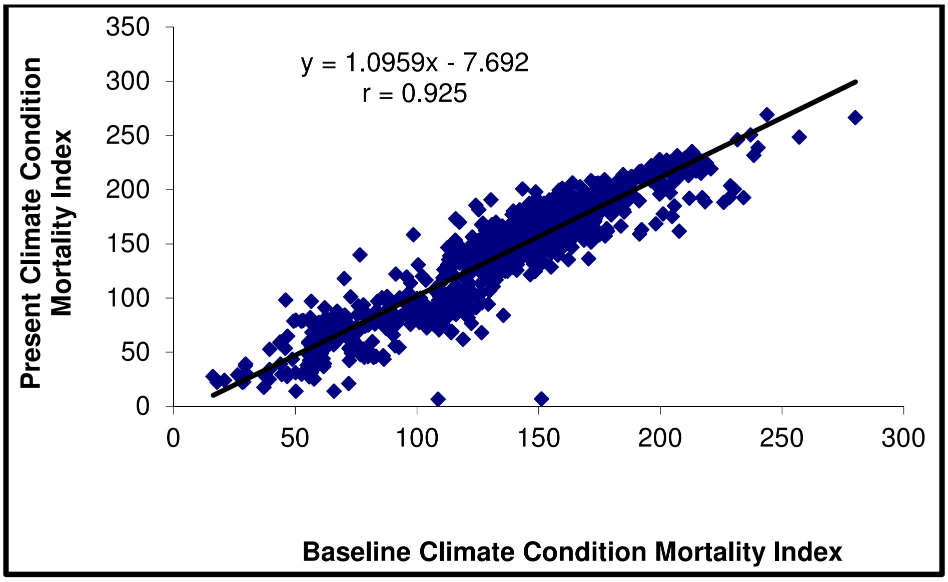


Figure D.46 Relationship between *C. partellus* mortality index generated from the ECHAM5/MPI-OM GCM's present climate scenario and baseline climate scenario for the same time period [1971 – 1990], with each point representing results from a Quinary Catchment

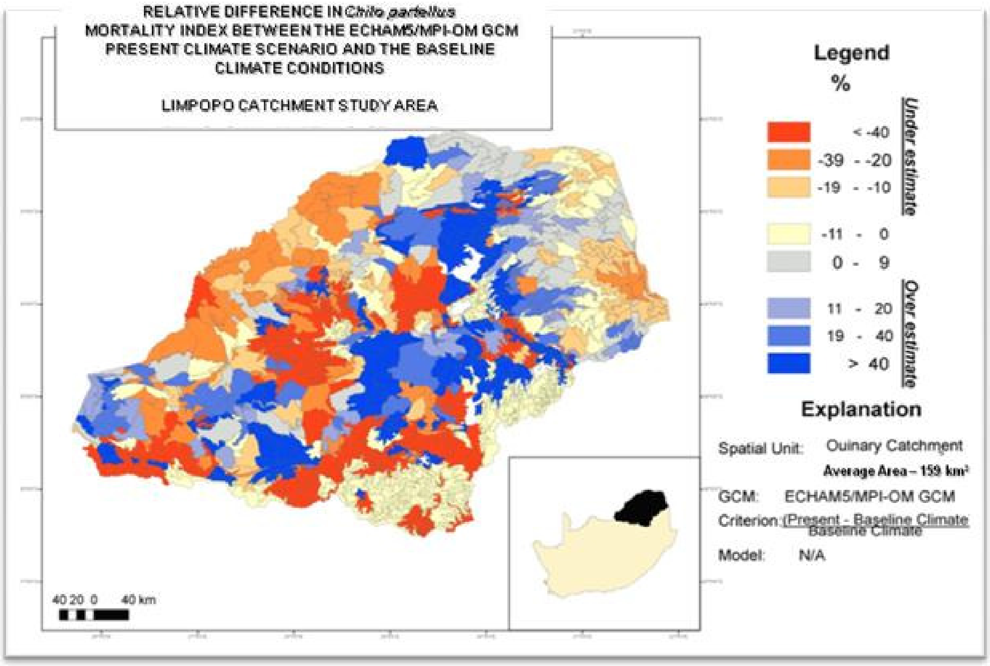


Figure D.47 Relative difference between predictions of *C. partellus* mortality index generated from the ECHAM5/MPI-OM GCM's present climate scenario vs. baseline climate conditions

D.6 Projections of Distribution Patterns of the *Chilo partellus* Mortality Index

If the temperature over the Limpopo Catchment were to increase as a result of human-induced climate change, the *C. partellus* distribution would not be affected by any reduction in the low temperatures days below its lethal limit, i.e. the mortality index. In testing this hypothesis, the ECHAM5/MPI-OM GCM's projections of present [1971 – 1990], intermediate future [2046 – 2065] and distant future [2081 – 2100] minimum daily temperature for a 20 year period, assigned to each Quinary in the Limpopo Catchment, were used to determine the distribution patterns of the number of days not conducive for *C. partellus*.

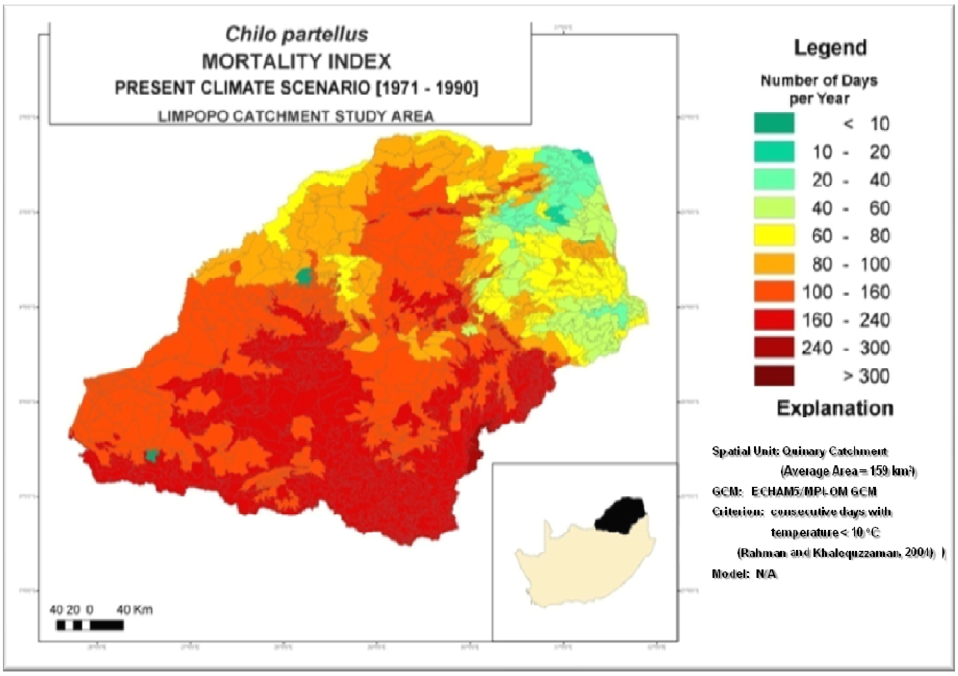


Figure D.48 Mean period (days) of *C. partellus* mortality per annum: ECHAM5/MPI-OM GCM's present climate

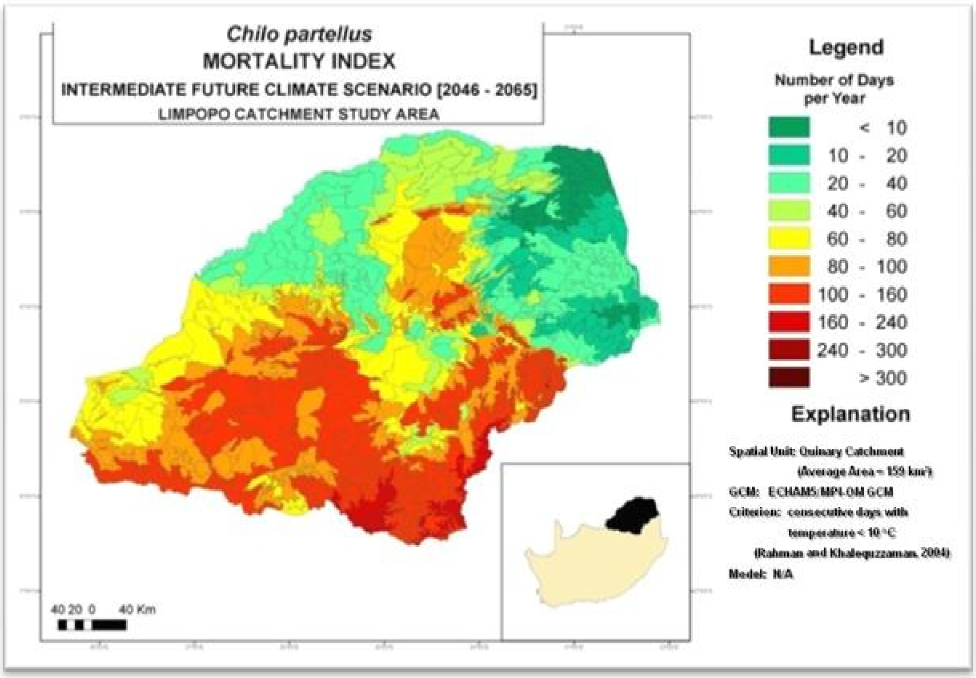


Figure D.49 Mean period (days) of *C. partellus* mortality per annum: ECHAM5/MPI-OM GCM's intermediate future climate

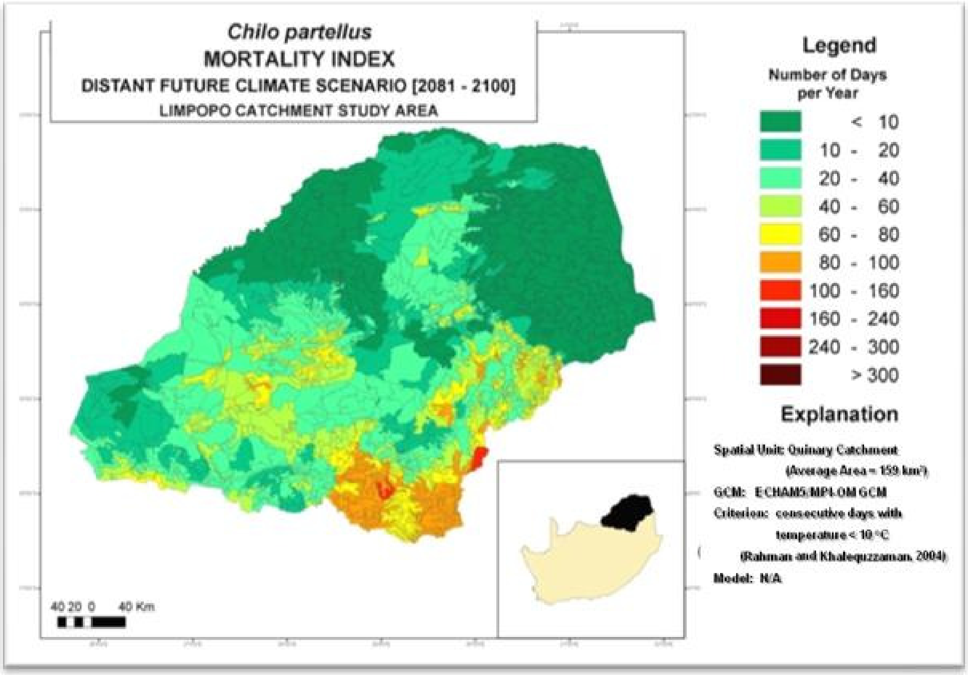


Figure D.50 Mean period (days) of *C. partellus* mortality per annum: ECHAM5/MPI-OM GCM's distant future climate

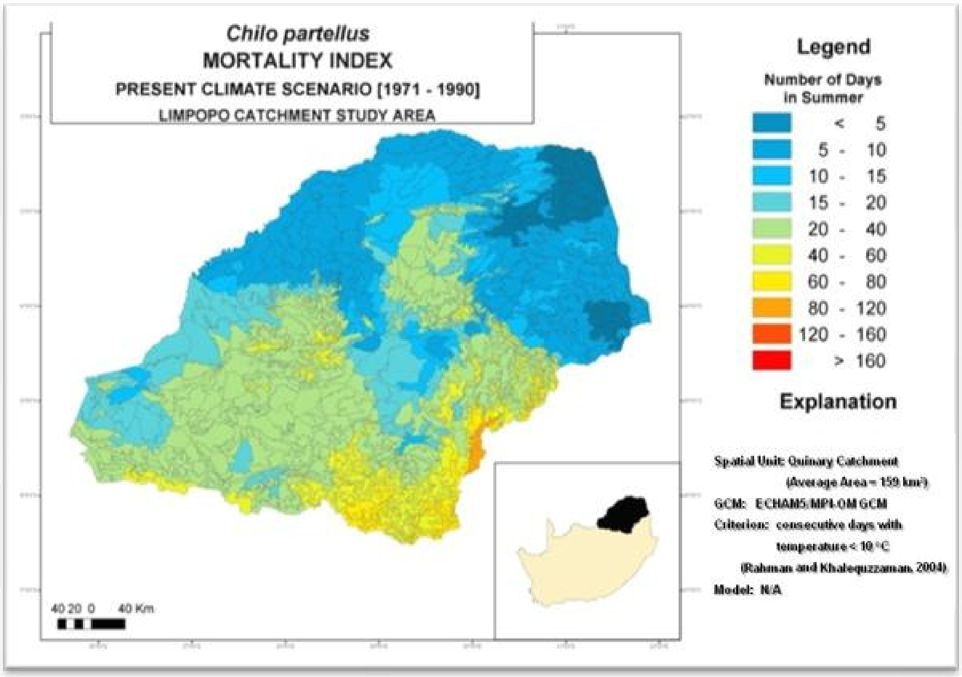


Figure D.51 Mean period (days) of *C. partellus* mortality in summer season [October – March]: ECHAM5/MPI-OM GCM's present climate

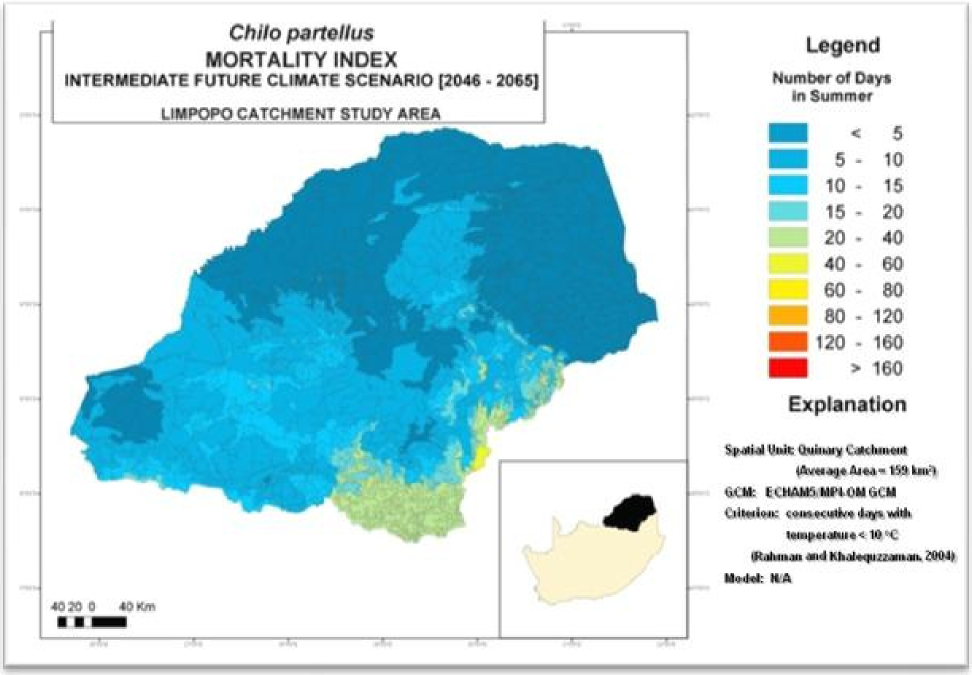


Figure D.52 Mean period (days) of *C. partellus* mortality in summer season [October – March]: ECHAM5/MPI-OM GCM's intermediate future climate

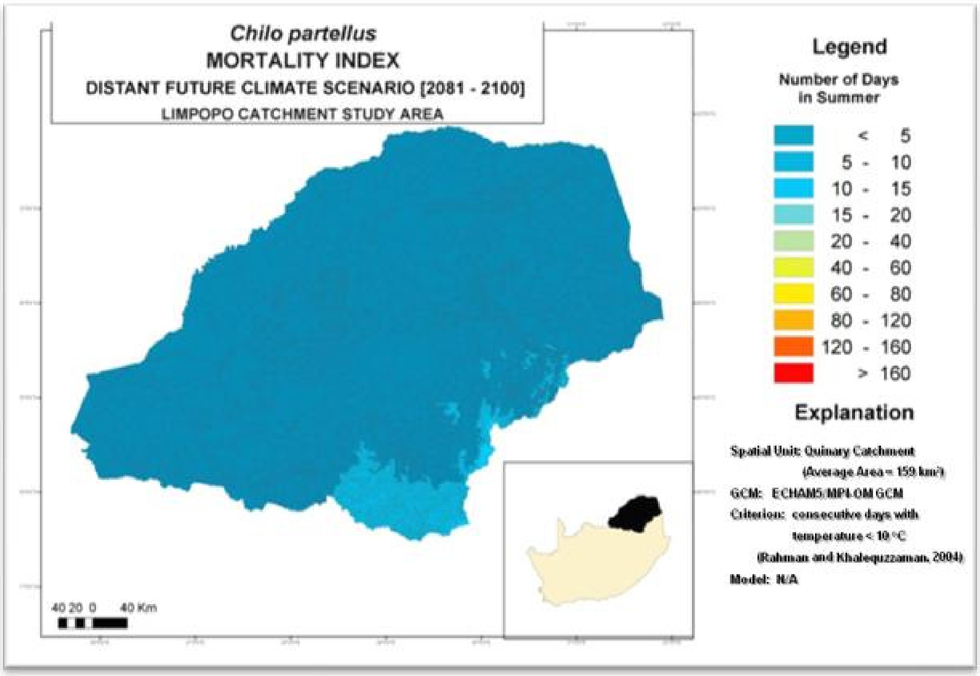


Figure D.53 Mean period (days) of *C. partellus* mortality in summer season [October – March]: ECHAM5/MPI-OM GCM's distant future climate

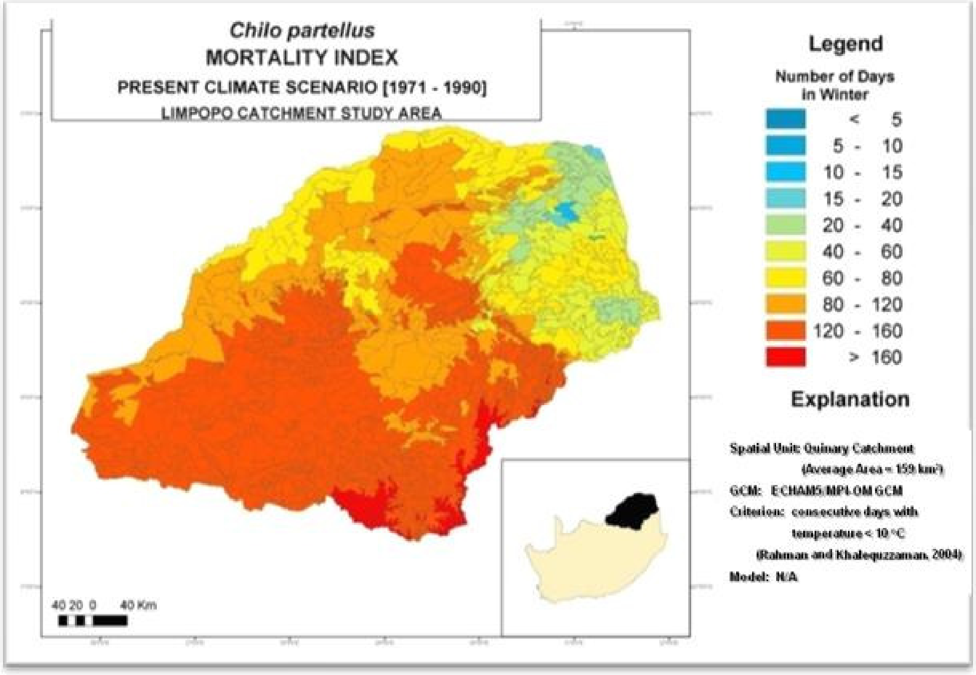


Figure D.54 Mean period (days) of *C. partellus* mortality in winter season [April – September]: ECHAM5/MPI-OM GCM's present climate

