# Modelling the Impact of Future Climate Change on Subregional Wheat Production in the Western Cape

Submitted by

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*To Jordan and Casey*

*who amaze me*

*every day*

# Abstract

Climate change is evident in the Western Cape province of South Africa, particularly in observed trends in average temperatures. Further increases are expected in the future, based on General Circulation Model (GCM) projections, as highlighted in the Inter-governmental Panel on Climate Change (IPCC) 4th (and previous) assessment reports. Whilst it is recognised that rises in temperature coupled with changes in rainfall will impact wheat yields (the province's dominant field crop), little information exists to guide adaptation planning, especially on the potential range of climate change impacts on dryland winter wheat production. Furthermore the Western Cape is a highly diverse region with regard to geology, soils, topography, climatic influences and agricultural systems. Future climate change therefore, is likely to have different impacts in different zones of the province where wheat is produced. To address this heterogeneity, the APSIM crop model was applied to assess future climate impacts on wheat in 21 relatively homogeneous farming areas (RHFAs) across the province.

After parameterising the model for each RHFA and describing the uncertainties encountered through the simulation process, two modelling approaches were undertaken. Firstly, wheat sensitivity analyses were conducted per zone, using a series of perturbations of baseline climate data (temperature: +1°C and +2°C; rainfall: +10%, -10% and 0%; $CO_2$ at 350 ppm and 500 ppm) to drive APSIM. This provided insight into zonal yield responses to individual and combined changes in key climate parameters. Losses of up to 20.7% were modelled under the +2°C perturbation, but these were largely compensated for by the increase in $CO_2$ level. Secondly, in order to explore the spatial and temporal impacts of future climate change on wheat yield and production risk, statistically downscaled climate data from an ensemble of 8 GCMs representing plausible climate scenarios at a daily time step for the periods 1979 to 1999; and 2046 to 2065 were used to drive APSIM per RHFA. Zonal yields under baseline and future climate change scenarios were simulated, and likely changes in future yield for the period 2046 to 2065 were calculated. The likely yield impacts resulting from the choice of shorter or longer season-length cultivars and from changes in nitrogen application levels in this future period were also investigated per RHFA, as was the magnitude of the response per RHFA to $CO_2$ increases. Likely changes in risk were investigated through comparisons between interannual variation at simulated baseline and future conditions.

Based on the ensemble of downscaled GCM projections driving APSIM, future yield responses were generally positive in the south and south-eastern wheat zones of the province. The western wheat zone yield projections demonstrated a greater level of uncertainty than the southern zones, and smaller or negative median yield impacts were modelled, particularly in the Swartland subregion, which also showed the highest potential sensitivity to cultivar choice under future climate conditions. Future risk patterns are likely to remain close to those currently experienced, although a few RHFAs in which increases in risk were indeed indicated, are already considered risky and marginal for wheat production. Responses to elevated atmospheric $CO_2$ varied considerably between zones, but together with expected increases in precipitation in some areas, largely compensated for yield losses due to future warming, across most of the province. In the generally shallow soils of the Western Cape, simulations at low nitrogen application levels generally resulted in increased yields under future conditions compared to the baseline simulation at the corresponding N application.

Within the constraints of uncertainties inherent in long-term agro-climatic modelling, this study has served to highlight areas where climate change may be expected to have negative and positive impacts in the province, as well as highlighting potential site specific adaptation and research measures to mitigate or take advantage of those impacts. This contributes towards focusing future research and development to facilitate gradual adaptation of local wheat production to a changing climate.

# Acknowledgements

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## List of Abbreviations

| | |
|---|---|
| ACRU | Agricultural Catchments Research Unit (Agrohydrological model, University of KwaZulu-Natal) |
| AgMIP | The Agricultural Model Intercomparison and Improvement Project |
| APSIM | Agricultural Production Systems Simulator |
| ARC | Agricultural Research Council (South Africa) |
| CEC | Crop Estimates Committee (South Africa) |
| CORDEX | Coordinated Regional Climate Downscaling Experiment |
| CSAG | Climate Systems Analysis Group, UCT |
| CSIR | Council for Scientific and Industrial Research (South Africa) |
| CSIRO | Commonwealth Scientific and Industrial Research Organisation (Australia) |
| DSSAT | Decision Support System for Agrotechnology Transfer |
| EVI | Enhanced Vegetation Index |
| FACE | Free Air $CO_2$ Enrichment |
| GCM | Global Climate Model or Global Circulation Model |
| GIS | Geographic Information Systems |
| IPCC | Intergovernmental Panel on Climate Change |
| NDVI | Normalized Difference vegetation Index |
| PICES | Producer Independent Crop Estimate Survey (South Africa) |
| RDP | Regional Development Plan (Originally *“Streeksontwikkelingplan”* in Afrikaans) |
| RHFA | Relatively Homogeneous Farming Area |
| RUE | Radiation Use Efficiency |
| SAFEX | South African Futures Exchange |
| SRES | Special Report on Emissions Scenarios (of the IPCC) |
| TE | Transpiration Efficiency |
| WCDA | Western Cape Department of Agriculture |
| WUE | Water Use Efficiency |

# Chapter One: Introduction and objectives

## 1.1 Rationale and scope of the study

The Intergovernmental Panel for Climate Change (IPCC) Fourth Assessment Report (see IPCC, 2007b) provides evidence that climate change is occurring. The most apparent observed change is that of increased average global temperatures, whilst strong evidence also points to a number of other implications of this change, such as an increase in the occurrence of extreme climate events such as heat waves, droughts and floods. The regional implications of these changes are not constant throughout the globe, and are expected to be particularly severe in parts of Africa.

Southern Africa, and in particular the Western Cape (location map shown in Figure 1.6 on page 18), is expected to become warmer and drier (Christensen et al., 2007). Considerable work has been done in recent years in assessing the potential impacts of climate change on the local climate through the application of downscaling techniques to Global Climate Models (GCMs). The source GCMs are coarse in resolution (in the region of 300 x 300km) and need to be downscaled to account for local variables and variations. Local experts have made substantial contributions in the field of downscaling (e.g. Hewitson et al., 2005b; Hewitson and Crane, 2006).

A detailed climate change report on the Western Cape was prepared for the provincial government in 2007 (One World Sustainable Investments, 2007). The report indicated a strong likelihood of warming, reduced rainfall in the western parts of the province, with increased frequency and intensity of extreme events - all for the period 2030 – 2045, based on modelling undertaken by Hewitson and colleagues at the Climate Systems Analysis Group (CSAG) at the University of Cape Town. The lack of scientifically-based climate change impact studies on dryland cropping available for the province was evident during the consultative working group meetings contributing to this publication, and provided impetus for the commencement of this study.