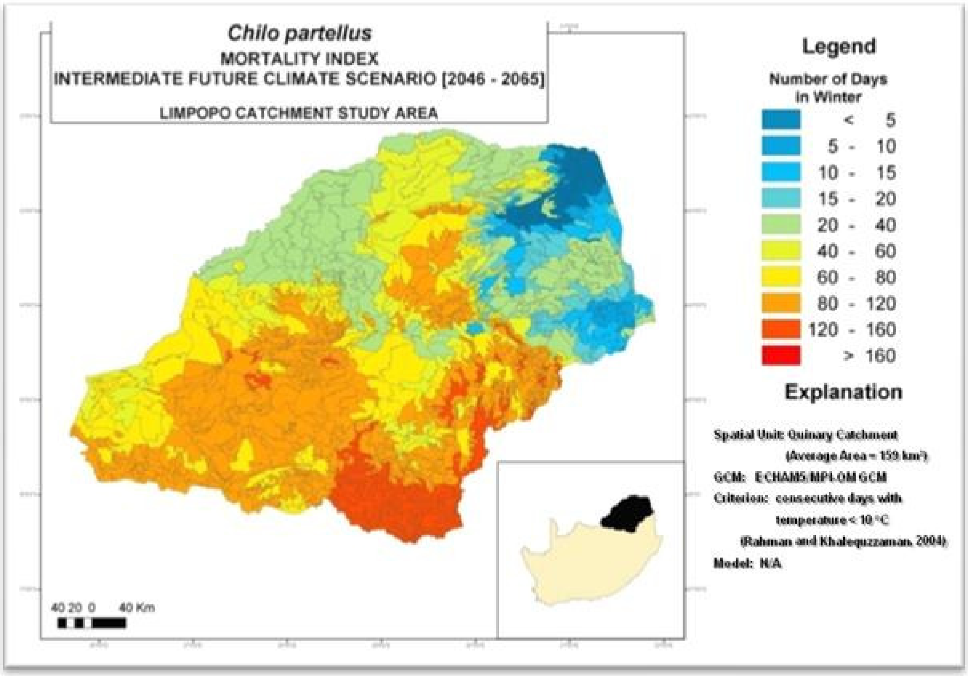


Figure D.55 Mean period (days) of *C. partellus* mortality in winter season [April – September]: ECHAM5/MPI-OM GCM's intermediate future climate

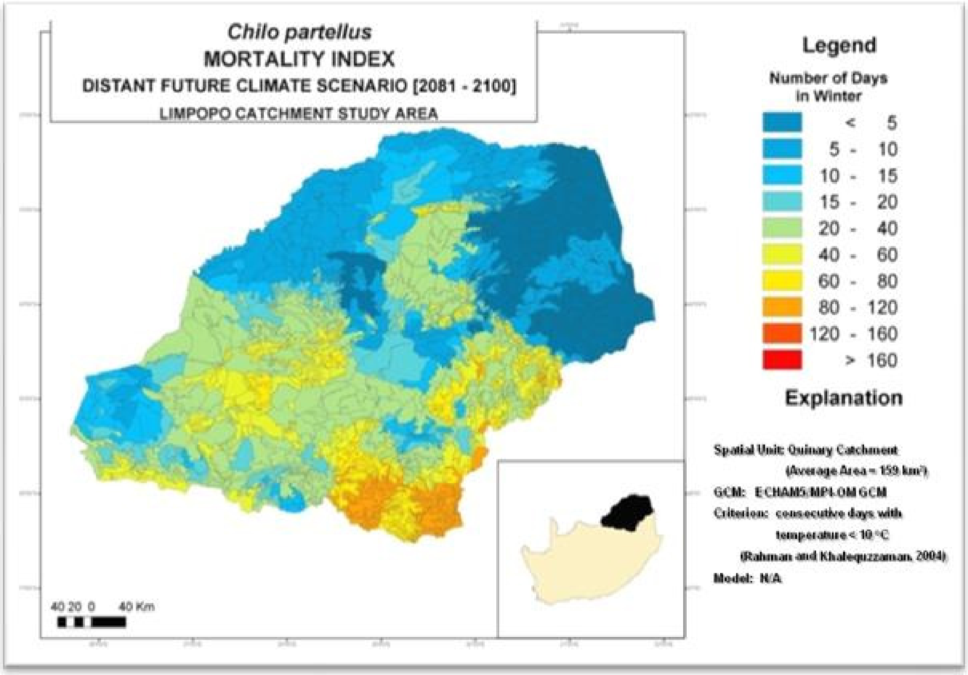


Figure D.56 Mean period (days) of *C. partellus* mortality in winter season [April – September]: ECHAM5/MPI-OM GCM's distant future climate

APPENDIX E: PROJECTED EFFECTS OF CLIMATE CHANGE SCENARIOS ON S*triga asiatica* WITCH WEED

In the previous appendix, the impacts of climate change on the *Chilo partellus* development period for each life stage, as well as its life cycles and mortality are presented. In this appendix, weed severity indices (WSI) for estimating the likely distribution of the agricultural yield *reduction* factor *viz*. *Striga asiatica*, a parasitic witch weed, are discussed. These indices were developed by the candidate from a review of literature and used for predicting its spatial distribution.

E.1 Chapter Overview

The objective of this study was to develop temperature based algorithms for estimating the likely distribution of the *Striga asiatica* over the Limpopo Catchment. This was undertaken by developing climate-indices for estimating the *S. asiatica* life cycles, *viz* seed conditioning, germination, emergence, flowering and production. The temperature database referred to in **Chapter 3**, of baseline climate conditions for the period 1971 - 1990 and the downscaled ECHAM5/MPI-OM GCM climate values for present [1971 – 1990], intermediate future [2046 – 2065] and distant future [2081 – 2100], were used in determining the likely distribution patterns in the *S. asiatica*. The analyses for the *S. asiatica* distribution were conducted at daily time-step and at high spatial resolution Quinary level over the Limpopo Catchment. Further analysis was conducted, *viz.* the validation analysis, to determine if there is a relationship between present climate scenario and baseline climate WSI predictions.

The validation analysis indicated that there is a relatively strong correlation between the present climate scenario and baseline climate condition estimation of WSI, thus suggesting that the model could better predict the baseline climate conditions. This would suggest a high confidence in the GCM's predictability of future climate conditions assuming that all other things are the same. This assumption does not hold considering the uncertainties surrounding the current GCMs, hence a good predictability of the baseline climate conditions does not necessarily imply increased confidence in the GCM climate projection.

The findings of the projections suggest a likely increase in the number of development day per year optimal for *S. asiatica* in the future climate scenarios, based on the ECHAM5/MPI-OM

GCM, mainly in the southern periphery of the Catchment. The statistics indicate a decline in the inter-annual variability of the life cycle's occurrence, from the northern towards the southern periphery of the Catchment. These analyses suggest a proliferation in the infestation of the *S. asiatica* under the ECHAM5/MPI-OM GCM projections over the Limpopo Catchment.

E.2 Introduction

Striga asiatica (*Lutea*) Kuntze (*Scrophulariaceae*) is commonly known as witch weed. The name 'witch weed' was given to this weed due to the consequences it poses on the growth and potential yields of its host plant, including its parasitic mode of attaching and penetrating into the host's roots, for direct extraction of water and nutrients (Shank, 2008). NBII and ISSG (2008) reported that *S. asiatica* can have a severe impact on human livelihoods by affecting agricultural production at subsistence farming level and hence contributing to aggravating hunger and poverty. This parasitic weed affects important crops mainly in agricultural lands with light soils, which are usually of low nitrogen fertility and which receive uneven or light rainfall. Wet soils and/or nitrogen rich soils limit the weed's growth or reduce host plant damage. Important crops likely to be infected are maize, millet, rice, sorghum, sugarcane, cowpea, sunflower, tomatoes and some legumes roots (APHIS, 2000; CDFA, 2006). According to Johnson (2008), *S. asiatica* has a wide distribution and is listed as a weed in approximately 35 countries, including countries in Africa, India and America.

S. asiatica is an indigenous parasitic weed found in semi-arid and tropical grassland regions of Africa, Asia and Europe, and it also thrives in temperate regions outside its niche environment (NBII and ISSG, 2008). In the Limpopo Province (within the Limpopo Catchment) McNab (2005) documented that *S. asiatica* was observed attacking subsistence farmed crops such as maize, sorghum and millet, as well as wild grass. In South Africa witch weed was reported as the most serious weed likely to result in complete crop yield loss (Waterhouse and Mitchell, 1998). During a visit to the Limpopo Department of Agriculture Towoomba (Bela-bela) research station, maize crops were found to be preferred by the *S. asiatica* (**Figure E.1**), rather than than sunflower. Total losses from infestation might have a greater negative impact on emerging agricultural production compared to commercial farming, mainly because commercial farmers are able to afford the high costs, they have access to expertise for the control of parasite infestation, and hence they have means to recover from total yield losses.

Figure E.1 Maize crop infestation by Red-flowered *Striga asiatica* at Towoomba research station, Limpopo

Striga asiatica occurrence is dependent, inter alia, on its threshold climatic conditions (which are discussed below in this Chapter) being met in regions into which the weed has been introduced. Witch weed was selected as an agricultural reduction factor for the reasons mentioned above and its distribution was mapped based on laboratory established threshold temperature parameters. The threshold parameters were obtained from a review of literature.

E.3 The *Striga asiatica* (*Lutea*) Kuntze Witch Weed Life Cycle

There are numerous modes by which this *S. asiatica* can be introduced to new regions by seed dispersal. In the literature these modes are said to be "wind, water, soil movement, human activities, and by clinging to the feet, fur, or feathers of animals, farm machinery, tools, shoes, and clothing" (NBII and ISSG, 2008: 2). According to a CDFA (2006) report, *S. asiatica* requires approximately 60 days to complete its life cycle (from germinating seeds to producing viable seeds for the next generation). Eight distinct life development stages of *S. asiatica* were identified in literature:

- Seed production stage: Production of viable seed by the weed starts within 2 weeks from the flowering stage (CDFA, 2006). The seeds are very small, with each having a size ranging from 0.10 to 0.40 mm and a weight of about 3-5μg (micrograms). In the Limpopo Province, *S. asiatica* was observed producing about 800 to 500 000 seeds per capsule, depending of the species level of development. *Striga asiatica* is not easily controllable owing to its ability to produce a large amount of seeds (Shank, 2008).

- Seed dormancy and after- ripening stage: Seeds require an after-ripening period to germinate within the same season. The seeds must be conditioned in a moist environment before they respond to a germination stimulant from a potential host plant. For example, in semi-arid regions, such as the study area, germination is linked with the beginning of the rainfall season with two or more consecutive days of precipitation. These requirements ensure that the newly developed *S. asiatica* seeds do not germinate too late in the growing season, when the host plants are scarce (Rich and Ejeta, 2007). The after-ripening period required under warm climate conditions is approximately 6 weeks and for cold climatic conditions as long as 40 weeks. In contrast, dormant seeds can endure freezing conditions up to 49 days before the seeds are no longer viable for germination (CDFA, 2006). Under field conditions seeds can remain viable for germination in the soil for up to 14 years or until optimal conditions for germination are met (Rich and Ejeta, 2007).
- Conditioning stage: After-ripening, *S. asiatica* seeds require a pre-conditioning period. This is a period when seeds which are imbedded in soils become moistened due to the start in the rainfall season and optimal temperature regimes (estimated to be between 20 and 40 ^{o}C) for a period of 10 to 21 days. This period often coincides with the period when the host plants begin to germinate (Rich and Ejeta, 2007).
- Germination stage: Seeds that have been pre-conditioned and after-ripened will germinate in response to chemical stimulants from the host plant, which guides the weed's haustorium to the host's roots. Without a host plant, the germinated seeds will survive for a few days and may radically elongate by 2-3 mm in about 4 to 10 days, while the seed is sustained by a small seed reserve (Rich and Ejeta, 2007). When suitable conditions are met, germination could occur within 24 hours. However, seed germination might decrease and some seeds enter into secondary dormancy if there is no chemical stimulant within 3 weeks of the conditioning period (CDFA, 2006).
- Attachment and penetration stage: At this stage *S. asiatica* develops haustorium for attaching to, and penetrating into the host plant roots, which is essential for its underground development, then emergence above the ground, followed by flowering and seed production (Rich and Ejeta, 2007). Once the haustorial hairs of the *S. asiatica* have developed and attached to the host plant's root, it penetrates into the host plant

roots by opening a connection between the host and parasite xylems. No direct connection is formed with the host plant's phloem.

- Underground development stage: After the haustorial hairs have created a connection with the host, the haustorium may continue developing. The *S. asiatica* will extract the host plant's sugars and inorganic mineral for development and shoot.
- Emergence stage: A few days after the xylem connection between *S. asiatica* and the host plant have been formed, the cotyledon leaves emerge from the seed coat and within a few weeks the shoots emerge above ground.
- Flowering: S*triga asiatica* flowers a few weeks after emergence and self-pollinates (**Figure E.1**). Seed production starts approximately 2 to 3 weeks after pollination (CDFA, 2006; Rich and Ejeta, 2007).

Rich and Ejeta (2007) state that additional information on the *Striga species* biology may lead to the improvement of methods for controlling the parasite in agricultural crop fields. Available control methods of the *Striga species* include resistant hybrid host plants, herbicides, biological control, improved agricultural practices and biotechnology.

Striga asiatica germination time, the potential to attach to a suitable host (i.e. exposure to a chemical stimulant from the host) and chances of effectively producing seeds for infestation are linked to climatic conditions and the agricultural ecosystem. *Striga asiatica* seed conditioning and germination were found to be dependent on temperature, with higher temperature regimes during conditioning resulting in reduced conditioning time for the seeds to germinate. Seed germination would only occur if the following conditions are met: conditioning time, concentration of the stimulant (release by the host plant) and temperature, i.e. for the seeds to shift from the conditioning to the germination phase (Hsiao *et al*., 1988).

E.4 Response of *Striga asiatica* Seed Conditioning and Subsequent Germination to Temperature

The findings of the study by Hsiao *et al.* (1988) on the effects of temperature on seed germination of *S. asiatica* were that the seed conditioning period before germination was dependent on temperature, with high temperatures resulting in a shorter seed conditioning time required for germination (cf**. Figure E.2**). Seeds treated in water and 10^{-8} M *dl-strigol* concentrations (a chemical to induce germination) were conditioned up to 52 days and even though conditioning had begun, the seeds showed no signs of germination. Only after an additional 2 days at 30°C did the seeds germinate (about 74 to 91% seed germination). Thus, either lower temperatures by themselves, or both lower temperature regimes and *strigol* treatment in the experiment, indicated that seed conditioning at low temperatures need longer conditioning time or require a higher temperature for few days for successful conditioning.

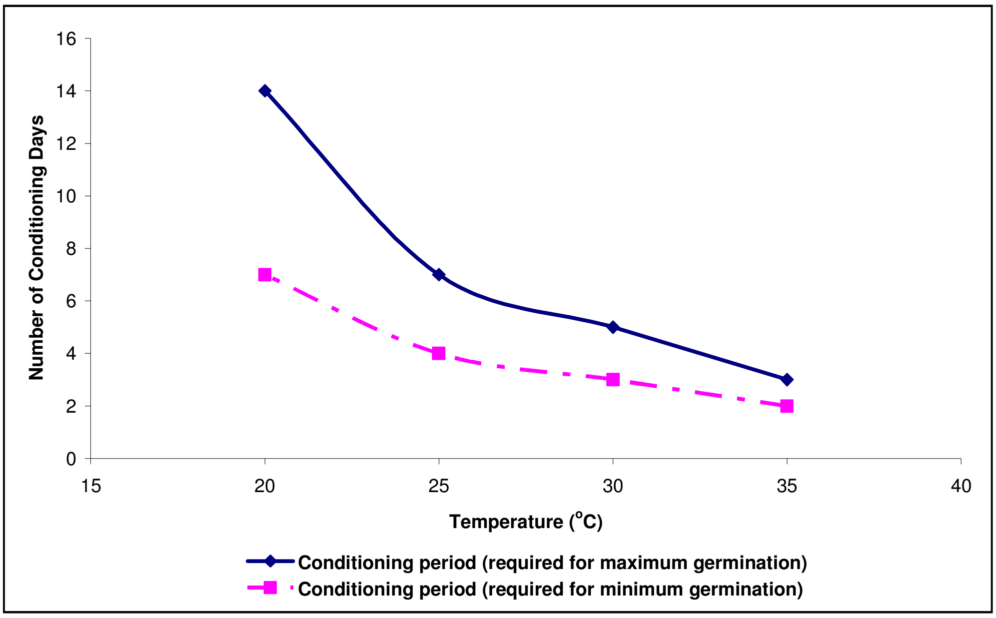


Figure E.2 Response of the *Striga asiatica* seed conditioning period in days (in water) required before germination, to a range of temperature regimes (after Hsiao *et al.*, 1988) i.e. without *dl-strigol* or a chemical stimulation for seeds to emerge from the conditioning phase

The Hsiao *et al.* (1988) laboratory experiment study has shown evidence of the shifting of *S. asiatica* seeds from the conditioning to the germination stage to be dependent on the "conditioning period and temperature, and *strigol* concentration used during conditioning and/ or germination period(s)" (Hsiao *et al.*, 1988: 71). **Figure E.3** shows the percentage of *S. asiatica* germination responses to increase in temperature, and also the conditioning period in **Figure E.2** before germination. A conclusion which can be deduced from their study is that the first stages of development of *S. asiatica* are dependent on temperature regimes. Responses of other development stages to temperature are discussed in the following section.

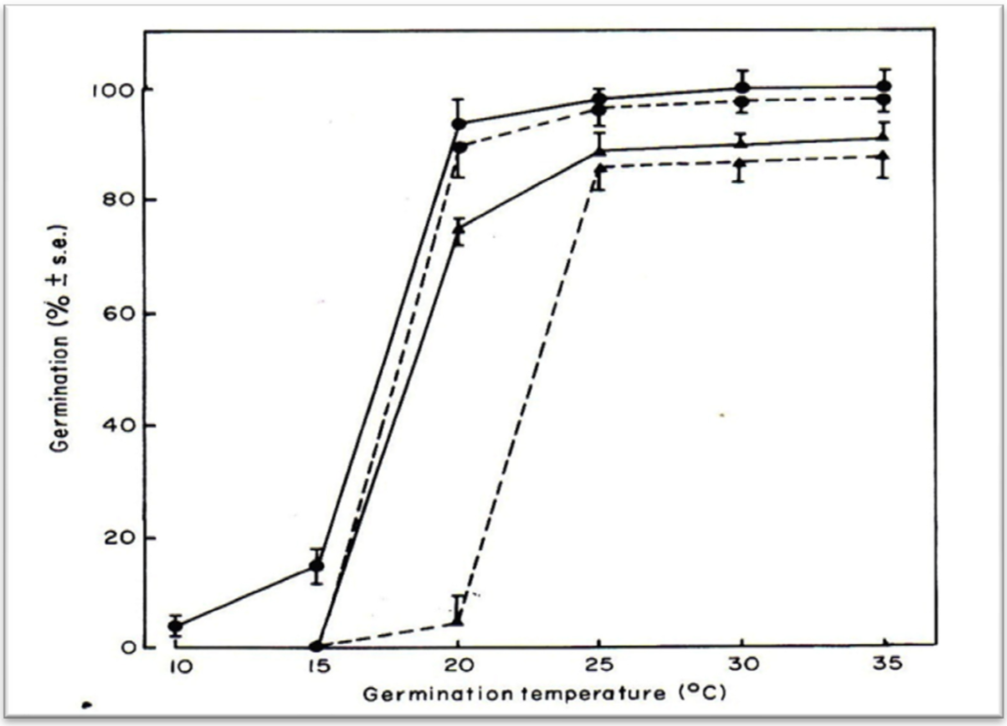


Figure E.3 Percentage of germination (including standard error, s.e.) of one year old *S. asiatica* seed conditioned in water (–) or 10^{-8} M *dl-strigol* (- - -) at 30°C for 7 (▲) or 14 (●) days before terminal treatment with fresh *dl-strgol* of 10^{-6} M at 10 to 35 °C for 24 hours (Hsiao *et al.*, 1988)

E.5 Determination of *Striga asiatica* Distribution Patterns

The techniques for determining the potential distribution patterns of the *S. asiatica* climatic niche areas, on the basis of its prevalence rates or WSI over the Limpopo Catchment, was developed from the literature review and the procedures are discussed below. WSI is defined as the rate of a particular *S. asiatica* stage occurrence (in number of days per season), where the temperature are above its lower developmental temperature for a specific stage of the life cycle.

Patterson *et al.* (1982) assessed the effects of temperature on *S. asciatica* in six day/night temperature conditions (ranging from 17/11, 20/14, 23/14, 23/17, 26/17, 26/20, 29/20, 29/23, 32/23 to 32/26 °C day/night temperatures, respectively) in controlled greenhouse environments, on sorghum and maize host plants in the USA. Their findings were that temperature played an important role in the development of witch weed and its impact on the host plant. In Patterson *et al.*'s (1982) experiment, seeds were conditioned and later germinated with ethylene stimulation above a constant night and day time or minimum and maximum daily temperature threshold with a mean of 16 ^{o}C. Germination was observed above a constant mean daily temperature threshold of 20 ^{o}C. Furthermore, *S. asciatica* emergence from the soil ground, flowering and viable seed production was observed at mean daily threshold temperatures above 22 ^{o}C.

Assuming that conditions were met for *S. asiatica* to occupy the Catchment and no other factors other than threshold daily temperatures were affecting the development, the threshold conditions mentioned above, which are critical for the *S. asiatica* development stages, were used in developing the following WSI:

A. Seed conditioning index: This is defined as consecutive days with an average temperature above 16 ^{o}C, with this index denoting conditions required before germination. It was assumed that soil moisture conditions required for conditioning are met throughout the year. The higher the index is above the threshold temperature, the more likely it is for the witch weed to be conditioned.
B. Germination index: This is defined as consecutive days with a mean temperature above 20 ^{o}C. This index represents the potential optimal distribution areas for *S. asiatica* germination, assuming the presence of host plants. The higher the index is above the threshold temperature, the more likely the witch weed is to germinate. Germination will be possible if the seeds are conditioned and exposed to adequate soil moisture.
C. Emergence-flowering-seed production index: This is defined as consecutive days with a mean temperature above 22 ^{o}C. The higher the number of consecutive days above the threshold temperature, the more likely the witch weed will emerge, flower and produce seeds. The three stages in *S. asiatica* infestation were merged in this analysis, because they share the same mean threshold temperature. It should be noted that these stages do not occur at the same time, but in succession. The *S. asiatica* seeds will emerge above ground only if its seeds are germinated, after development, flowering will occur at the same threshold temperature and hence produce viable seeds for the next generation or life cycle.

Indices were fitted through the algorithm below;

$$WSI = (\sum (\text{If } T_{mean} > \beta i, 1, 0)/n) \quad (E.1)$$

where WSI : weed severity index;

B : threshold temperature (^{o}C);

T_{mean} : sum of minimum and maximum daily temperature (^{o}C) divided by 2; and

n : time period (for example 20 years).

The WSI algorithm (**Equation E.1**) and the above mentioned A, B and C indices or temperature threshold were used to simulate the climatic niche i.e. the rate of occurrences (number of days per annum/season) of the *S. asiatica* development stages. The twenty year baseline climate condition [1971 – 1990] data of daily maximum and minimum temperature from the South African daily temperature database, compiled by Schulze and Maharaj (2004), was used in simulating the climatic niche of the *S. asiatica* development stages. These climatic niche areas simulations of the WSI development stages were used to produce maps of potential the distribution patterns of *S. asiatica* conducive days over the Limpopo Catchment at Quinary level. The simulations were of the following statistics i.e. mean number of days per year, summer [October – March] season and winter [April – September] season, including the inter-annual coefficient of variability (CV, %), to describe the simulated *S. asiatica* distribution patterns in the Catchment.

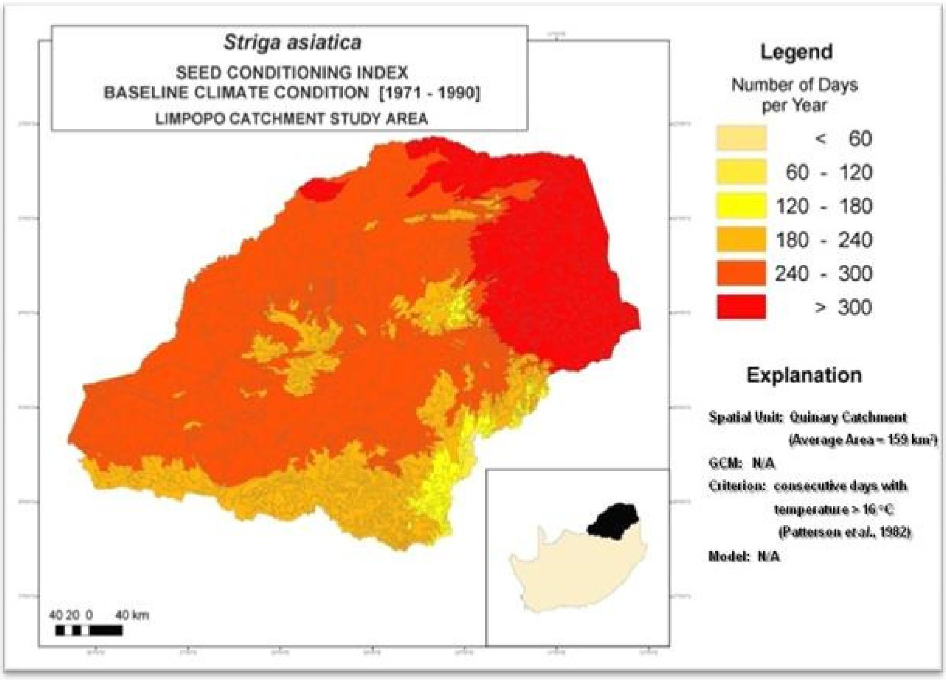


Figure E.4 The *Striga asiatica* seed conditioning index for baseline climate conditions

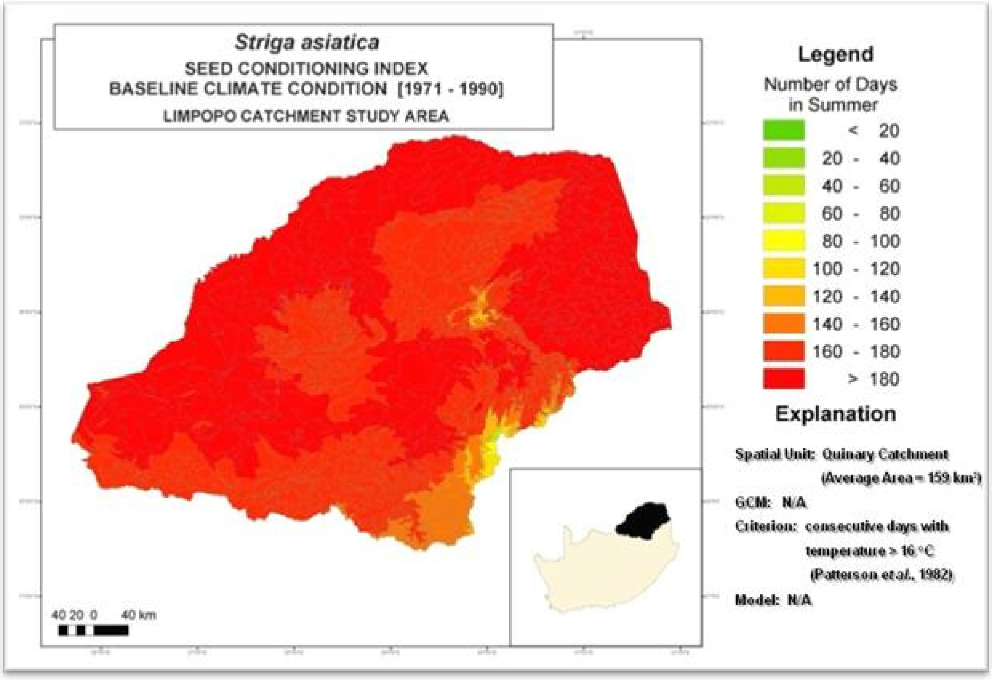


Figure E.5 The *Striga asiatica* seed conditioning index in the summer season [October – March] for baseline climate conditions

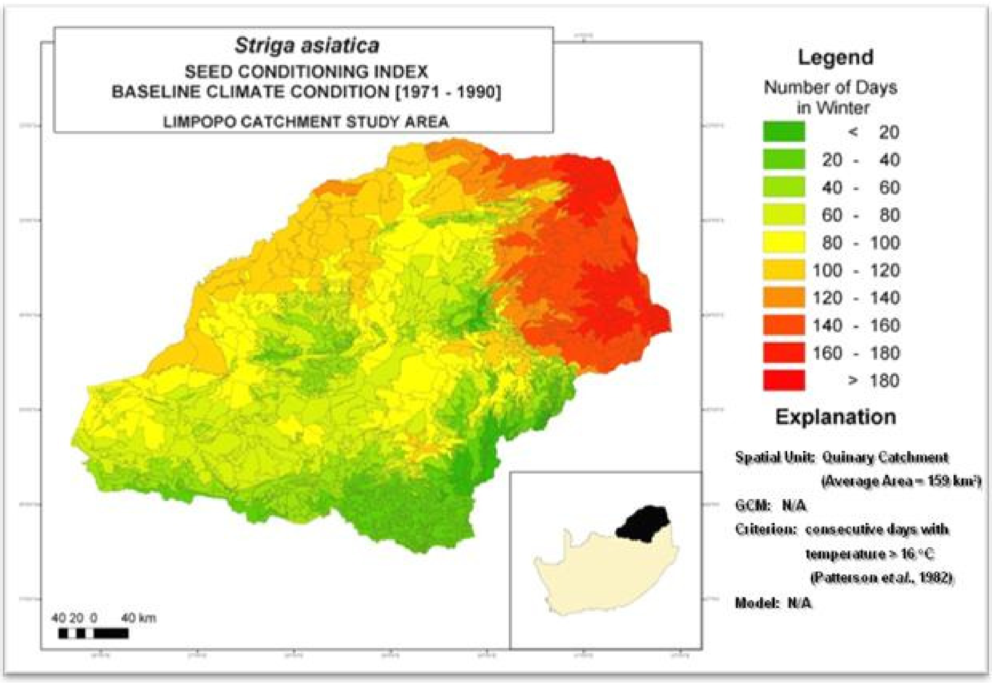


Figure E.6 The *Striga asiatica* seed conditioning index in the winter season [April – September] for baseline climate conditions

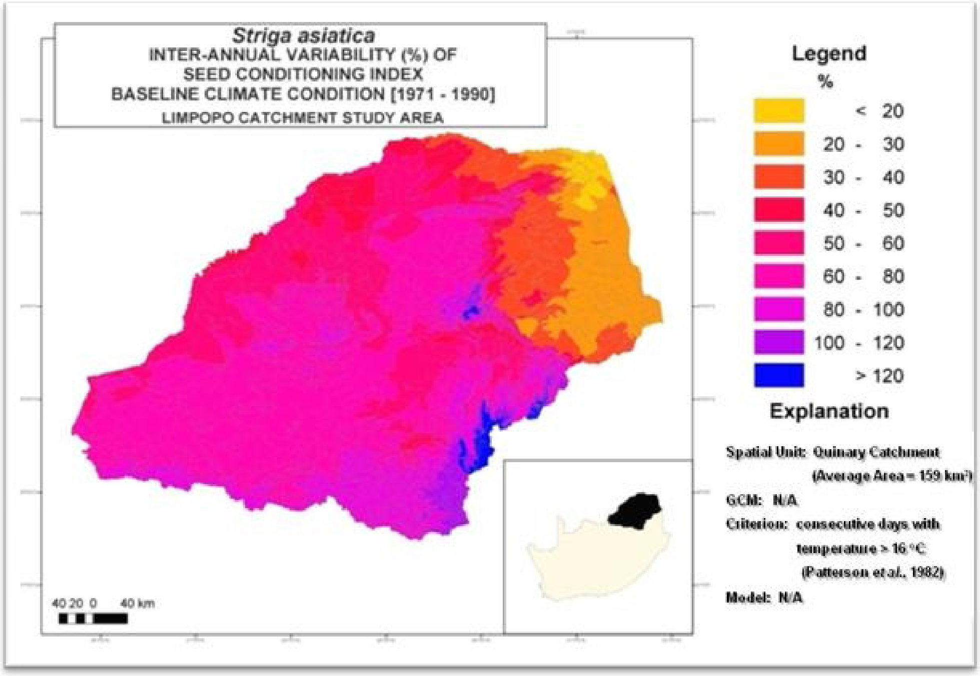


Figure E.7 Inter-annual variability (%) in the *S. asiatica* seed conditioning index for baseline climate conditions

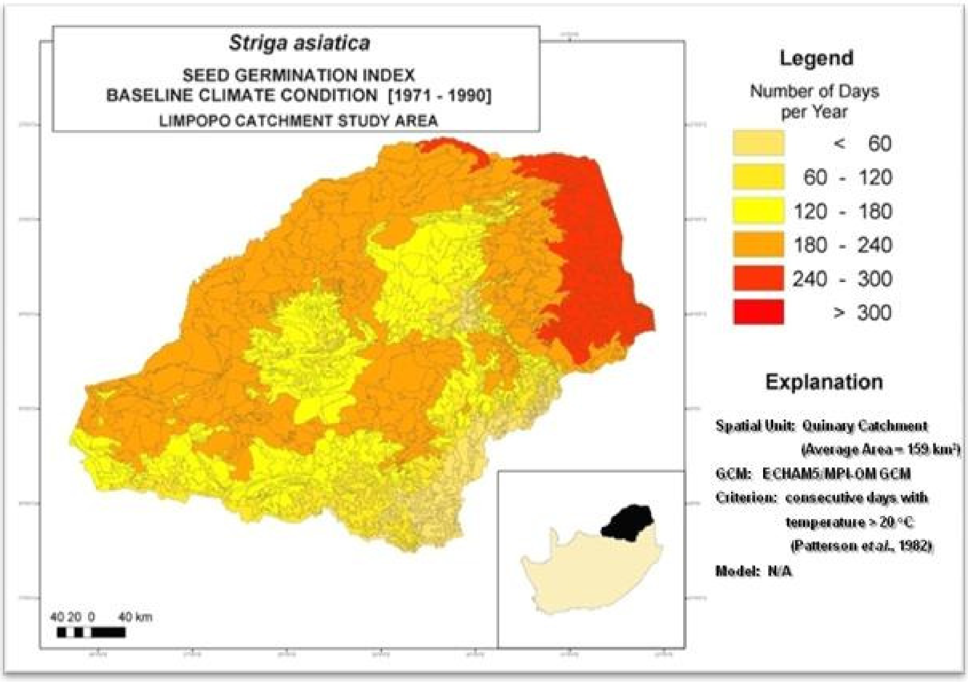


Figure E.8 The *Striga asiatica* seed germination index for baseline climate conditions

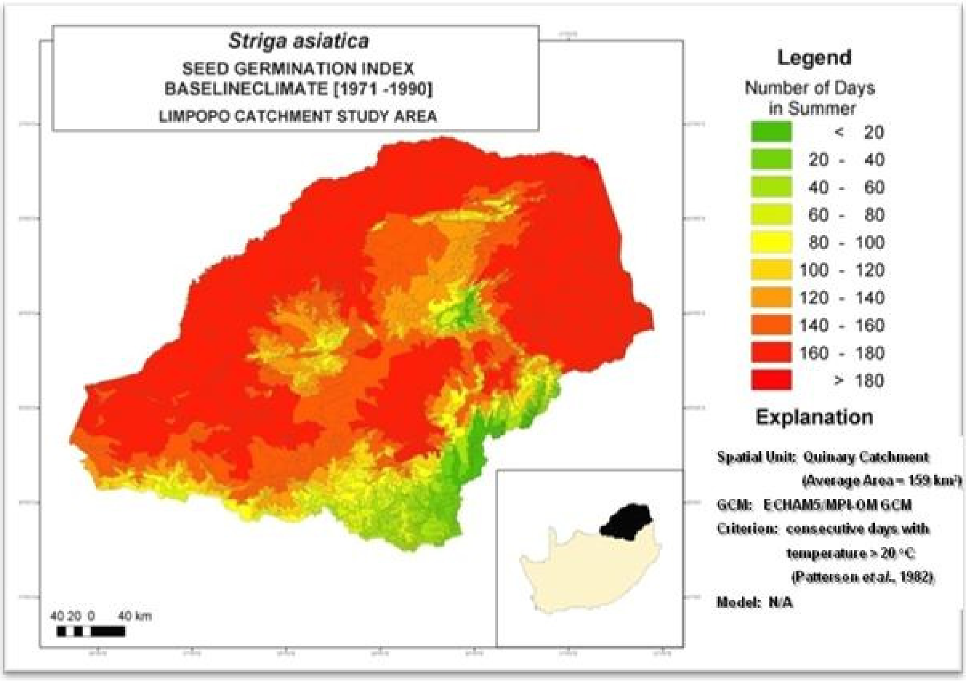


Figure E.9 The *Striga asiatica* seed germination index in the summer season [October – March] for baseline climate conditions

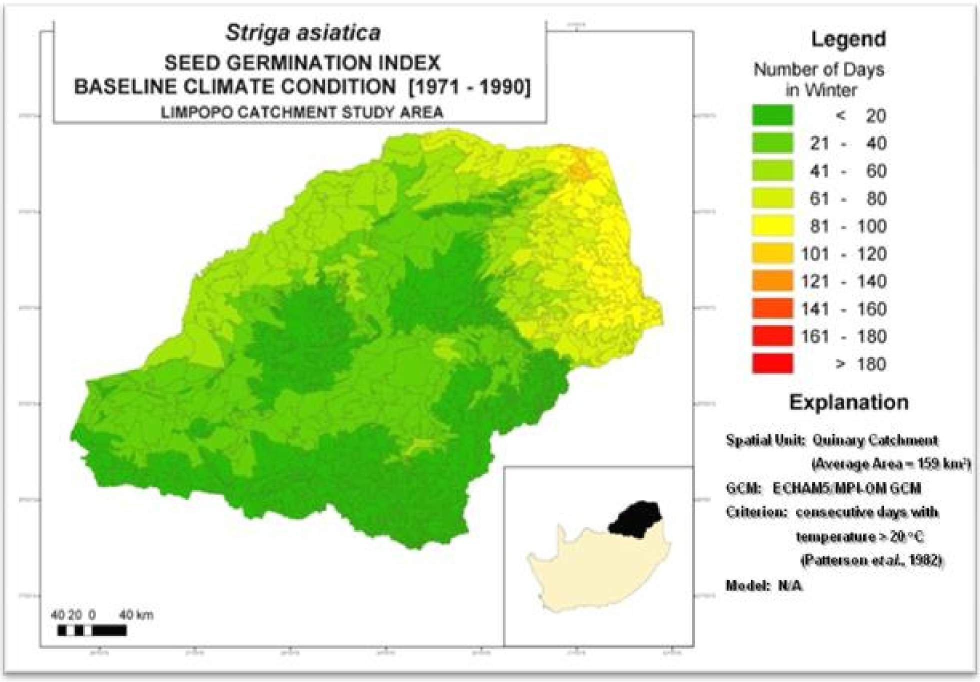


Figure E.10 The *Striga asiatica* seed germination index in the winter season [April – September] for baseline climate conditions

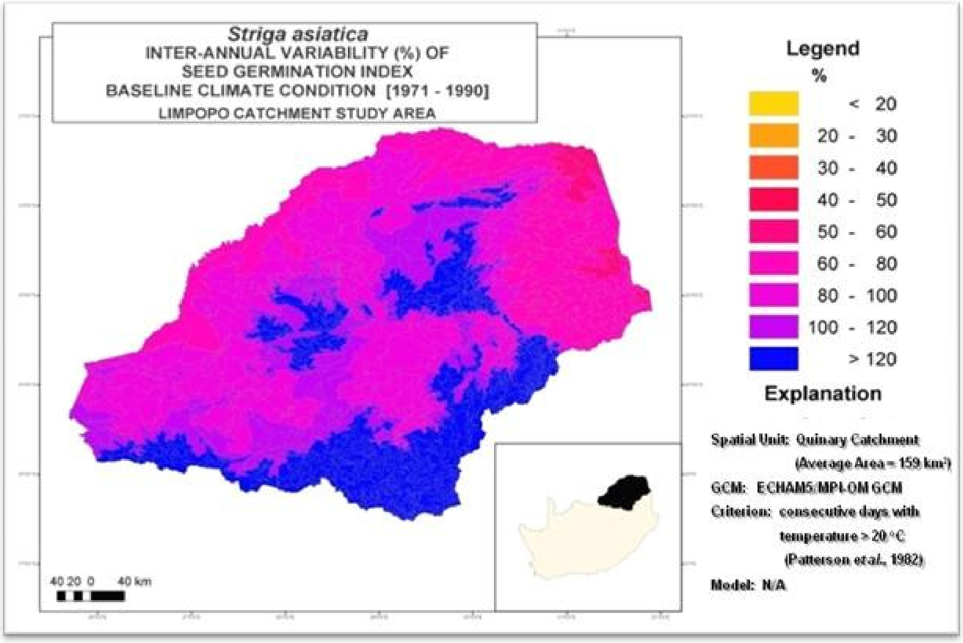


Figure E.11 Inter-annual variability in the *S. asiatica* seed germination index for baseline climate conditions

E.6 Validation of the ECHAM5/MPI-OM GCM's Output Against that of Baseline Climate Conditions for the Prediction of the *Striga asiatica* Development Stages

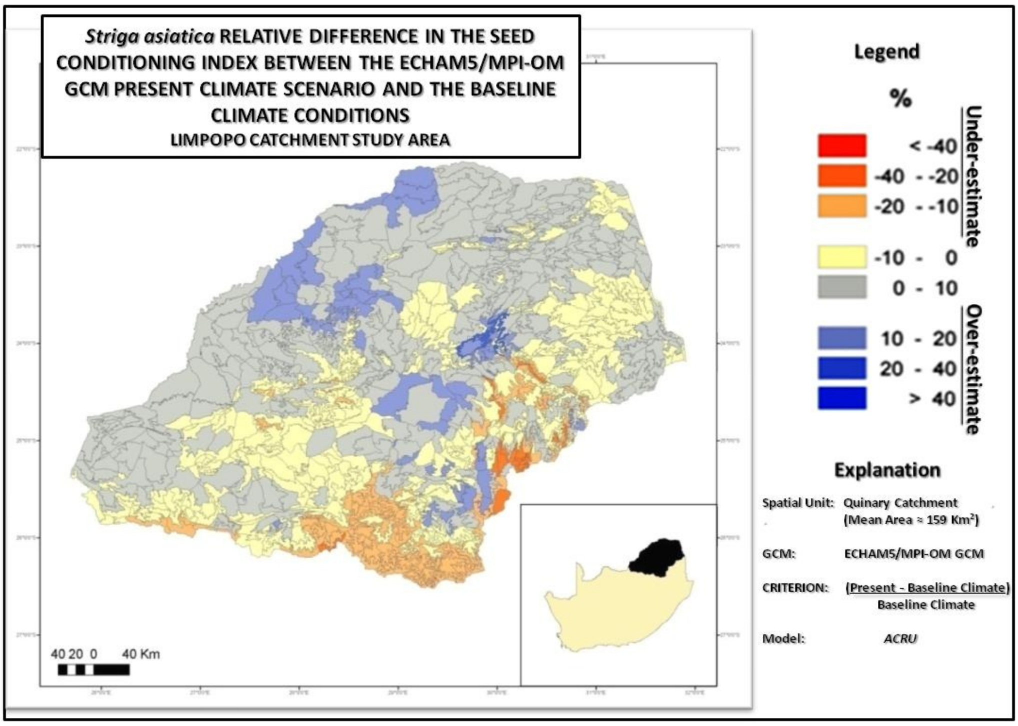


Figure E.12 Relative difference in the *S. asiatica* seed germination index generated from the ECHAM5/MPI-OM GCM present climate scenario vs. that from baseline climate conditions for the same time period