South Africa's Second National Communication under the United Nations Framework Convention on Climate Change (UNFCCC) (DEA, 2011) documents current understanding of climate drivers, climate projections and sectoral impacts in South Africa, together with mitigation and adaptation options according to the UNFCC guidelines. The section on winter wheat production in the Western Cape briefly states the expectation that the local wheat crop could suffer between 5 and 70% reduction in yield by mid 21st century. This was not based on any detailed process model results since none was available.

Given the projected direction of climate change in the region, there is a tendency in the media and regional socio-economic reporting to emphasise the expected negative impacts of climate change on a number of agricultural commodities, including wheat. In the absence of available, detailed information, statements are often encountered (particularly in economic analyses and policy documents) which "broad-brush" the entire region regarding expected yield *declines* under climate change. Whilst such blanket estimates certainly have their place at certain policy or administrative levels, it would be preferable to base local adaptation on studies undertaken at a corresponding level, particularly since climatic conditions in the Western Cape differ considerably from those of South Africa as a whole (Section 2.2). Many agricultural representative bodies have taken certain climate impacts and vulnerabilities for granted without exploring which climate parameters and conditions are actually responsible for specific vulnerabilities to climate change, and how these might respond under future climate scenarios (Ziervogel and Taylor, 2008). The associated uncertainties of predictions are also not generally considered. This has led to the general expectation of reduced dryland future wheat production under future climate change amongst the Western Cape agricultural community (DEA, 2011).

The Western Cape, however, is a highly diverse region with regard to topography, soil types and climate. This variability dictates the need for either subtle or distinct differences in farming practices in different sub-regions. This is evident upon examination of the wide range of agricultural activities in the 80 relatively homogeneous farming areas (RHFAs) in the Western Cape (Department of Agriculture Western Cape, 1990).

In order to assess the potential impacts of climate change on agriculture in the Western Cape in greater detail, it is proposed that a subregional (zonal) approach be followed. A spatial or geographic approach is required, in combination with appropriately downscaled climate data and production models, in order to assess the sensitivity or vulnerability of various commodities to climate change based on their location. Wheat (*Triticum aestivum*) is the most important field crop in the Western Cape (Department of Agriculture, 2010) and the most extensively grown commodity in the province and is thus the focus of this study.

The fundamental scope of this thesis is to make informed use of the following tools, data and technologies in order to assess the likely response of wheat yields in the province to future climate change at a sub-regional scale:

- Downscaled future and control climate (daily) data projections for 8 GCMs for each study zone
- A daily climatic baseline dataset per study zone
- A proven, daily time-step, deterministic crop model to be parameterised for local conditions to calculate wheat yield under projected future scenarios
- Geographic Information System (GIS) tools to facilitate the zonal imperative of the study both in terms of spatial analysis in determining input parameters and for spatial analysis and presentation of outputs
- Information on the baseline wheat production systems, performance, representative soil descriptions and management practices per zone

## 1.2 Climate change modelling

### 1.2.1 GCMs

The IPCC defines a GCM (General Circulation Model or Global Climate Model) as a numerical (quantitative) representation of the climate system based on the physical, chemical and biological properties of its components, their interactions and feedback processes (IPCC, 2007b).

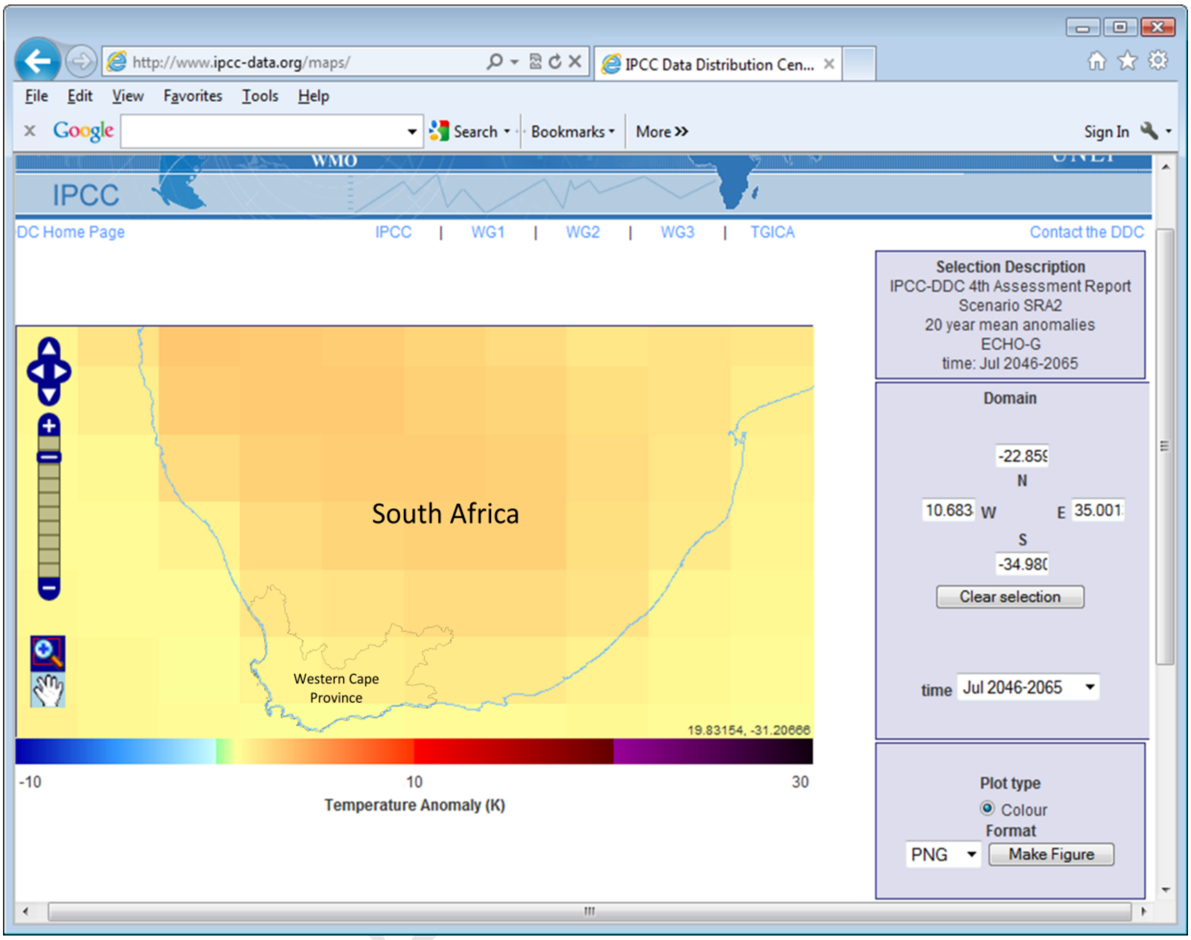
Global Climate Models or General Circulation Models (GCMs) are complex mathematical models representing the general circulation of the earth's atmosphere and/or oceans. There are both atmospheric GCMs (AGCMs) and oceanic GCMs (OGCMs). An AGCM and an OGCM can be coupled together to form an atmosphere-ocean coupled general circulation model (CGCM or AOGCM). With the addition of other components (such as a sea ice model or a model for evapotranspiration over land), the AOGCM becomes the basis for a full climate model. Coupled ocean-atmosphere models represent the pinnacle of climate modelling and as such, can provide plausible simulations of both the present annual mean climate and the climatological seasonal cycle over broad continental scales for most variables of interest for climate change. According to the IPCC (Working Group I), there is considerable confidence that climate models can provide credible quantitative estimates of future climate change, particularly at continental scales and above (IPCC, 2007b).