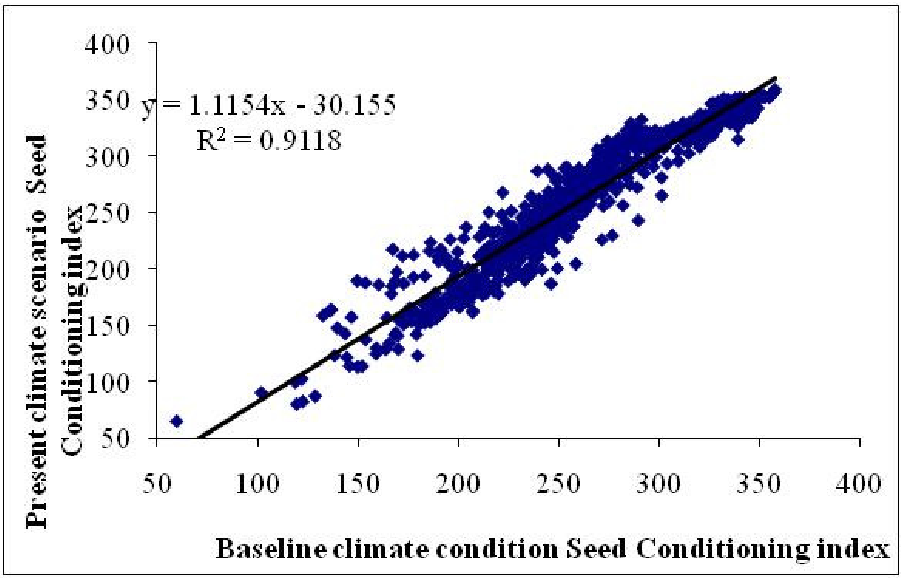


Figure E.13 Relationship between *S. asiatica* seed conditioning index generated from the ECHAM5/MPI-OM GCM present climate scenario and baseline climate conditions for the same period [1971 – 1990], with each point representing results from a Quinary Catchment

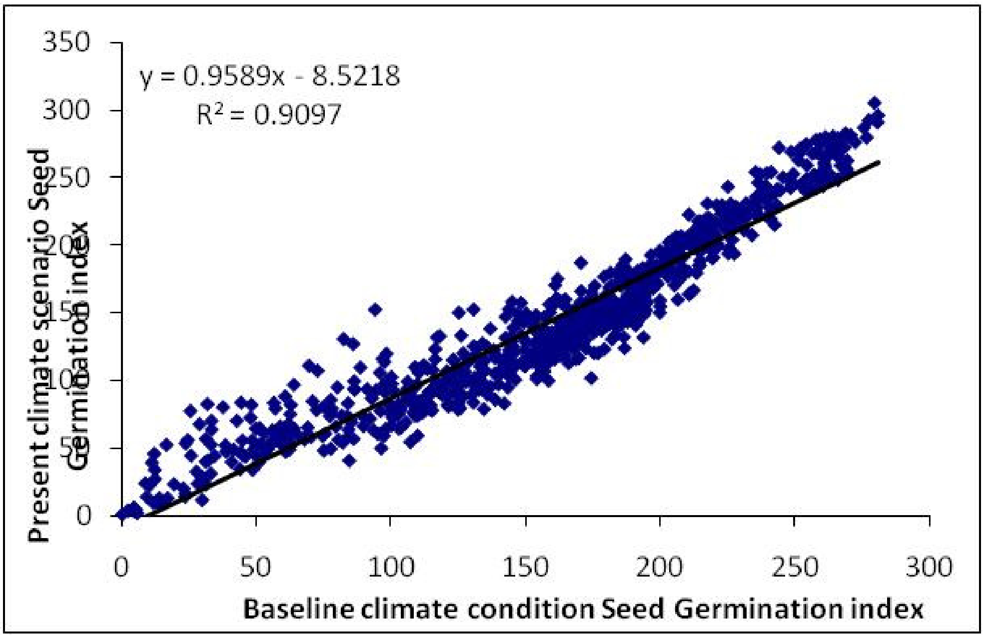


Figure E.14 Relationship between *S. asiatica* seed germination index generated from the ECHAM5/MPI-OM GCM present climate scenario and baseline climate conditions for the same period [1971 – 1990], with each point representing results from a Quinary Catchment

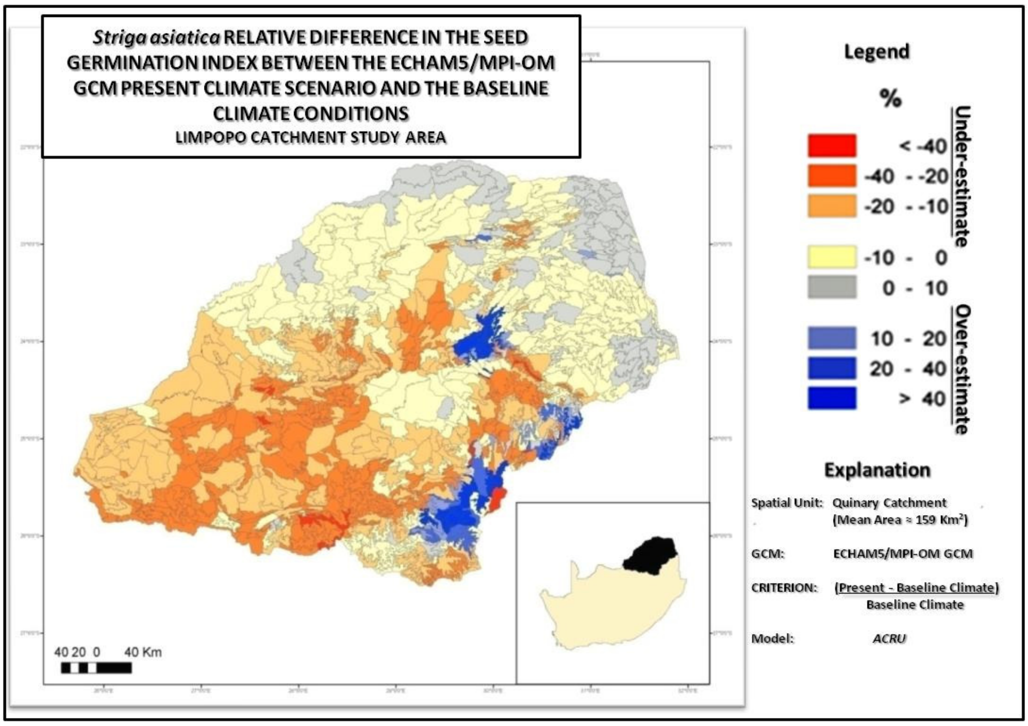


Figure E.15 Relative difference in the *S. asiatica* seed germination index generated from the ECHAM5/MPI-OM GCM present climate scenario vs. that from baseline climate conditions for the same time period

E.7 Projection of *Striga asiatica* Distribution Patterns

It was hypothesised that if the present temperature regimes were to increase due to anthropogenic forced climate change, the current climatic niche areas for the agricultural yield r*eduction* factor, *vi.z. S. asiatica* parasitic witch weed would expand or shift to regions previously less suitable.

The same approach was adopted for simulating the potential rate of parasitic witch weed incidences (i.e. conducive number of days per season) under baseline climate conditions (above section), was used to project the effects for the ECHAM5/MPI-OM GCM's climate change projections, i.e. for present [1971 – 1990], intermediate future [2046 – 2065] and distant future [2081 – 2100]. Maximum and minimum daily temperature projections of a 20 year time period assigned to each Quinary Catchment in Limpopo, input into the temperature based weed severity algorithms (cf. **Equation E.1**) to predict the parasitic witch weed climatic niche areas. These predictions were mapped over the Limpopo Catchment, for the mean annual conditions, ratio changes and inter-annual variability.

E.7.1 Projected effects of future climate conditions on the *Striga* asiatica seed conditioning index

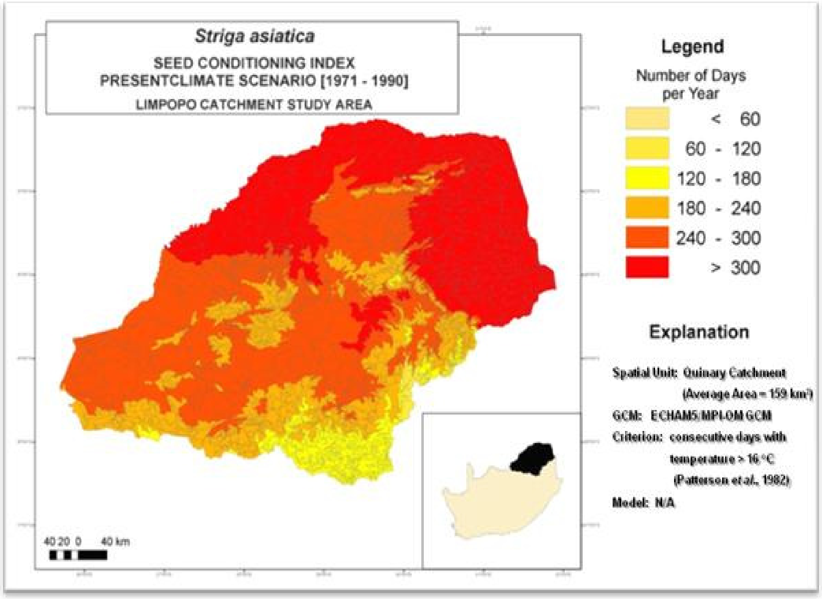


Figure E.16 The *Striga asiatica* seed conditioning index: ECHAM5/MPI-OM GCM's present climate

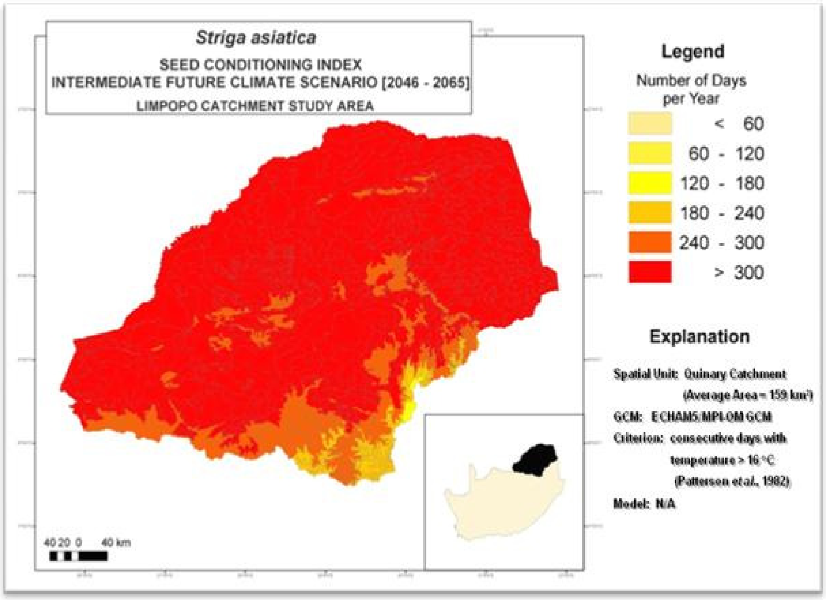


Figure E.17 The *Striga asiatica* seed conditioning index: ECHAM5/MPI-OM GCM's intermediate future climate

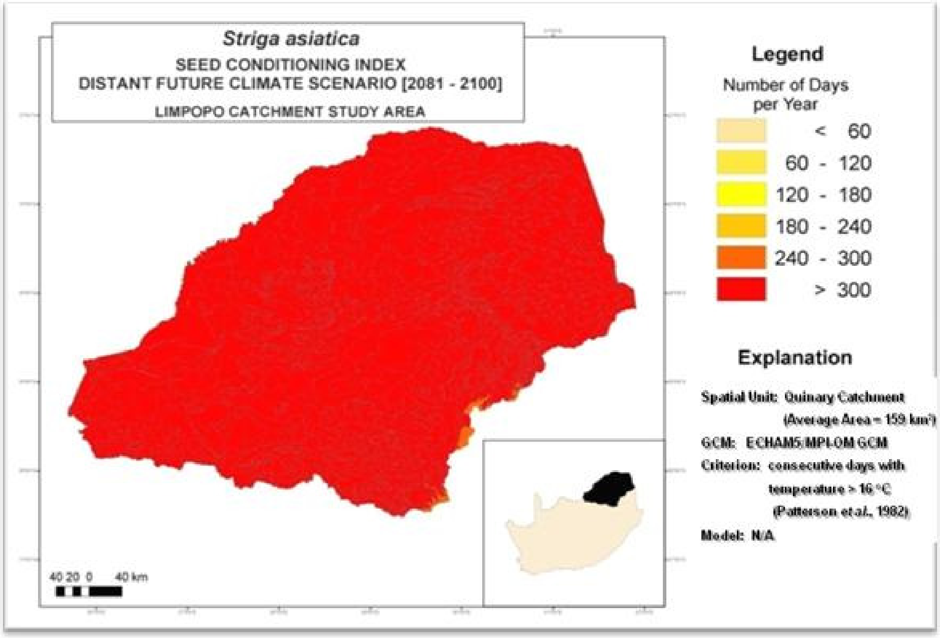


Figure E.18 The *Striga asiatica* seed conditioning index: ECHAM5/MPI-OM GCM's distant future climate

E.7.1.1 Ratio changes in *Striga asiatica* seed condition and germination INDEX

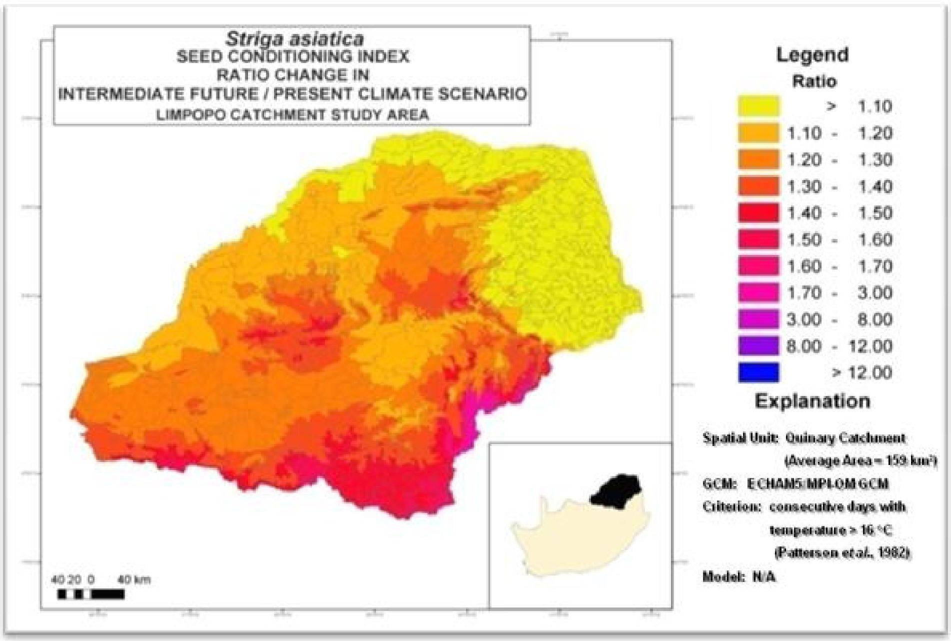


Figure E.19 Ratio changes in the *S. asiatica* seed conditioning index: ECHAM5/MPI-OM GCM's intermediate future / present climate

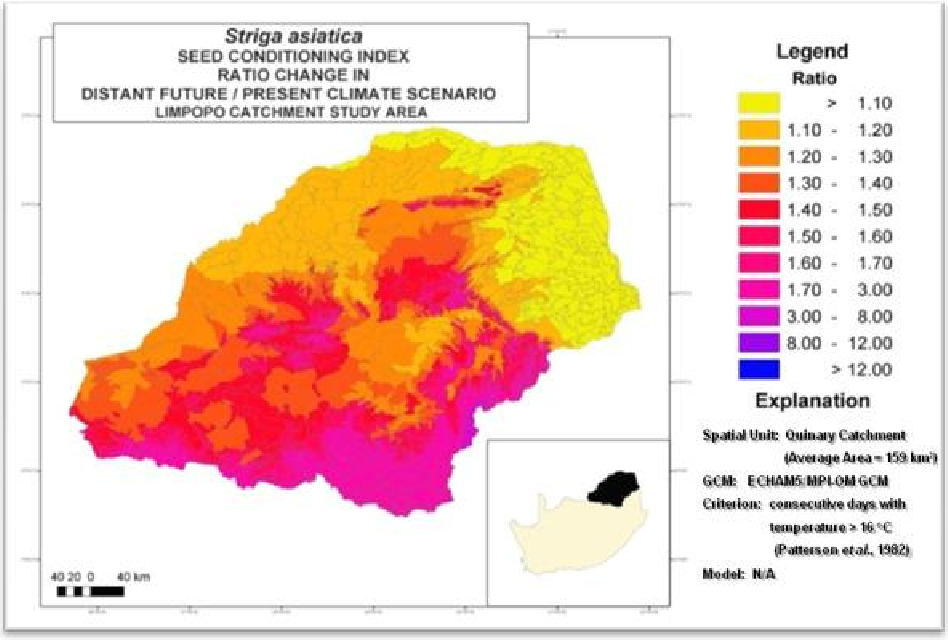


Figure E.20 Ratio changes in the *S. asiatica* seed conditioning index: ECHAM5/MPI-OM GCM's distant future / present climate

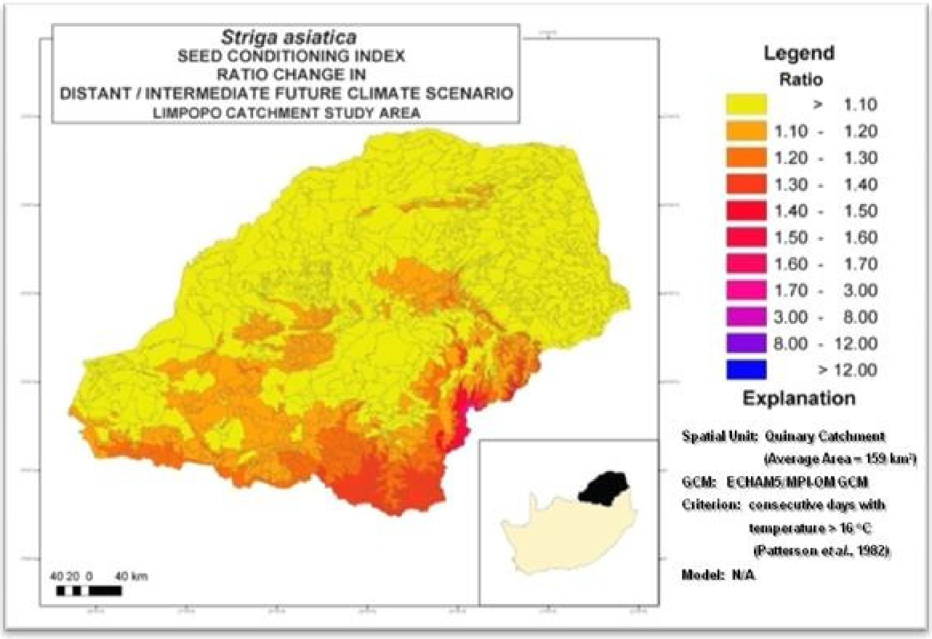


Figure E.21 Ratio changes in the *S. asiatica* seed conditioning index: ECHAM5/MPI-OM GCM's distant / intermediate future climate

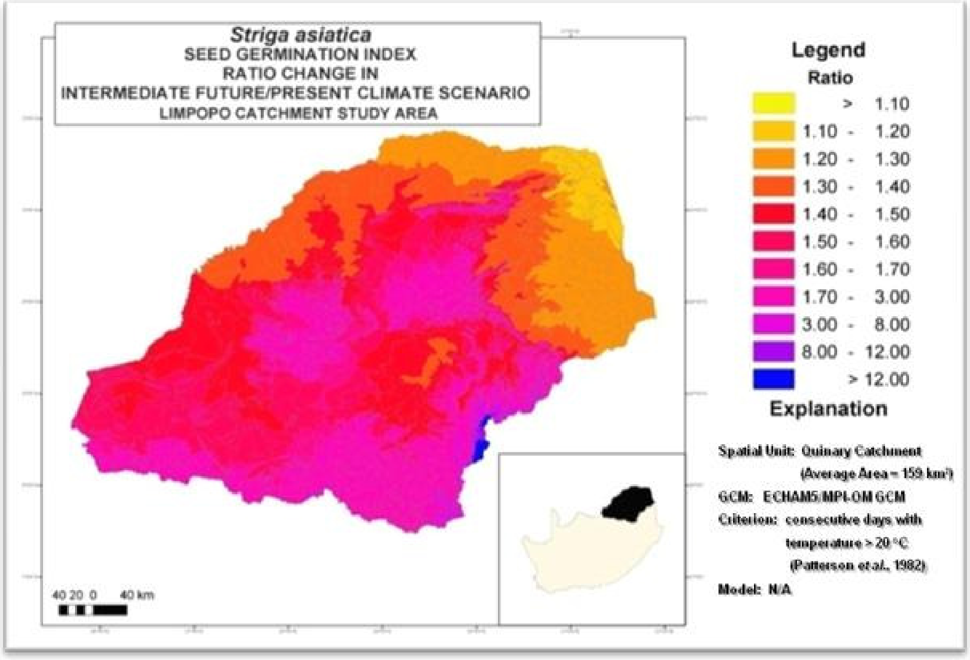


Figure E.22 Ratio changes in the *S. asiatica* seed germination index: ECHAM5/MPI-OM GCM's intermediate future / present climate