### 1.2.2 GCM-based forecasts for Africa and South Africa

In Africa warming is very likely to be larger than the global annual mean warming throughout the continent and in all seasons, with drier subtropical regions warming more than the moister tropics (IPCC, 2007b). Rainfall in southern Africa is likely to decrease in much of the winter rainfall region and western margins. (Christensen et al., 2007). The same chapter refers to the location of the Western Cape Province as one of five particular areas where regional projections indicate a “strong drying tendency” due to their location downstream of the polar boundaries of subtropical high pressure zones which are shifting poleward (another is south-western Australia).

The IPCC operates a Web portal which allows for spatial exploration of the GCM climatologies and anomalies (http://www.ipcc-data.org/maps). The broad scale of the source GCM data should be immediately apparent from the pixel size (Figure 1.1), with 3 or 4 modelled GCM output pixels covering the entire Western Cape.

Most of the (4th Assessment Report), 2007 source GCM data used in this study can be viewed on this site (IPCC-DDC, 2011).



Selection Description
IPCC-DDC 4th Assessment Report
Scenario SRA2
20 year mean anomalies
ECHO-G
time: Jul 2046-2065

Domain
N -22.85
W 10.683
E 35.001
S -34.98
time Jul 2046-2065

Plot type
● Colour
Format PNG

Figure 1.1. Screen capture from the IPCC Data Centre visualisation tool (IPCC-DDC, 2011) showing the scale of GCM output relative to the Western Cape province.

### 1.2.3 GCM-based climate scenarios

Climate scenarios are considered plausible representations of the future that are consistent with assumptions about future emissions of greenhouse gases and other pollutants and with our understanding of the effect of increased atmospheric concentrations of these gases on global climate (IPCC, 2011). A range of scenarios can be used to identify the sensitivity of an exposure unit – in this study, crop yield - to climate change and to help planners and policy makers decide on appropriate policy and strategic responses. The IPCC stresses that these climate scenarios are not predictions, like weather forecasts are, but are a plausible indication of what the future could be like over decades or centuries, given a specific set of assumptions. These assumptions include future trends in energy demand, emissions of greenhouse gases, and land use change as well as assumptions about the behaviour of the climate system over long time scales. It is largely the uncertainty surrounding these assumptions which determines the range of possible scenarios.

The IPCC's Task Group on Data and Scenario Support for Impact and Climate Assessment (TGICA) strongly recommends that users should apply multiple GCM scenarios in impact assessments, where these multiple scenarios span a range of possible future climates, rather than designing and applying a single "best-guess" scenario (IPCC-TGICA, 2007). The approach was implemented in this study through running an ensemble of eight different downscaled SRES A2[1] GCMs (daily data), i.e. "plausible future scenarios" as input to the crop model, discussed further in Section 4.3.4 (IPCC, 2007b). The use of A2 SRES scenarios alone, resulted from the limited availability of scenarios at the time of the commencement of this modelling project (discussed further in the next section, Section 1.2.4).

### 1.2.4 GCMs and downscaling

The climate change information required for many impact studies, however, is of a spatial scale much finer than that provided by the global climate models. This is especially true for regions of complex topography, coastal locations and regions with highly heterogeneous land-cover (Wilby et al., 2004). There are two downscaling methods that are commonly employed; dynamical downscaling, also known as Regional Climate Models (RCMs) and empirical/statistical downscaling. The latter is computationally less expensive and makes use of quantitative relationships between the state of the larger scale climatic environment and local variations sourced from historical data (Ziervogel and Zermoglio, 2009). A further

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[1] The SRES A2 storyline expects a very heterogeneous world with continuously increasing global population and regionally oriented economic growth that is more fragmented and slower than in other storylines. SRES refers to the IPCC Working Group III. (2000) IPCC Special Report: Emissions Scenarios. Summary for Policymakers, A Special Report of IPCC Working Group III.

option in empirical/statistical downscaling, is the use of weather generators to incorporate GCM outputs in daily weather data that are, to some extent, characteristic of expected future climatologies (Jones and Thornton, 2013; Semenov and Stratonovitch, 2010). This study made use of the CSAG empirical/statistical downscalings of the GCMs (Fourth Assessment Report, IPCC, 2007b) shown in Table 4.4 (page 77) available at the commencement of the study, based on the Hewitson and Crane (2006) downscaling method, described further in Section 4.3.4.1. The use of one SRES (A2) emissions scenario in this study may be considered a limitation and was a consequence of local downscaling availability at the commencement of this study. This may be a reasonable option, given that it closely tracks recent emissions levels which are unlikely to diverge to a great extent by mid 21st century (DEA, 2011) and that the "envelope of uncertainty" was sampled by a relatively large ensemble of 8 downscaled GCMs. (This issue is addressed in the discussion on uncertainties in Section 4.5.2).

## 1.3 Climate change and potential yield impacts on dryland agriculture

### 1.3.1 Introduction

The term "dryland" as used in this study refers to crop production under rainfed conditions, with no supplementary irrigation. (References to specific studies on dryland cropping under climate change are made in the literature review in Chapter Three).

In the Fourth Assessment report of the IPCC (Easterling et al., 2007) modelling results for a range of sites found that in mid- to high latitude regions, moderate to medium local increases in temperature (1 - 3°C), along with associated carbon dioxide ($CO_2$) increase and rainfall changes, can have small beneficial impacts on crop yields. In lower-latitude regions even moderate temperature increases (1 - 2°C) are considered likely to have negative yield impacts for major cereals. Further warming has increasingly negative impacts in all regions (with medium to low confidence indicated) (IPCC, 2007a).

On average, in cereal cropping systems worldwide, adaptations such as changing varieties and planting times enable avoidance of a 10-15% reduction in yield corresponding to 1 - 2°C local temperature increase (IPCC, 2007a). The benefit from adapting tends to increase with the degree of climate change up to a point.

A global assessment of agriculture under future climate change (Fischer et al., 2005) used the agro-ecological zone (AEZ) modelling framework, driven by 5 IPCC GCMs. Based on AEZ modelling for the 2080s they estimate:

- Gains in potential agricultural land globally
- In sub-Saharan Africa, a decrease of constraint-free prime land with high suitability for cropping - whilst net losses of some 12% of current cereal-production potential may be expected (also broadly consistent with findings of Jones and Thornton, (2003))
- Land suitable for wheat production in Africa may virtually disappear
- A high level of heterogeneous responses, even within the same country
- The comparative advantage for producing cereals is predicted to shift towards developed countries, with net imports by developing countries expected to rise by 25%.

The latter point reinforces previous findings by Parry et al, (2004) where higher yields were expected from production in the developed countries (which mostly benefit from climate change) compensating for declines projected, for the most part, for developing nations by the 2080s. Although global production appears stable, regional differences in crop production are likely to grow stronger through time, leading to a significant polarisation of climate change effects, with substantial increases in prices and risk of hunger amongst the poorer nations

Some examples of predicted yield responses under climate change from a variety of wheat modelling experiments for the latter half of the 21st century are summarised in Table 3.1, page 52. The range of expected yield changes is vast in some areas, but is generally expected to be positive in the wetter, more temperate regions whilst substantial yield reductions are likely in some of the drier regions of Australia.

### 1.3.2 Africa and South Africa

Studies quoted in Boko et al, 2007 state that by the 2080s wheat production could have disappeared from Africa. Further studies on agricultural impacts on Africa generally have generally focused on maize, rather than wheat, in their assessments. South Africa is considered to be among the most vulnerable to negative climate impacts on maize production (Jones and Thornton, 2003; Schlenker and Lobell, 2010; Wolfram and David, 2010). Even though wheat is the fifth most important source of calories in Africa, it was not considered in the Schlenker and Lobell (2010) study on African staple foods, as they considered it to be mostly an irrigated crop in Africa and their study concentrated on rainfed production.

A study by Benhin (2006) suggests that climate change is generally expected to be harmful to crop farming in South Africa. The study refers to work by du Toit et al. (2002) which showed that in the drier western areas of South Africa crop production would become more marginal, while in the eastern areas an increase in production was likely. A number of studies have investigated climate variability and potential future climate impacts on summer rainfall crops such as maize and sugar cane through the application of crop models (e.g. Bezuidenhout and Singels, 2007; Crespo et al., 2011; Moeletsi et al., 2011; Walker and Schulze, 2008). There was substantial crop modelling development work on wheat based in the Orange Free State province during the 1980s and 1990s reported on by Singels et al., (2010). This initial work was generally focused on specific management or irrigation issues, or model development (CERES-maize and PUTU). Further South African studies have understandably focussed mainly on summer cropping in terms of the major food security crop of the region, maize (Abraha and Savage, 2006; Crespo et al., 2011; Jones and Thornton, 2003; Tadross et al., 2009).

Recent studies on global "hotspots" generally show South Africa to be high on the scale of negative impacts with regard to crop production under future climate change (Fraser et al., 2013; Osborne et al., 2013). The impact projections are generally presented as world or continental-scale maps, in which impacts on the small, winter rainfall wheat production area of the Western Cape cannot readily be distinguished from South Africa as a whole. Given that the Western Cape climate differs markedly from the rest of the country it is important that local impact models attempt to investigate more localised impacts. Again most of these global studies tend to focus on maize production in South Africa, being the major national grain and food crop (DAF&F, 2011), rather than wheat.

### 1.3.3 Western Cape

In the absence of suitable impact assessments of wheat, recent climate change assessment studies commissioned either nationally, or by the Western Cape Provincial Government could say little on the prospects for the Western Cape wheat industry – one of the major production and land use sectors of the provincial economy - under future climate change (DEA, 2011; Midgley et al., 2005; One World Sustainable Investments, 2007) . Climate impact modelling work has centred largely on biodiversity (e.g. Hoffman et al., 2009a; Midgley et al., 2006) and certain agricultural commodities known to be particularly sensitive to climate warming, such as apples and pears (Cartwright, 2002; Grab and Craparo, 2011; Wand et al., 2008). There is no contemporary crop-model based climate change impact research on Western Cape dryland field crop production reported in the mainstream literature.

## 1.4 Dryland wheat production in the Western Cape province

### 1.4.1 Introduction and background

Of the South African provinces, the Western Cape province produces the most wheat – at 40% of the national total during the past 5 years (DAF&F, 2012). Figure 1.2 sets the context in which the South African wheat industry currently prevails.

Area planted and total production is declining and demand is growing, requiring increased imports. Nationally the areas planted to wheat have declined from 1.4 million hectares to the current levels shown in Figure 1.2. Wheat areas planted in the Western Cape have declined more than 50% over the last 25 years, from a high of 660 000 ha in 1988 to the current (at 2011) level of 265 000 ha (Grain SA, 2011). Wheat is produced almost entirely under dryland (rain-fed) conditions in the Western Cape Province. Small areas of irrigated wheat are in evidence under centre-pivots, usually as a rotation crop with vegetables, but these amount to less than 5% of total production (Statistics South Africa, 2002) . Originally, wheat was only produced in the winter rainfall area (in the Western Cape), but has also been cultivated on a large scale in the Free State province since the 1970s, and, increasingly, under irrigation in other provinces.

The vast expanses of former wheat lands now lying unutilised in parts of the province bear testimony to the tough economic times the wheat industry in the province has endured, particularly during the last 14 years, which has had little to do with climate change.