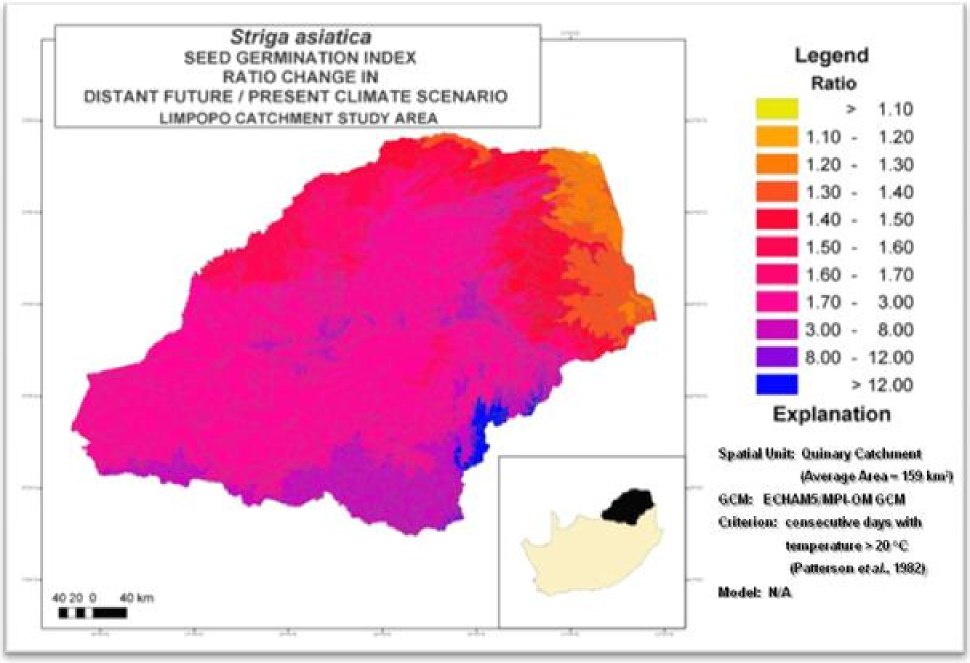


Figure E.23 Ratio changes in the *S. asiatica* seed germination index: ECHAM5/MPI-OM GCM's distant future / present climate

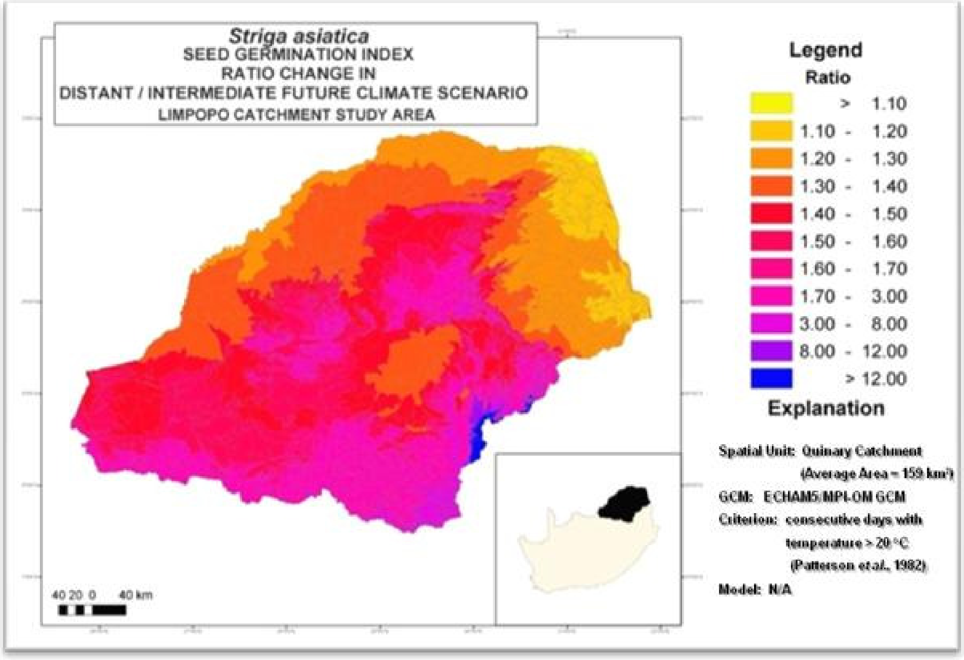


Figure E.24 Ratio changes in the *S. asiatica* seed germination index: ECHAM5/MPI-OM GCM's distant / intermediate future climate

E.7.1.2 Inter-annual variation

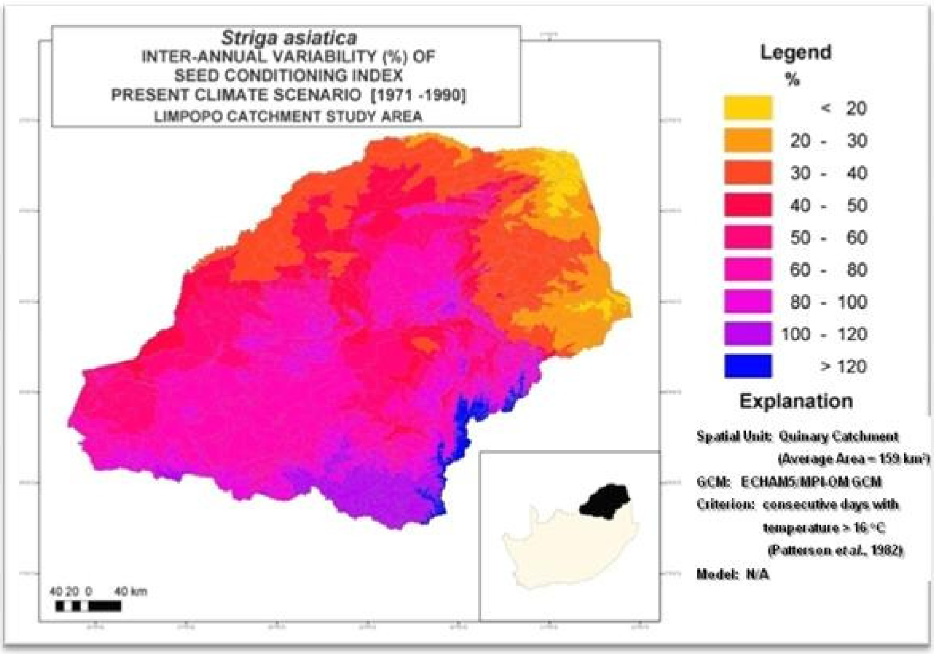


Figure E.25 Inter-annual variability (%) of the *S. asiatica* seed conditioning index: ECHAM5/MPI-OM GCM's present climate

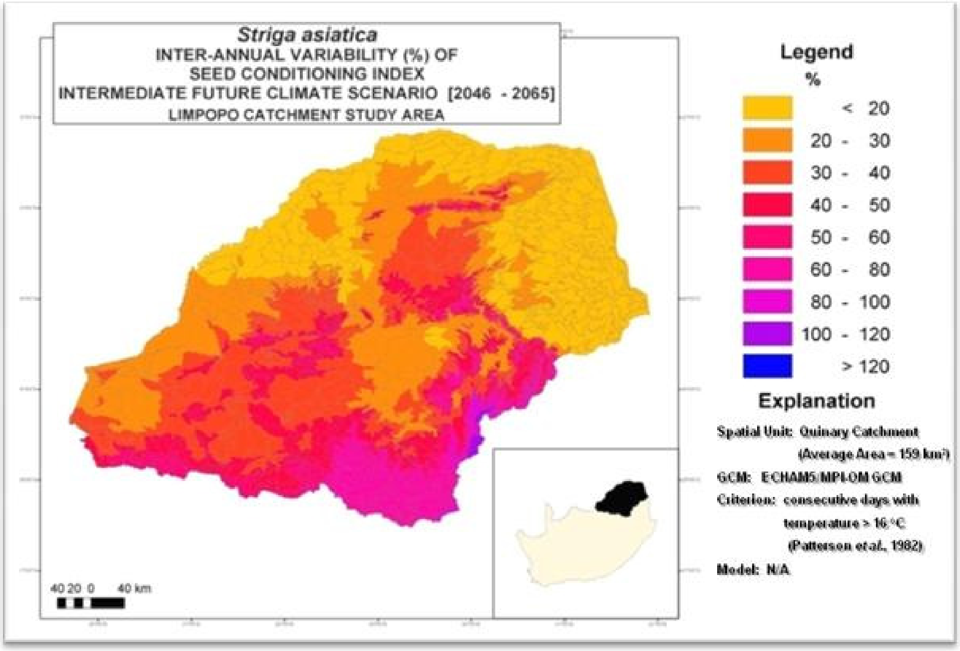


Figure E.26 Inter-annual variability (%) of the *S. asiatica* seed conditioning index: ECHAM5/MPI-OM GCM's intermediate future climate

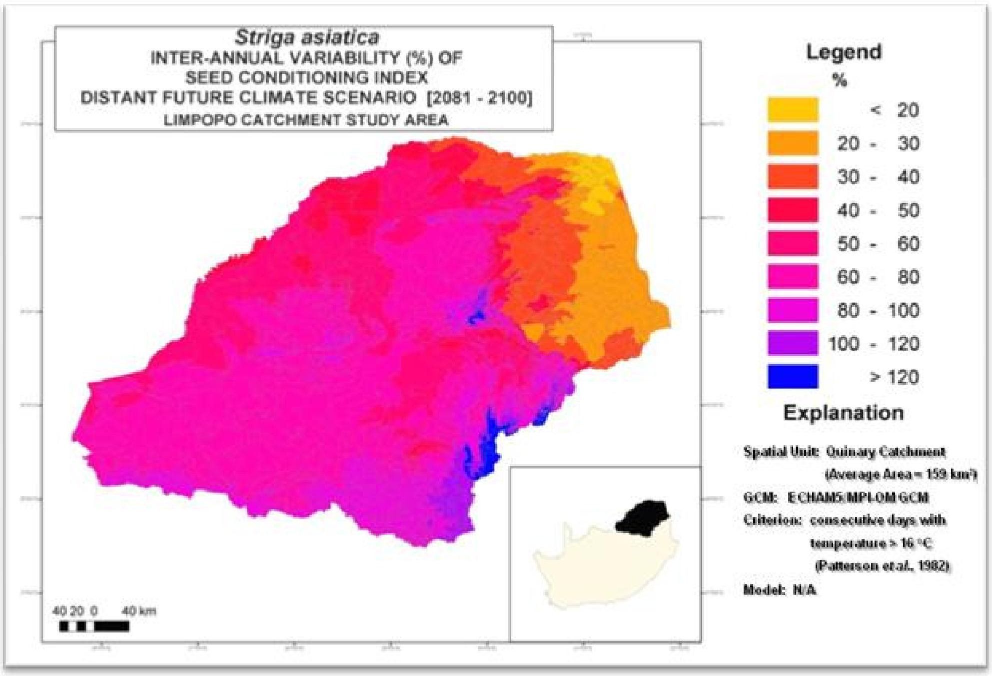


Figure E.27 Inter-annual variability (%) of the *S. asiatica* seed conditioning index: ECHAM5/MPI-OM GCM's distant future climate

Table E.1 Summarised inter-annual coefficients of variation of the *Striga asiatica* seed conditioning index for the Water Management Areas in the Limpopo Catchment for the ECHAM5/MPI-OM GCM's scenarios

Limpopo Catchment Water Management Areas	**Coefficient of variation (%) for *Striga asiatica* seed conditioning**						
	Baseline Climate Condition	**Present Climate Scenario**	**Intermediate Future Climate Scenario**	**Distant Future Climate Scenario**	**I : P**	**F : P**	**F : I**
Limpopo	64.85	61.06	32.54	64.85	0.53	1.06	1.99
Luvuvhu and Letaba	42.43	39.52	21.52	42.43	0.54	1.07	1.97
Crocodile (West) and Marico	71.39	74.19	41.13	71.39	0.55	0.96	1.74
Olifants	74.63	79.91	46.77	74.63	0.59	0.93	1.60

E.7.1.3 Seasonal distribution patterns

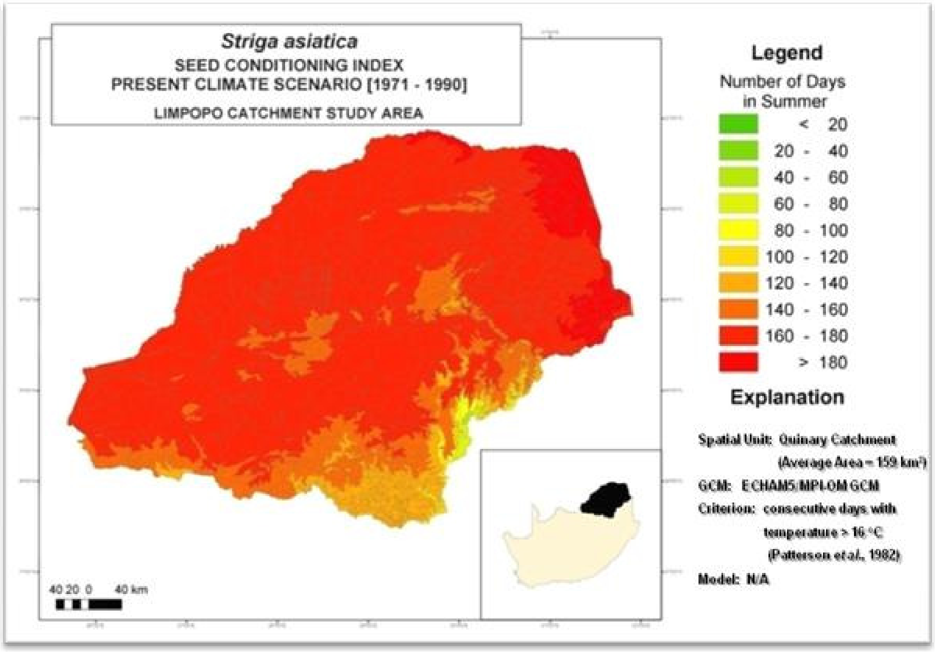


Figure E.28 Mean of the *S. asiatica* seed conditioning index in the summer season [October – March]: ECHAM5/MPI-OM GCM's present climate

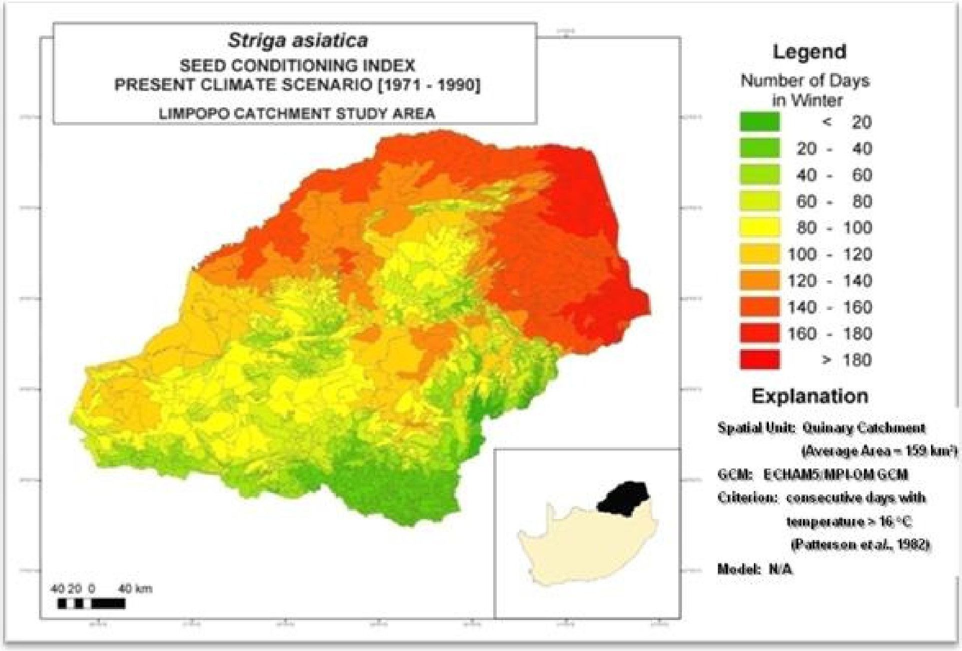


Figure E.29 Mean of the *S. asiatica* seed conditioning index in the winter season [April – September]: ECHAM5/MPI-OM GCM's present climate

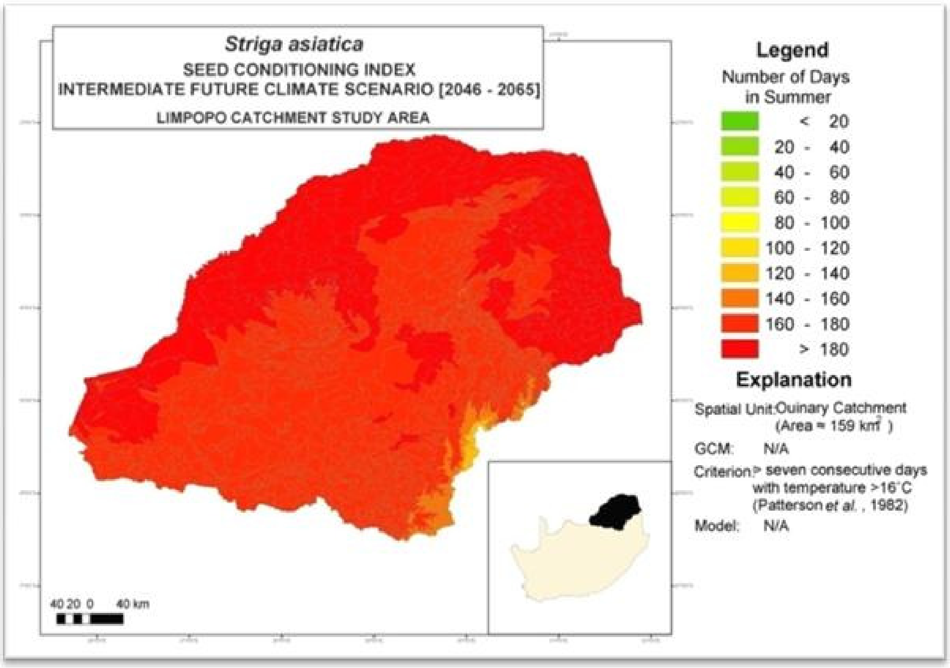


Figure E.30 Mean of the *S. asiatica* seed conditioning index in the summer season [October – March]: ECHAM5/MPI-OM GCM's intermediate future climate

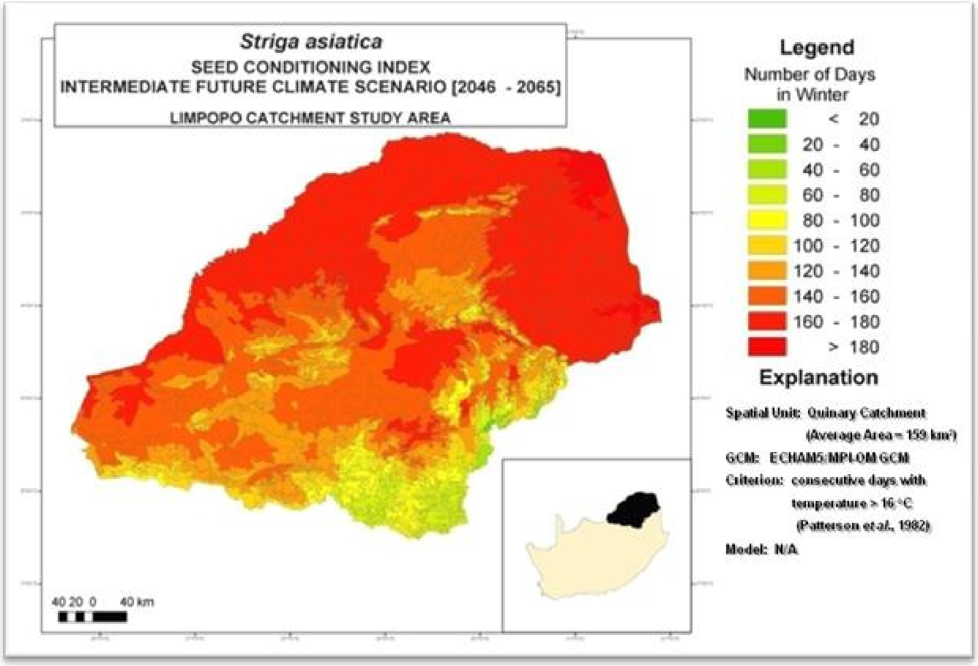


Figure E.31 Mean of the *S. asiatica* seed conditioning index in the winter season [April – September]: ECHAM5/MPI-OM GCM's intermediate future climate