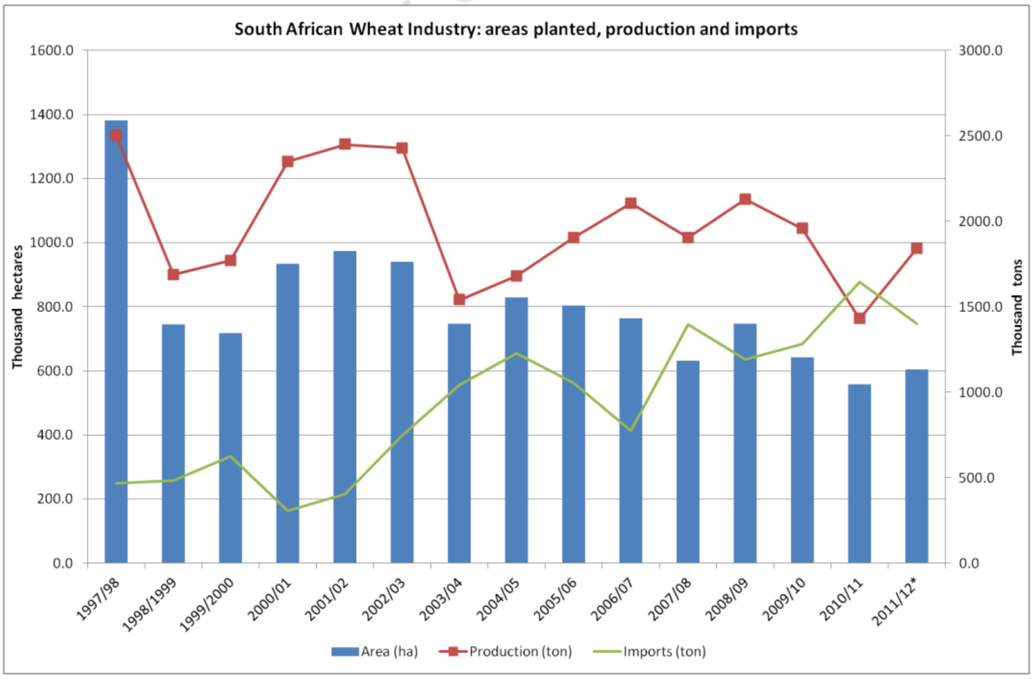

Figure 1.2. South African wheat areas, production and imports since 1998. The Western Cape production levels are approximately 40% of the national total (DAF&F, 2012).

Figure 1.3. Abandoned former wheat fields gradually reverting to natural vegetation, Rûens East (Photo M. Wallace).

The Wheat Board controlled wheat marketing until 1997 (using a single-channel, fixed price system), after which, due to political changes, new marketing legislation was introduced[2], and market forces prevailed to determine prices (BFAP et al., 2005). This suddenly increased the exposure of wheat farmers to market risk (see the sudden decline in area planted after 1997/98 in Figure 1.3) resulting in massive farmer insecurity, evident in the sharp decline in plantings and production. Prices became more volatile than in the past, since they fluctuate between the export and import parity levels, depending on whether there is a national surplus or a shortfall. South African wheat consumption in the decade prior to 2005 remained fairly stable at around 2.3 million tonnes per annum (BFAP et al., 2005) whilst in 2010/11 it was reportedly close to 3 million t/annum (DAF&F, 2011) whereas deliveries recorded (i.e. local production) were only half of that figure. Wheat shortfalls require imports from world markets, which makes the prevailing exchange rate an important factor in price determination.

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[2] The Marketing of Agricultural Products Act no 47 of 1996

The economic impact of deregulation caused some shifts in production areas – particularly evident by the expanses of “old lands” once used for wheat - particularly at the far eastern, western and north-eastern extents of the current “core” provincial wheat production area. The Western Cape, although a fairly stable production area, is far from the main consumer markets in Gauteng, a factor that increases transport costs. In terms of SAFEX pricing, farmers in the Western Cape are required to cover the cost of transport of their wheat to Randfontein (as a point of reference) in Gauteng – the so-called, and very unpopular “transport differential” (BFAP et al., 2005). This adds a further burden on Western Cape wheat growers. Many developed nations have farmer subsidies in place to support their local production and food security, whilst South Africa does not. Wheat farmers in many parts of the province are in a precarious position and have difficulty surviving financially under current conditions. There is a natural concern amongst the dryland wheat production community to learn what yield stresses can be expected due to a changing climate.

### 1.4.2 Socio-economic value

Wheat is the second most important grain crop produced in South Africa after maize. The Western Cape contributes almost half of the country’s total wheat production, with the remainder being produced in the summer rainfall areas. Some 300 000 ha were planted in the Western Cape in 2009, producing 787 500 tons of wheat with a value of approximately R1 700 million (Department of Agriculture, 2010). In the winter rainfall Western Cape, wheat is planted mainly between mid-April and the end of May and is mainly used for bread making. South Africa is a net *importer* of wheat and during the 2008/9 season approximately 27% of the wheat needed for domestic consumption had to be imported and this trend seems likely to continue, notwithstanding a very good production year in 2011/12 (Figure 1.2).

### 1.4.3 Geography and character of wheat production

The traditional major wheat growing subregions in the Western Cape are known as the Swartland, in the west of the province, and the Rûens in the south (Figure 1.4). Smaller plantings also occur in the north-west, parts of the Karoo and in the south-east although most of these peripheral areas can be considered marginal in terms of wheat profitability (Appendix Figure 25 gives an indication of the range of wheat production across the Western Cape). The Swartland and Rûens are characterised by hot, mostly dry summers and moist, temperate winters typical of Mediterranean climatic zones. The Swartland (the main wheat producing region within the province) is known for its consistency of wheat production. The region receives more than 80% of its rainfall during the winter months, April to September. Although both regions have a similar range of mean annual rainfall, the Rûens area receives a greater portion of summer rainfall, from 25% in the Caledon area to 45% in the east. The Rûens is generally more variable than the Swartland in terms of grain production as a result of its inherent rainfall variability.

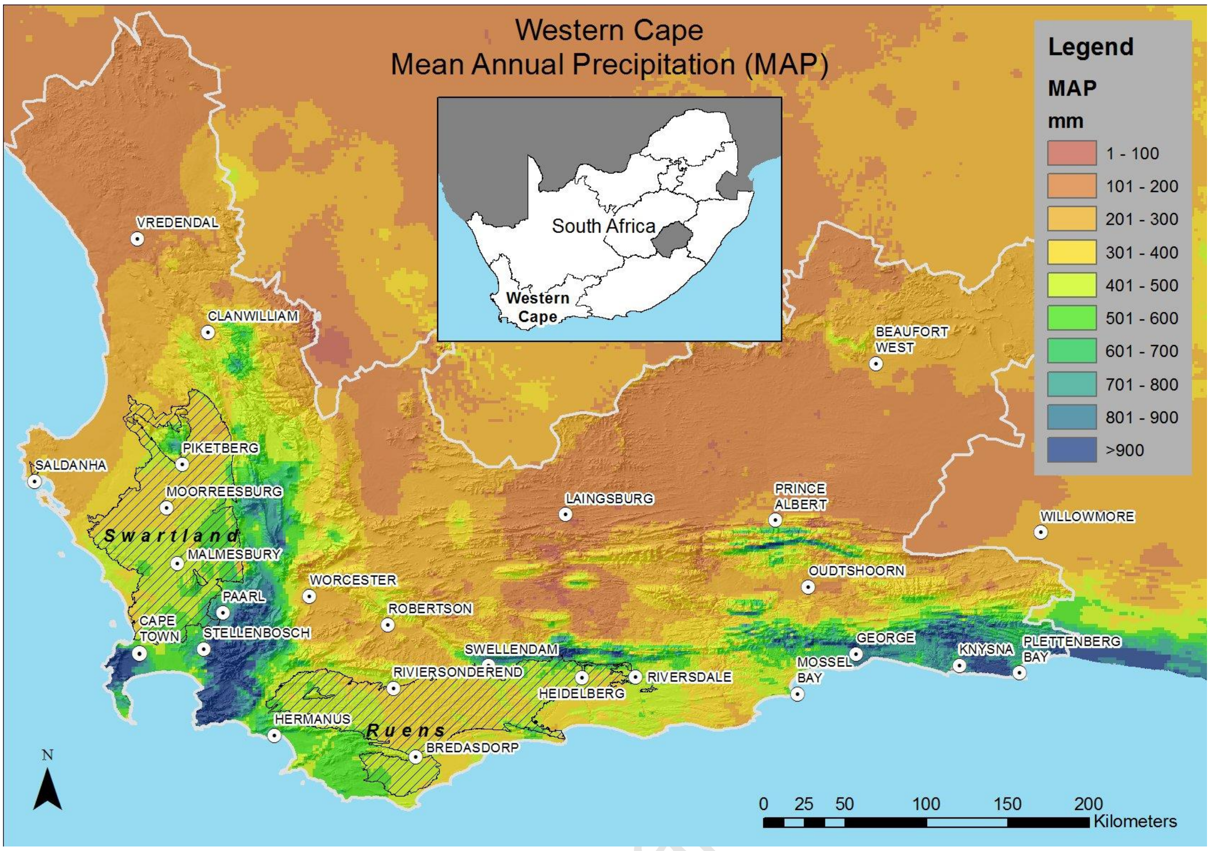

Figure 1.4. Western Cape mean annual precipitation showing the regions colloquially known as the Swartland and the Rûens.

Soils used for wheat production in both regions are generally relatively poor, with average depths of some 400 mm, high stone fractions and low water-holding capacity. Drainage issues occur in some regions with flatter topography and soil with a high clay fraction and/or duplex structure. Soil fertility is also generally low, although soil organic carbon stocks in the Rûens area are higher than in the Swartland due to the milder, moister summers allowing more rapid breakdown and incorporation of organic matter into the soil carbon pool (Hardy, 2007).

### 1.4.4 Wheat production systems

Systems have been developed over the years wherein small grain and livestock production complement one another to supplement whole farm income. Livestock – mostly sheep – utilize the wheat stubble as well as pasture crops such as medics (*Medicago* spp.) and lucerne (*Medicago sativa*) which are produced in rotation with wheat. Wheat residues may be grazed in-situ or hay may be baled to support the farm's livestock fodder flow or sold (Figure 1.5).

Figure 1.5. Wheat residues baled to support the on-farm livestock fodder-flow in the Rûens West area (Photo M. Wallace).

Summer pastures are more successfully produced in the Rûens area due to the higher summer rainfall component; whereas many parts of the Swartland are too dry in most summers to sustainably produce rain-fed pastures.

### 1.4.5 Wheat yield trends

Wheat has shown a marked increase (up to 250% in some countries) in yield over the last 50 years (Calderini and Slafer, 1998). Studies show that yields may have reached a ceiling, having levelled off during the last decade. Nicholls (1997) estimates that changes in climate have accounted for less than 50% of the observed increase in Australian wheat yields, with the remainder emanating from technology advances such as new cultivars and improved management practices. When analysing historical data, and where key variables are available (or can be inferred), crop modelling can help to overcome the issue of changes in trends of wheat yield by allowing environmental influences rather than technological advances to determine yields (by keeping factors such as improved cultivars, pest & disease control, plant nutrition and mechanisation at constant levels, as required).

Technological advances have played the major role in the trajectory of yield improvements over the last 50 years and are considered likely to do so into the future (Asseng and Pannell, 2013; Fischer et al., 2009; Jaggard et al., 2010; Monjardino et al., 2013) notwithstanding the possibility that (conventional) plant breeders may be approaching a yield “ceiling” in the world’s major food crops (Jaggard et al., 2010). Given the associated uncertainties, however, the majority of climate change impact studies imply no change in agricultural technologies – other than modifications to management practices such as planting dates, annual cultivar choice assumptions and other farm-level choices (Trnka et al., 2004b). In a study using 4 SRES scenarios forcing the HadCM3 GCM, Ewart et al.,(2005) did include technology advances in modelling future European crop productivity, finding technology to be the most important driver but conceding that relationships determining technology development remain unclear and will require further research focus. The study found that technological advances would be able to exceed predicted changes in demand. Africa is unlikely to be so fortunate. Organisations such as CIMMYT[3] and CGIAR[4] and their partner organisations are actively involved in technological programmes to improve wheat yields in resource poor areas such as in developing parts of Africa, where demand for wheat as a staple is growing (Negassa et al., 2012).

## 1.5 Wheat production in subregions of the Western Cape

### 1.5.1 Introduction

The Western Cape is a highly heterogeneous region with regard to topography, geology and climatic influences. The region is dissected by the Cederberg and Olifantsrivier mountains in the west and the Langeberg and Swartberg ranges in the south-east. Wheat production generally occurs between the mountains and the ocean to the west and south of these ranges respectively as shown in Figure 1.6. A number of relatively homogeneous

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[3] International Maize and Wheat Improvement Centre, http://www.cimmyt.org/en/what-we-do/wheat-research

[4] Formerly the Consultative Group on International Agricultural Research, now restructured into a consortium but retaining the name. See http://www.cgiar.org/whats-new-in-research/

farming areas (RHFAs) were identified by scientists and extension workers during the 1970s, where farming practices, soils and climate were relatively similar. Some 80 of these zones were identified and demarcated for the province. Wheat production can be considered the primary agricultural enterprise in 10 of these zones, whilst playing a significant role in a further 11 zones in the small-stock/small grain milieu. Some of the latter have become considered as very marginal in terms of wheat production, but are deemed worthy of consideration in this wheat study due either to their historical wheat production or the remarkable persistence of wheat as a marginal yet significant component of farming systems in the particular RHFA.