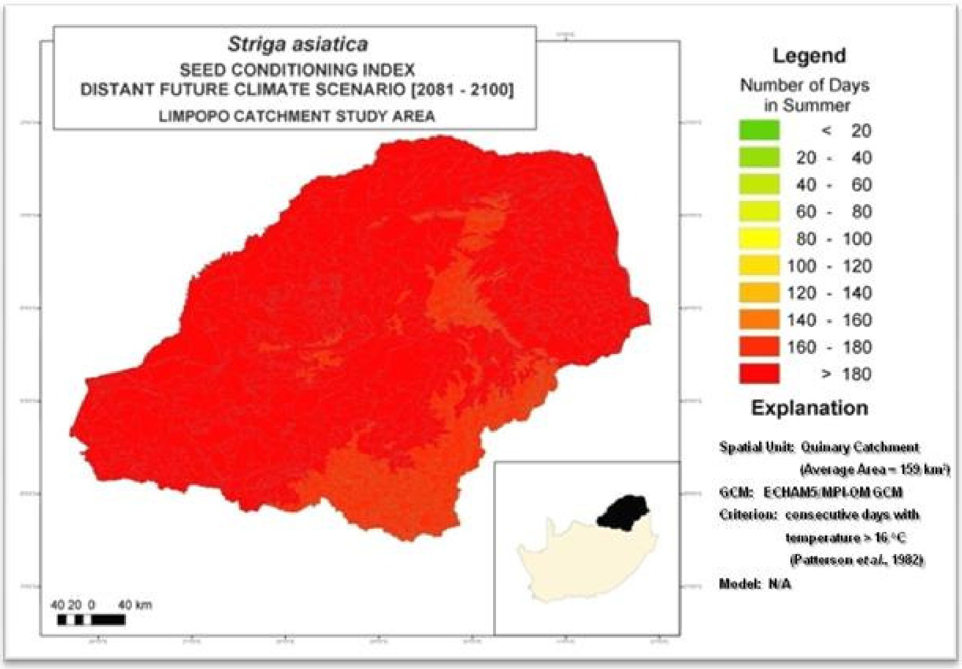


Figure E.32 Mean of the *S. asiatica* seed conditioning index in the summer season [October – March]: ECHAM5/MPI-OM GCM's distant future climate

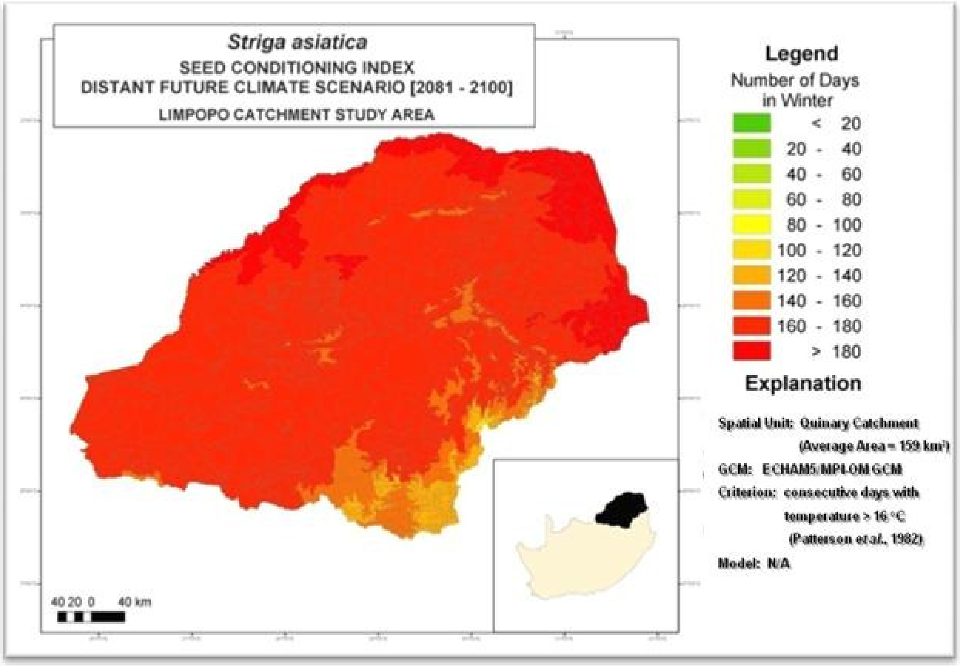


Figure E.33 Mean of the *S. asiatica* seed conditioning index in the winter season [April – September]: ECHAM5/MPI-OM GCM's distant future climate

E.7.2 Projected effects of future climate conditions on *Striga asiatica* seed germination index

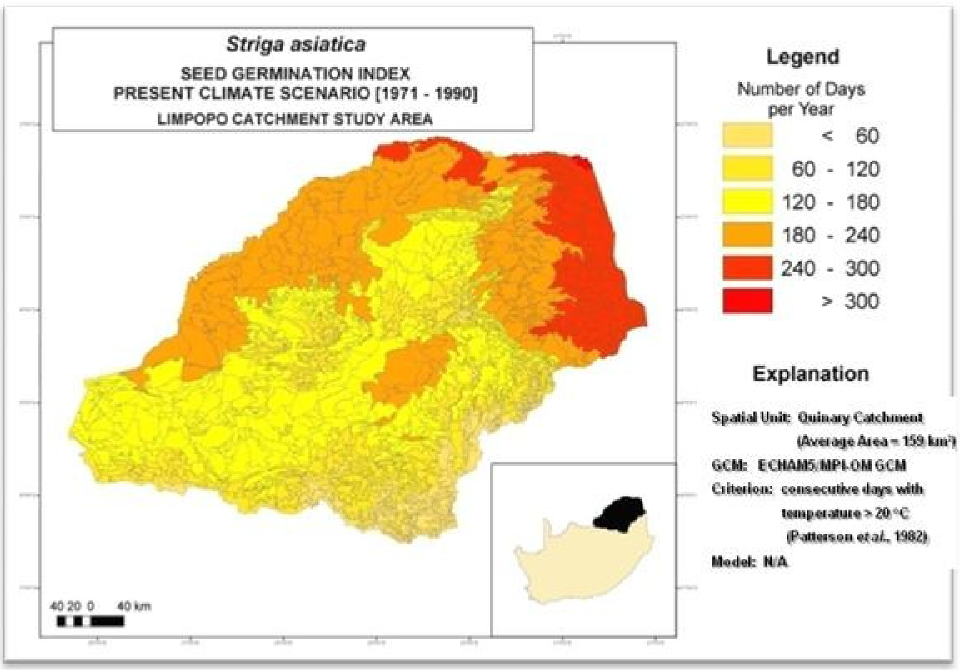


Figure E.34 Mean of the *S. asiatica* seed germination index: ECHAM5/MPI-OM GCM's present climate

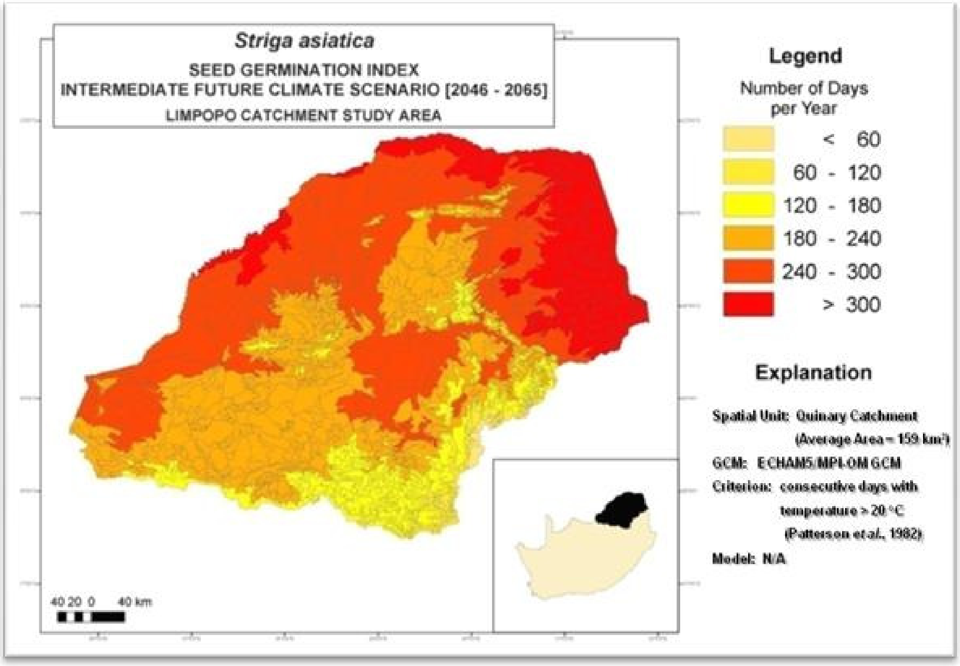


Figure E.35 Mean of the *S. asiatica* seed germination index: ECHAM5/MPI-OM GCM's intermediate future climate

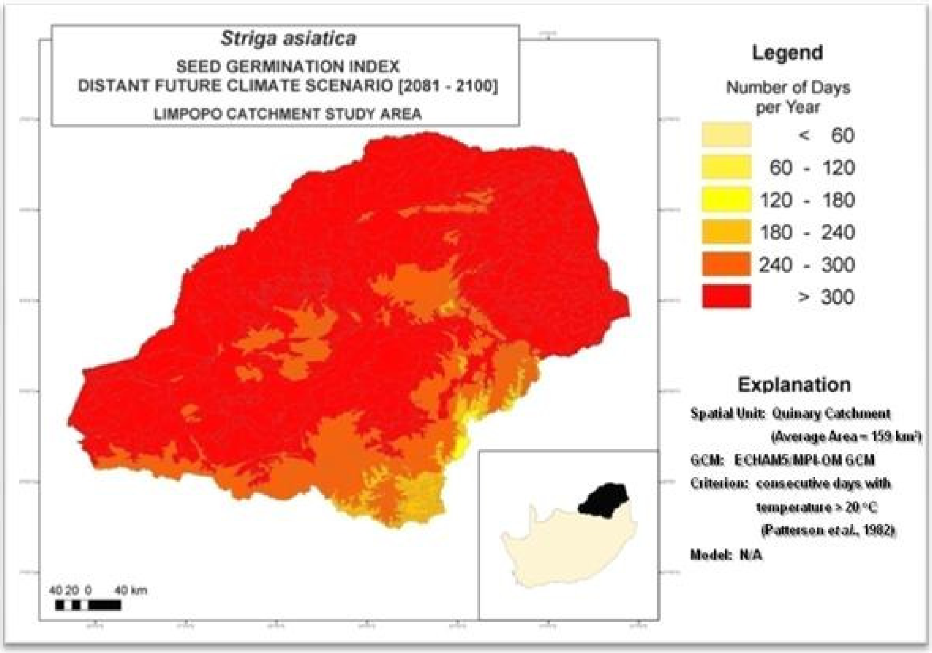


Figure E.36 Mean of the *S. asiatica* seed germination index: ECHAM5/MPI-OM GCM's distant future climate

E.7.2.1 Inter-annual variation

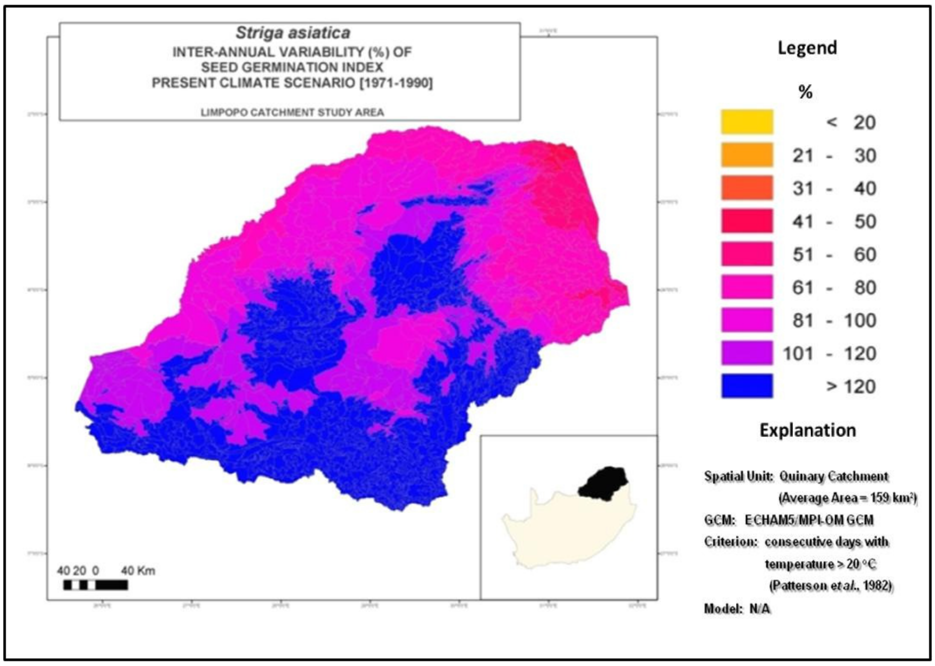


Figure E.37 Inter-annual variability (%) of the *S. asiatica* seed germination index: ECHAM5/MPI-OM GCM's present climate

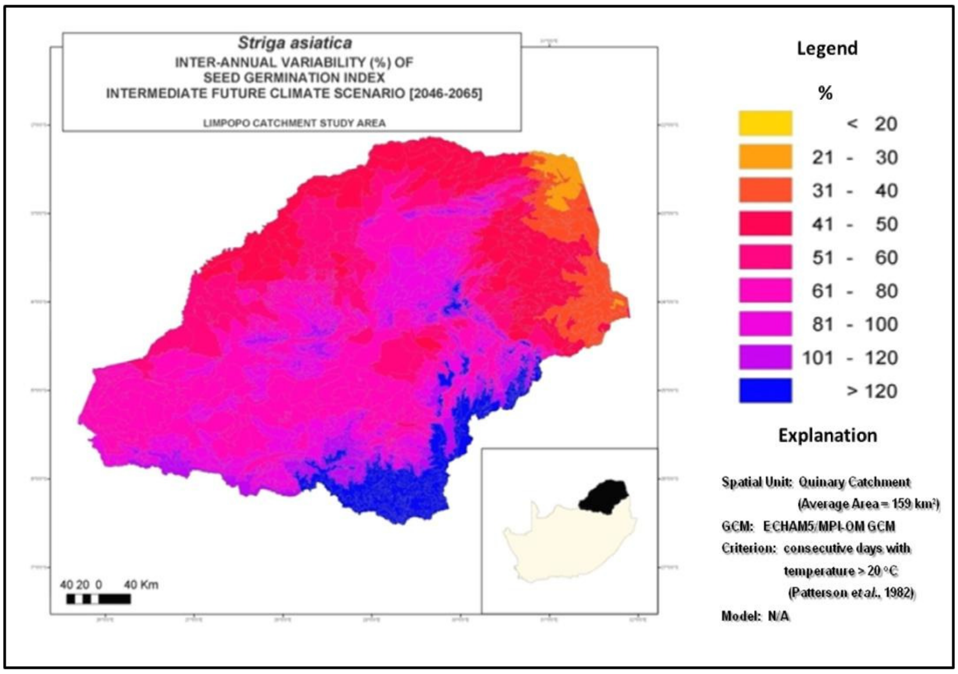


Figure E.38 Inter-annual variability (%) of the *S. asiatica* seed germination index: ECHAM5/MPI-OM GCM's intermediate future climate

Table E.2 Summarised inter-annual coefficients of variation of the *Striga asiatica* seed germination index for Water Management Areas in the Limpopo Catchment for the ECHAM5/MPI-OM GCM's scenarios

Limpopo Catchment Water Management Areas	**Coefficient of variation (%) for *Striga asiatica* seed germination**						
	Baseline Climate Condition	**Present Climate Scenario**	**Intermediate Future Climate Scenario**	**Distant Future Climate Scenario**	**I : P**	**F : P**	**F : I**
Limpopo	111.83	125.11	73.76	111.83	0.59	0.89	1.52
Luvuvhu and Letaba	100.84	93.88	54.90	100.84	0.58	1.07	1.84
Crocodile (West) and Marico	114.19	140.29	84.47	114.19	0.60	0.81	1.35
Olifants	184.18	188.25	100.39	184.18	0.53	0.98	1.83

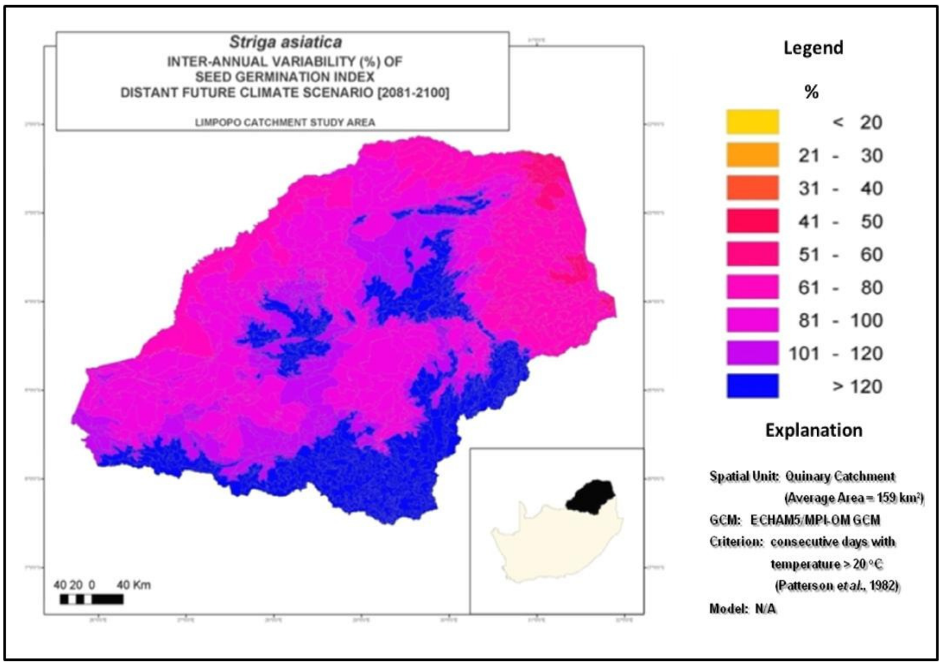


Figure E.39 Inter-annual variability (%) of the *S. asiatica* seed germination index: ECHAM5/MPI-OM GCM's distant future climate

E.7.2.2 Seasonal distribution patterns

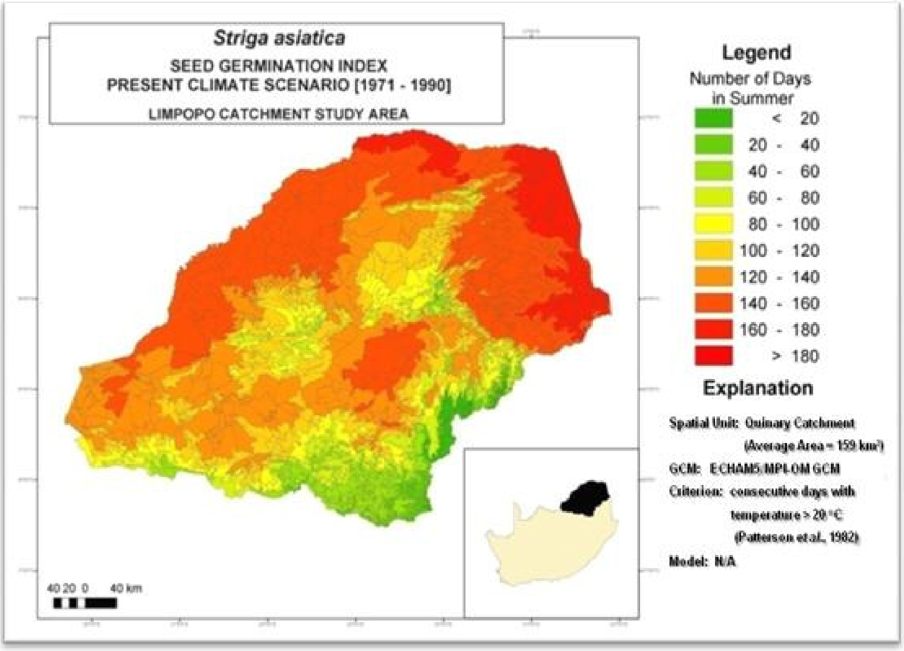


Figure E.40 Mean of the *S. asiatica* seed germination index in the summer season [October – March]: ECHAM5/MPI-OM GCM's present climate

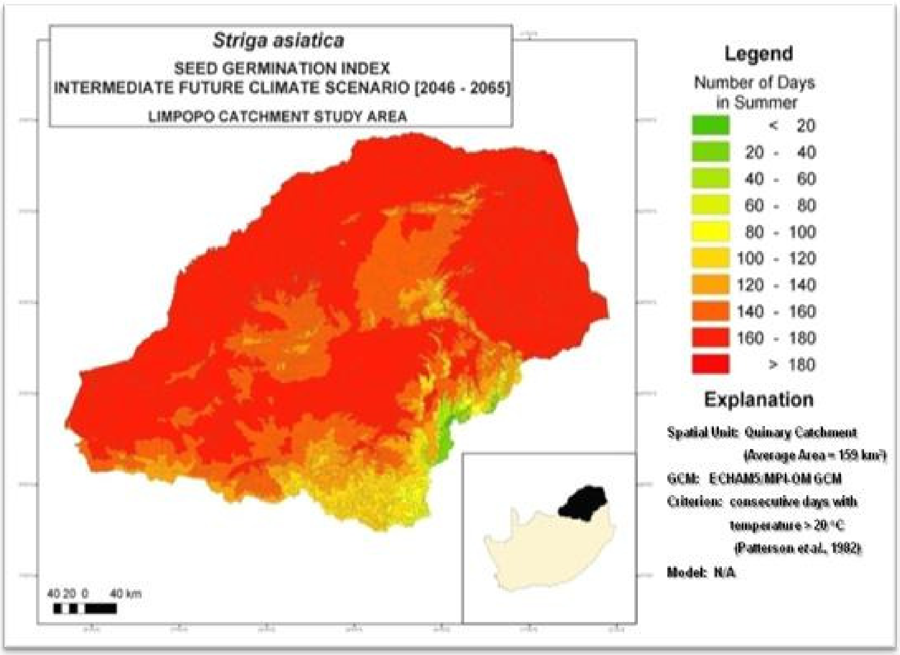


Figure E.41 Mean of the *S. asiatica* seed germination index in the summer season [October – March]: ECHAM5/MPI-OM GCM's intermediate future climate

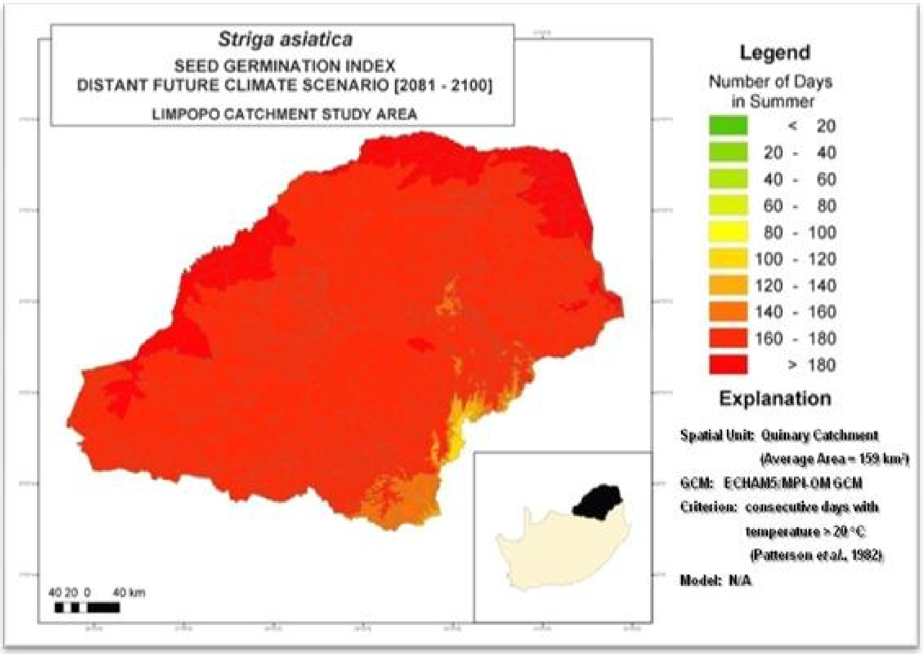


Figure E.42 Mean of the *S. asiatica* seed germination index in the summer season [October – March]: ECHAM5/MPI-OM GCM's distant future climate

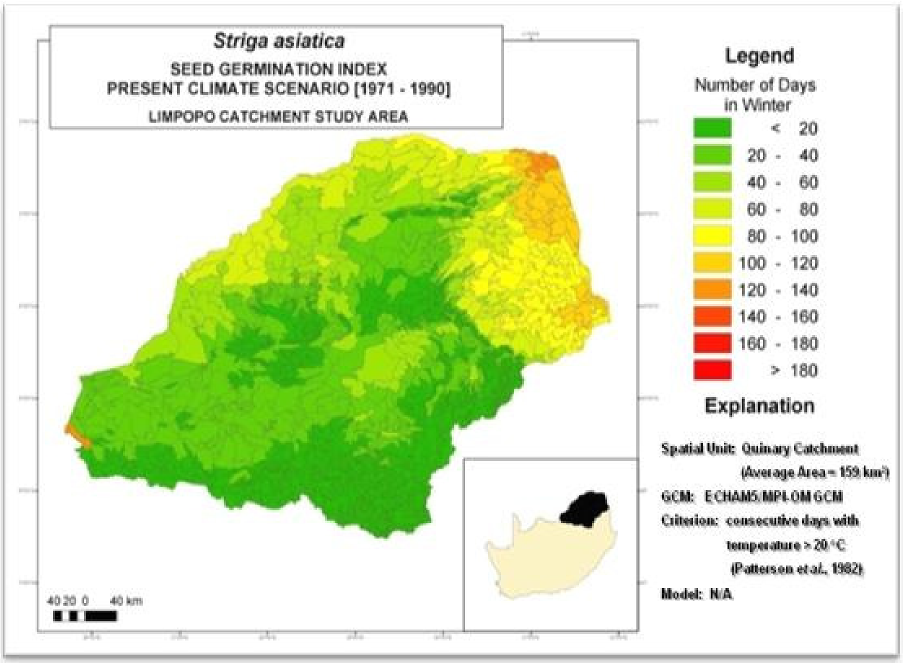


Figure E.43 Mean of the *S. asiatica* seed germination index in the winter season [April – September]: ECHAM5/MPI-OM GCM's present climate

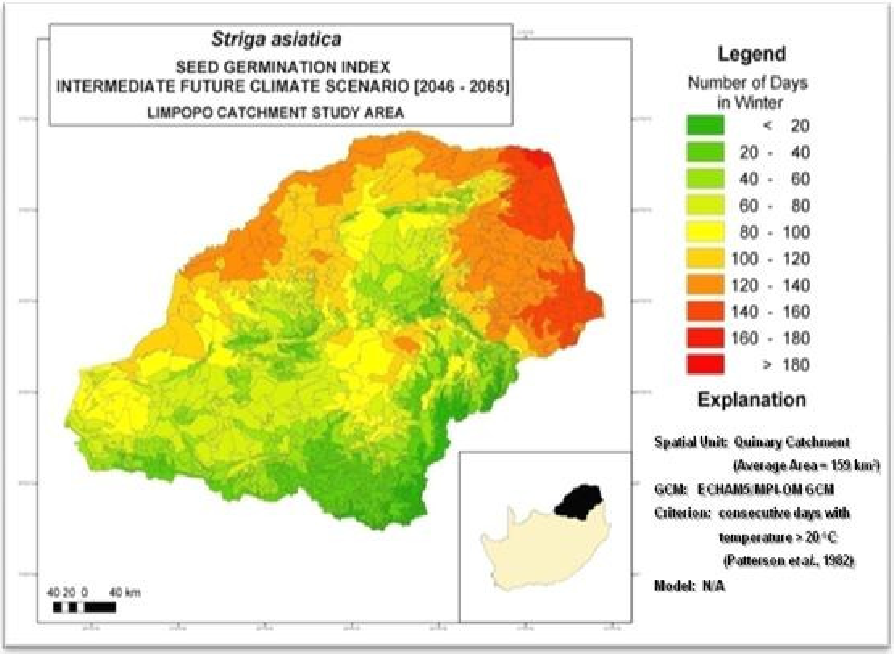


Figure E.44 Mean of the *S. asiatica* seed germination index in the winter season [April – September]: ECHAM5/MPI-OM GCM's intermediate future climate

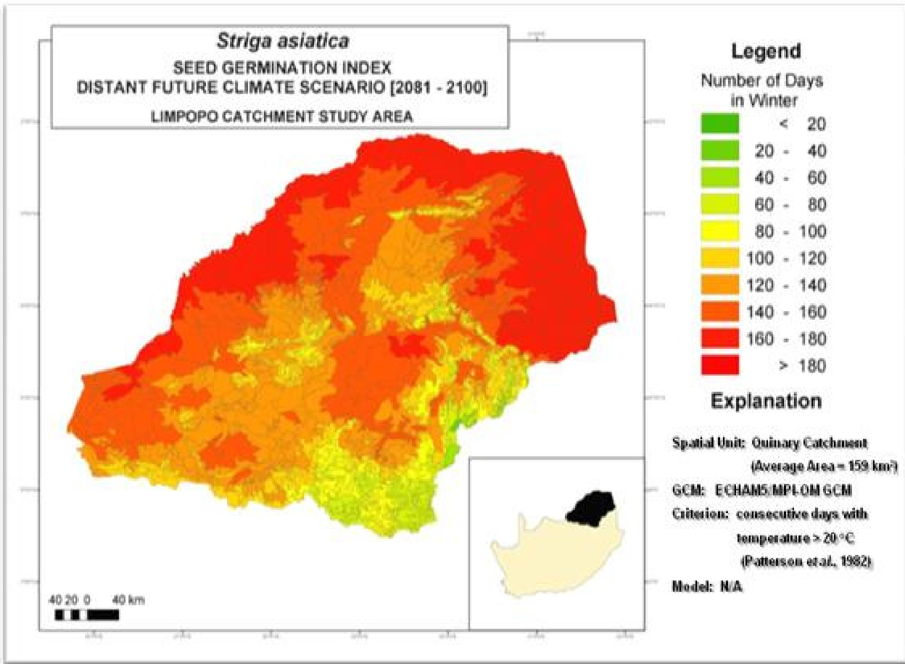
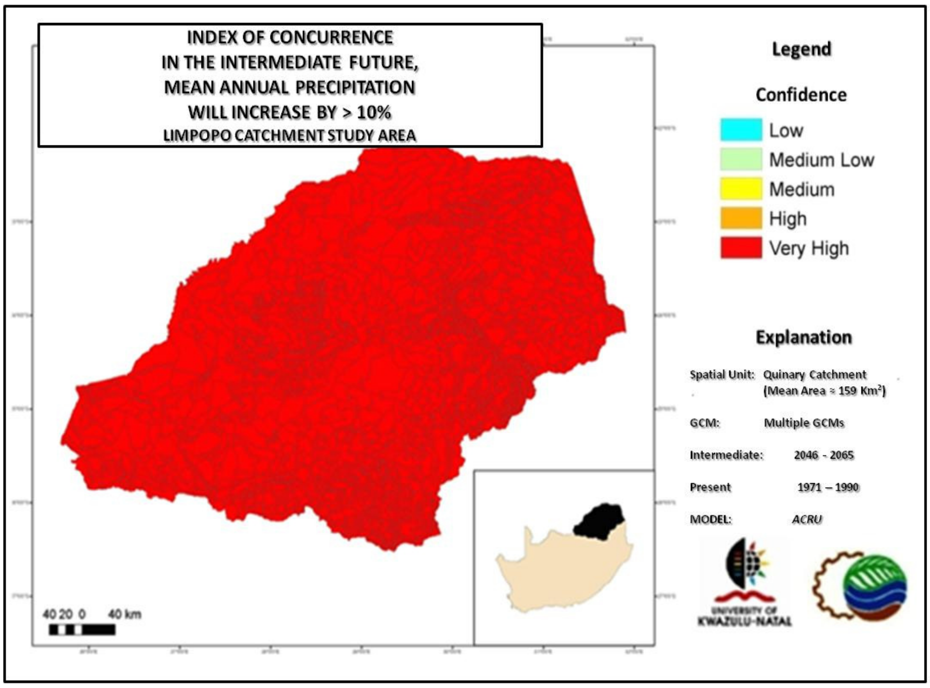


Figure E.45 Mean of the *S. asiatica* seed germination index in the winter season [April – September]: ECHAM5/MPI-OM GCM's distant future climate

APPENDIX F: MAPS OF INDEX OF CONCURRENCE IN CLIMATE PROJECTIONS



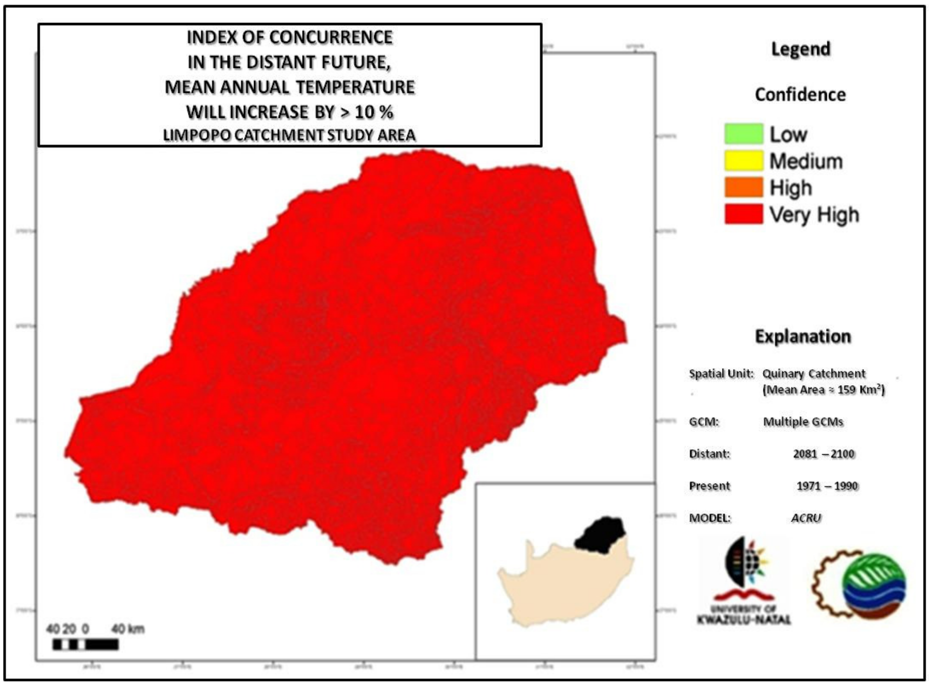
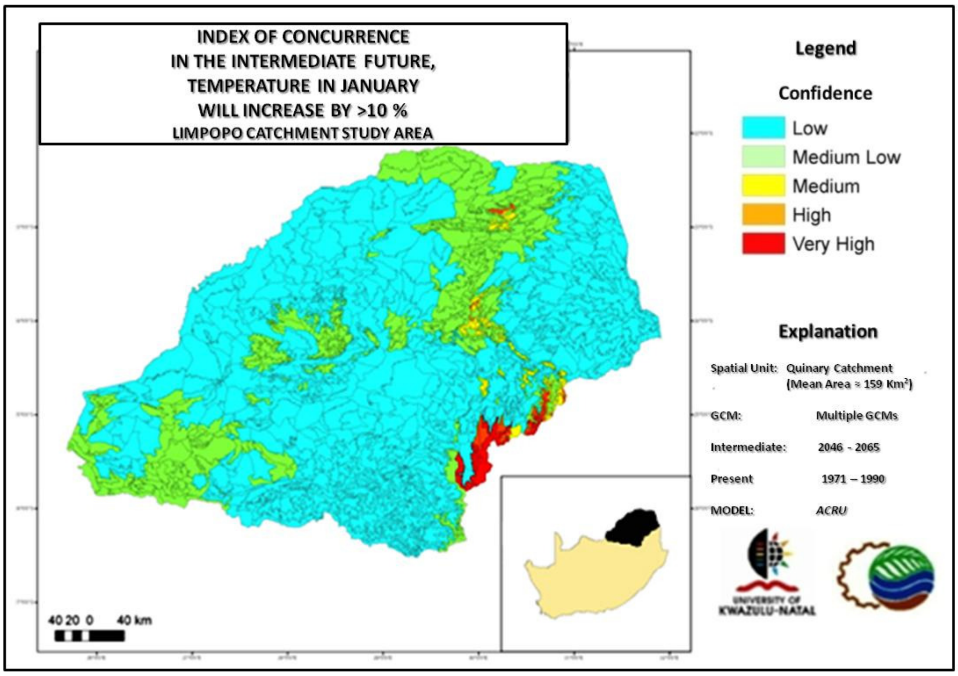


Figure F.1 Uncertainty analyses, expressed by the index of concurrence, that in the intermediate (top) and distant (bottom) future climates the mean annual temperatures are projected to increase by more than 10 % over the Limpopo Catchment (Source information: Schulze and Kunz, 2010a)



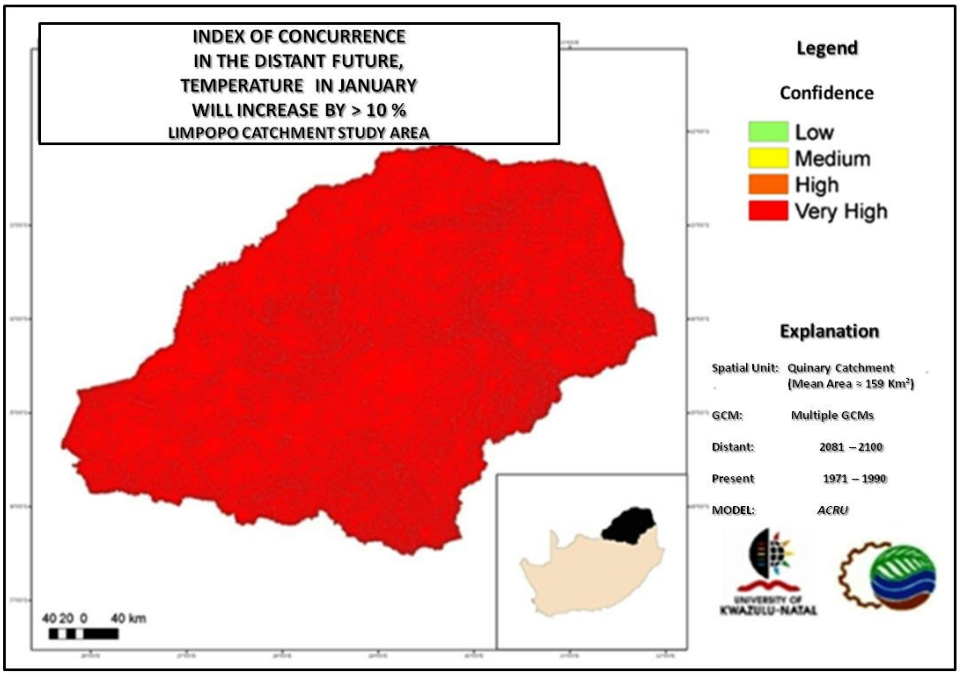
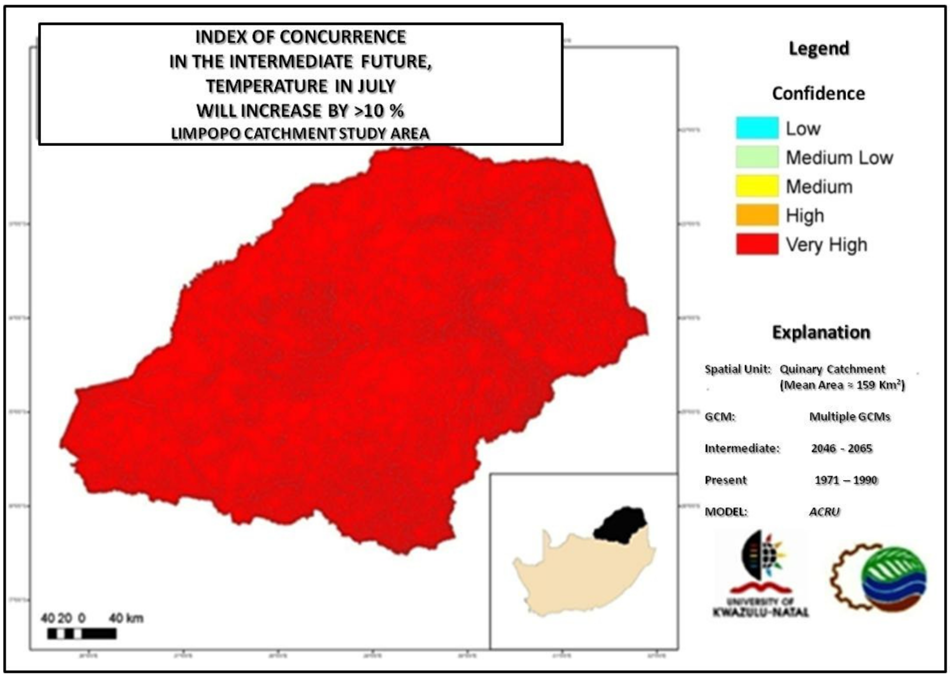


Figure F.2 Uncertainty analyses, expressed by the index of concurrence, that in the intermediate (top) and distant (bottom) future January's maximum temperatures are projected to increase by more than 10% over the Limpopo Catchment (Source information: Schulze and Kunz, 2010b)