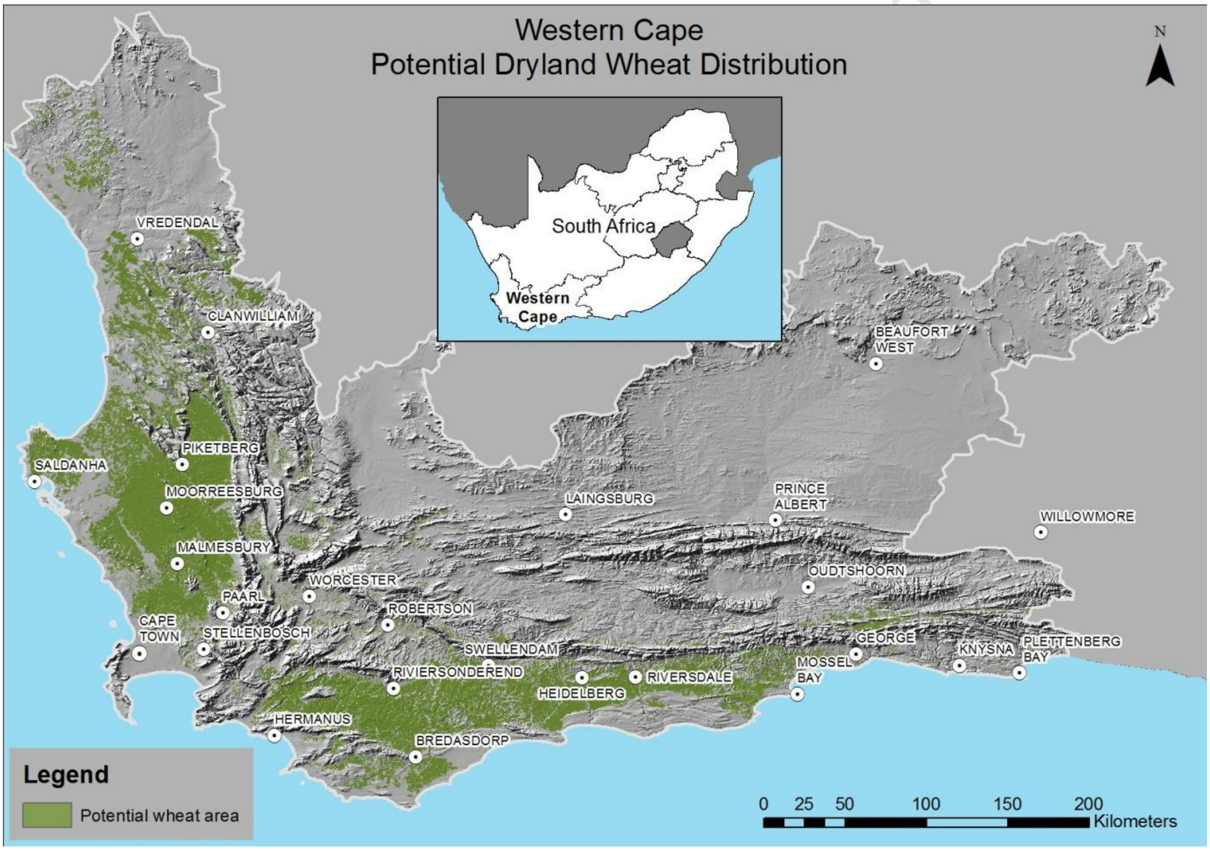

Figure 1.6. Wheat areas in the Western Cape (including areas where wheat may be produced speculatively depending on climate or market conditions).

## 1.5.2 Relatively homogeneous farming areas (RHFAs) of the Western Cape

The information on wheat zones was obtained mainly from the archives at the Department of Agriculture, Elsenburg (Department of Agriculture Western Cape, 1990), and supplemented by interaction with regional extension officers, farmers and also personal observations of the author during 15 years of field experience in the region.  The methodology behind the selection of the zones is discussed in Section 4.2.