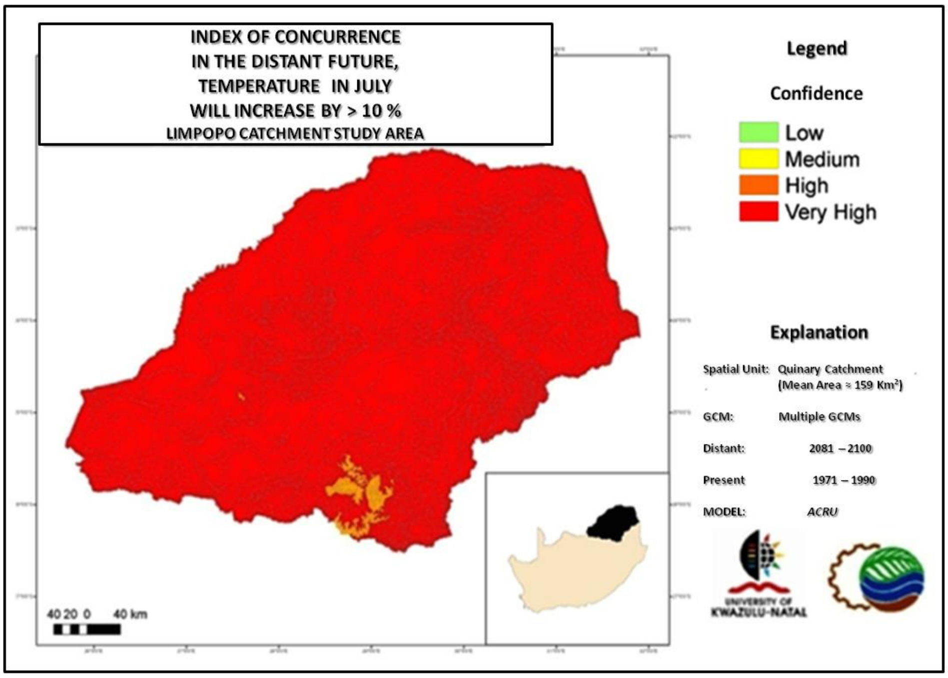
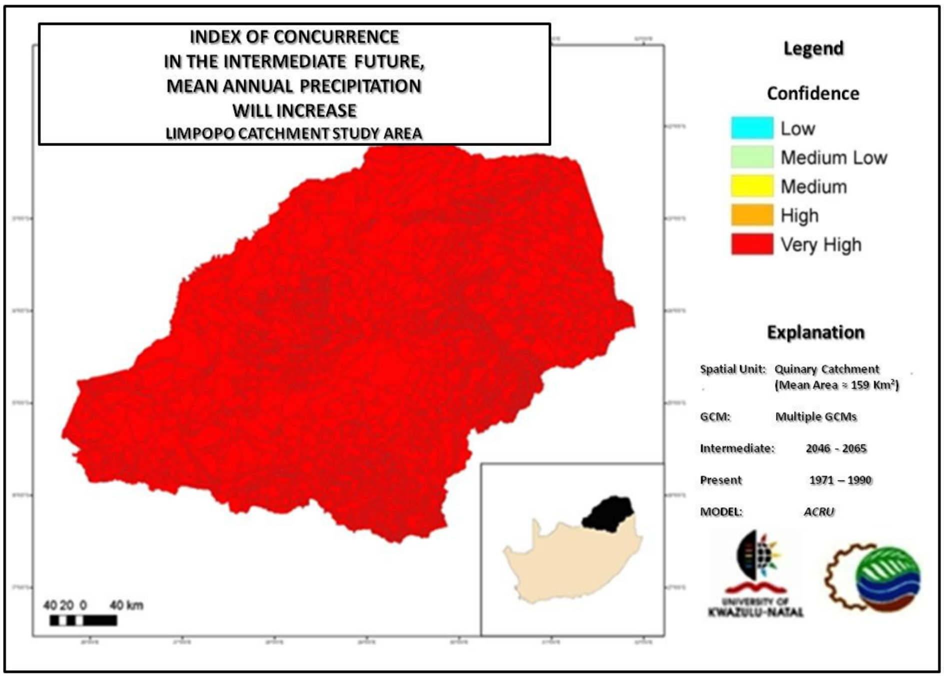


Figure F.3 Uncertainty analyses, expressed by the index of concurrence, that in the intermediate (top) and distant (bottom) future July's minimum temperatures are projected to increase by more than 10% over the Limpopo Catchment (Source information: Schulze and Kunz, 2010b)



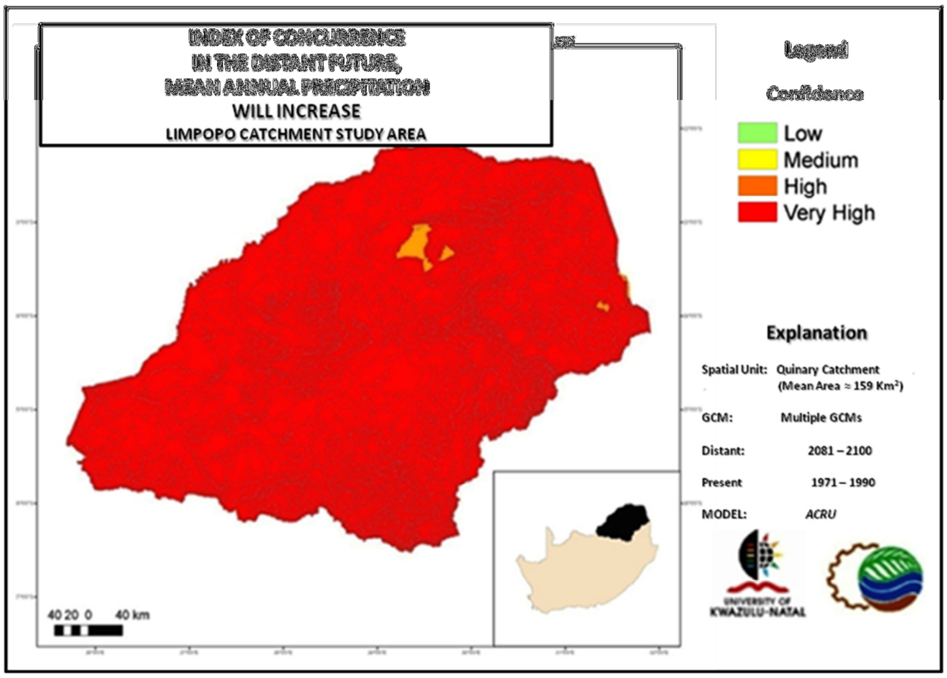
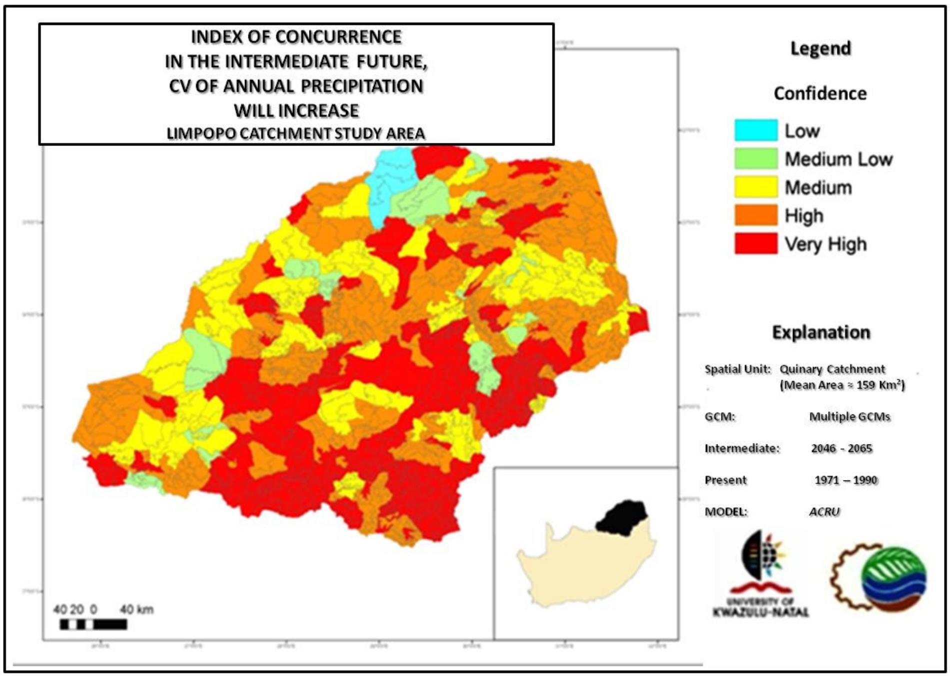


Figure F.4 Uncertainty analyses, expressed by the index of concurrence, that in the intermediate (top) and distant (bottom) future climate the mean annual precipitation is projected to increase (Source information: Schulze and Kunz, 2010c)



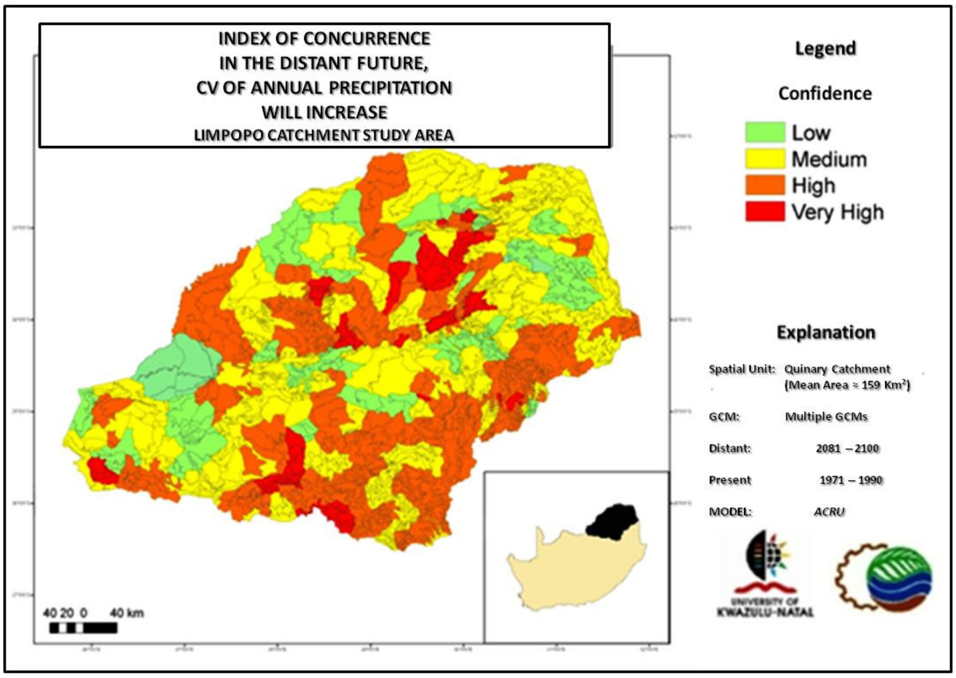
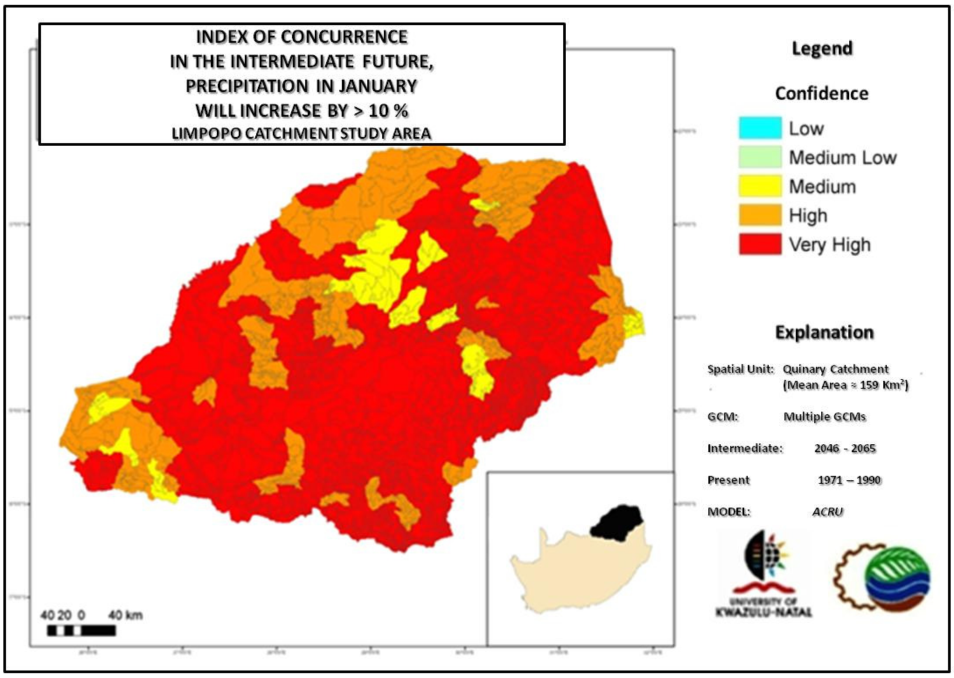


Figure F.5 Uncertainty analyses, expressed by the index of concurrence, that in the intermediate (top) and distant (bottom) future climates the coefficients of variation of precipitation are projected to increase (Source information: Schulze and Kunz, 2010, Personal Communication)



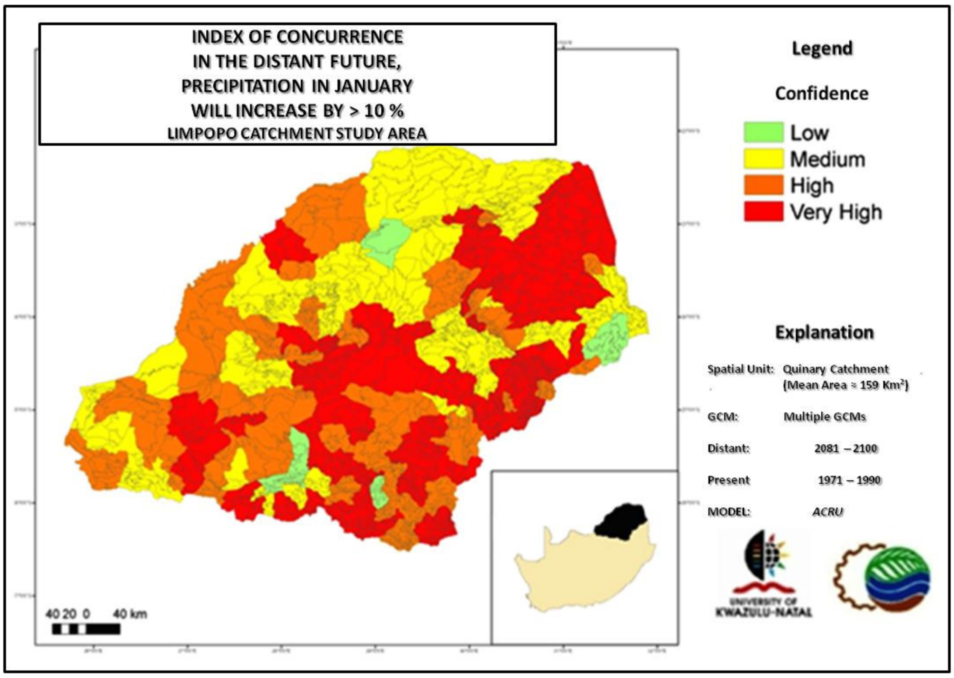
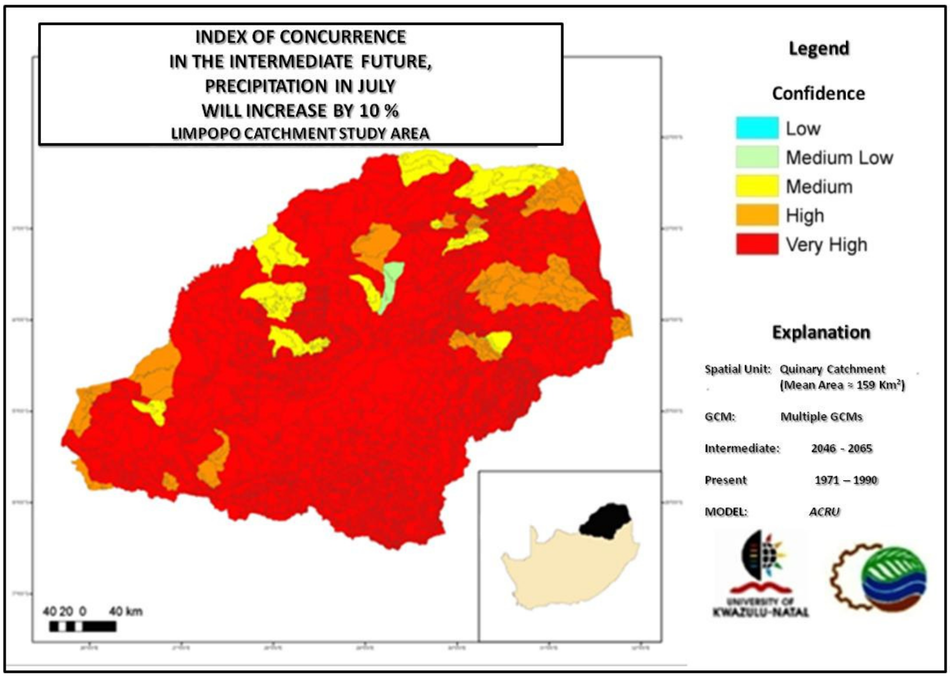


Figure F.6 Uncertainty analyses, expressed by the index of concurrence, that in the intermediate (top) and distant (bottom) future January's precipitation is projected to increase by more than 10 % (Source information: Schulze and Kunz, 2010d)



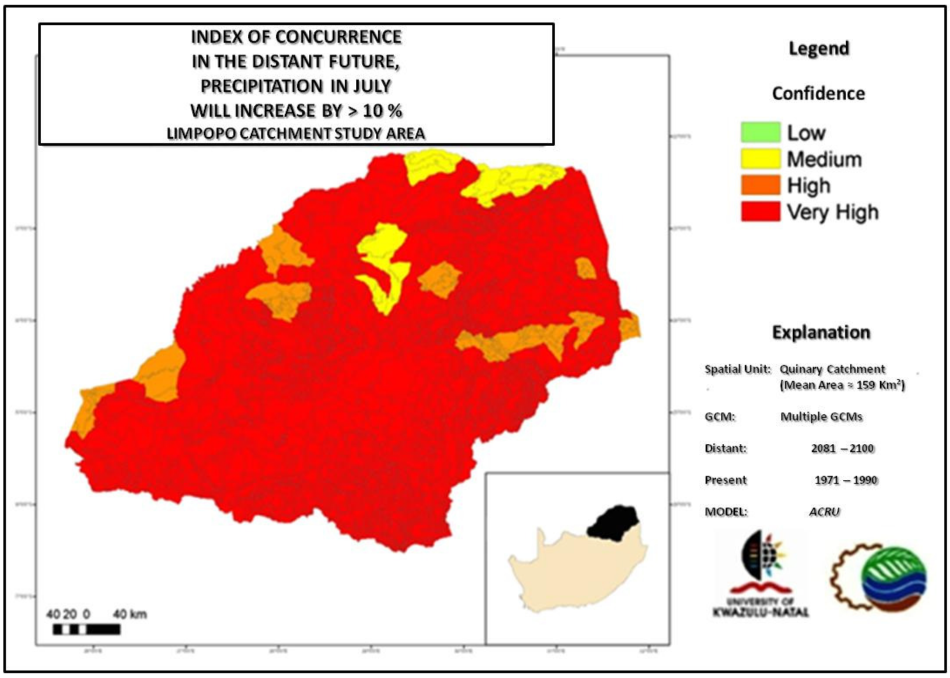


Figure F.7 Uncertainty analyses, expressed by the index of concurrence, that in the intermediate (top) and distant (bottom) future July's precipitation is projected to increase by more than 10 % (Source information: Schulze and Kunz, 2010d)

APPENDIX G: REVIEW OF THE EFFECTS OF CLIMATE CHANGE ON INVASIVE ALIEN PLANTS

A component of new work conducted as part of this research was on the development of algorithms for an invasive alien plant, *viz*. the *Striga asiatica* witch weed. Because of length restrictions to this dissertation, the development of the algorithms and the results from climate change studies are presented in **Appendix E**. A brief review of the effects of climate change on invasive alien plants is, however, given below.

In this section, weeds and other invasive plant species are referred to as Invasive Alien Plant Species (IAPS). Herbaceous crops and IAPS tend have similar growth rates, resource use, stress tolerance and reproductive efforts. This similarity is due to some of the IAPS being from other locations. The IAPS will therefore possibly affect the crop yields in the same trophic level (Bunce and Ziska, 2000). The competitive difference between crops and IAPS is due to their different photosynthetic pathways, for example, crops being primarily C_3 and IAPS species mainly C_4. The difference in the photosynthetic pathways will have potential implications on the responses of agricultural systems to physical environmental changes, as most C_4 IAPS species are already adapted to higher temperatures and drier climatic conditions, which might prevail in certain areas under climate change (Bunce and Ziska, 2000).

Elevated atmospheric CO_2 concentrations might positively stimulate the net photosynthesis and growth of both IAPS and crops if they both have C_3 pathways. The competition between C_3 IAPS and crops will oppose some of the beneficial effect of CO_2 fertilisation on crop yields (Bunce and Ziska, 2000). According to Rosenzweig and Hillel (1998), most of the major crops have C_3 pathways (e.g. wheat, rice and soybeans) and many of the worst IAPS have C_4 pathways, thus the effect of CO_2 fertilisation is likely to favour C_3 crops.

The Bunce and Ziska (2002) projections of the interactive effects of elevated CO_2 concentrations with a rise in temperatures and soil aridity indicated that it tends to favour both C_4 crops and IAPS. The prevalence and strength of IAPSs will therefore probably change because of the projected physical environmental changes, with the agro-ecosystems' composition resulting in their co-existence, or alternatively one invading the other. Sherry *et al.* (2007) also stated that the changes in response to climate change between the phenology and growth of species could result in new patterns of co-existence during reproduction, which would affect the competitive interaction of species and thus their composition. The competitive advantage of species of different photosynthetic pathways, i.e. C_3 vs. C_4 is determined mainly by factors affecting the plant development stages, such as rates of germination, leaf initiation, tillering, branching, flowering and senescence. For example, field conditions with elevated CO_2 concentrations showed more rapid emergence of IAPS seedlings due to their small seeds compared to those of crops. The study by Bunce and Ziska (2002) suggests that high seedling emergence will give the IAPS a high competitive advantage over crops.