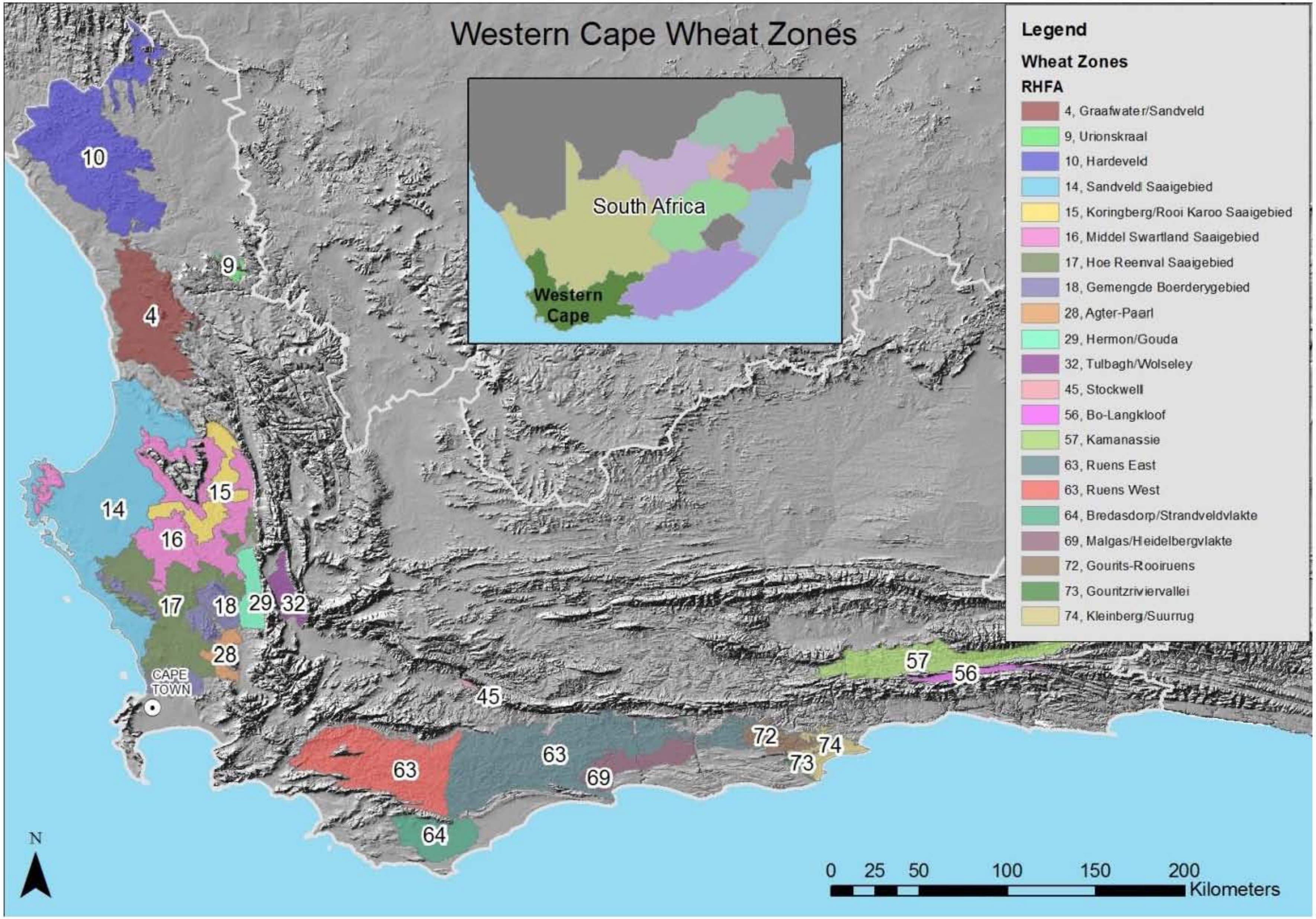

Figure 1.7. Map showing RHFAs used in this study.

Table 1.1 List of RHFA study zones (categorised as primary or secondary wheat production areas)[5].

| **Category** | **RHFA Name** | **RHFA Number*** |
|---|---|---|
| Primary | Agter-Paarl | 28 |
| | Hoë Reënval Saaigebied | 17 |
| | Hermon/Gouda | 29 |
| | Middel Swartland Saaigebied | 16 |
| | Gemengde Boerderygebied | 18 |
| | Koringberg/Rooi Karoo Saaigebied | 15 |
| | Rûens West | 63e |
| | Rûens East | 63w |
| | Bredasdorp/Strandveld Plain | 64 |
| | Malgas/Heidelberg Plain | 69 |
| Secondary | Gourits-Rooirûens | 72 |
| | Kleinberg/Suurrug | 74 |
| | Tulbagh/Wolseley | 32 |
| | Graafwater/Sandveld | 4 |
| | Sandveld Saaigebied | 14 |
| | Urionskraal | 9 |
| | Stockwell | 45 |
| | Kamanassie | 57 |
| | Bo-Langkloof | 56 |
| | Hardeveld | 10 |
| | Gouritz Rivier Valley | 73 |

* As used in the RDP manuals ( (Department of Agriculture Western Cape, 1990)

Figure 1.7 and Table 1.1 define the 21 RHFAs used in this study. The spatial context of the zone can add to the interpretation and understanding of yield responses and sensitivities. More detailed topographic maps of each zone are available in Appendix I, and narrative characterisation of the zones is presented in Section 2.5.

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[5] The Afrikaans word "saaigebied" appearing in many of the above names, means "sowing area", in other words areas where annual field crops are sown.

## 1.6 Crop Modelling

Crop models (in the mechanistic sense) are essentially collections of mathematical equations that represent the various processes occurring within the plant and the interactions between the plant and its environment. Owing to the complexity of biological and environmental systems it is impossible to fully represent the system in mathematical terms thus agronomic models condense current knowledge and assumptions regarding these processes and interactions to seek a simplified representation of reality. Crop modelling is now considered a natural component of the toolbox of crop science – a view that has emerged only in the last 25 years (van Ittersum and Donatelli, 2003b).

Table 1.2. Attributes of crop models of different complexity (after Schulze, 2007).

| | **Levels of complexity of crop models** | | |
|---|---|---|---|
| **Attribute** | **Simple** | **Intermediate** | **Complex** |
| Model structure | Experience and rate-based climatic threshold yield functions. | Phenology driven, soil water deficit yield functions (simple water balance) | Genetics, physiology, phenology & management based growth, development and yield functions |
| Model time step | Annual, seasonal, monthly | Monthly / Daily | Daily |
| Climate variables | Rainfall<br>Temperature (max & min)<br>Heat units | Rainfall<br>Temperature<br>Reference potential evaporation | Rainfall<br>Temperature<br>Solar radiation<br>Reference potential evaporation,<br>CO2 transpiration |
| Soil variables | Single soil layer<br>Texture class<br>Normative weightings (deep/shallow, clay/sand) | 1 – 2 horizons<br>Horizon thicknesses<br>Retention constants<br>Drainage permeability | Multiple soil layers<br>Detailed physical & chemical layer descriptions<br>Pedotransfer functions<br>Previous crop residues<br>Root depth<br>Organic carbon |
| Management options | Normative weightings (excellent – poor) | Plant date<br>Cultivar attributes<br>Tillage options | Plant date / rule-based options<br>Cultivar attributes<br>Tillage options<br>Plant density/depth<br>Row spacing<br>N-fertilization<br>Irrigation |

Table 1.2 (above) summarises the different levels of complexity available for crop modelling. In the South African context where complete and continuous observed daily weather data records for long periods are scarce, there is a temptation to select a simple or intermediate model. However, Nonhebel (1994) warns of the possible inaccuracies inferred from using (monthly or 10-day) averaged weather data in crop models. Especially in the water-limited growth conditions of the Western Cape, it is rainfall *distribution* through the season that is critical to wheat performance – rather than simple monthly or seasonal totals. For this reason a modelling approach based on daily time step input weather data is followed in this study. The difficulties inherent in procuring such data in South Africa are a deterring factor precluding more widespread application of this approach.

The stringent soil parameterisation required in the complex model is also a consideration, as "ready-to-use" detailed, multiple soil layer data are simply not available as they are in some other countries and must be user-derived. A further factor deterring more widespread usage, is that complex crop models such as those within the APSIM (Agricultural Production Systems Simulator) or DSSAT (Decision Support System for Agrotechnology Transfer) crop simulation suites are primarily designed for use by researchers and require a considerable level of agronomic training and experience (Holzworth et al., 2006). This can be regarded as safe practice in any case, as an uninformed user could too easily enter unrealistic parameters and be misled by subsequent outputs.

The South African crop modelling community although small, has a strong research track-record, being currently active mainly in sugarcane and maize modelling in the summer rainfall region of South Africa (as reviewed by Singels et al., 2010). Very little activity in the modelling of winter rainfall wheat is recorded in the last 2 decades however – resulting in a dearth of information regarding both the *status quo* baseline and the potential impact of climate change on wheat yield in the Western Cape.

The development and level of maturity of the APSIM model (Keating et al., 2003) with its rigorous and disciplined validation (Holzworth et al., 2006) and extensive testing in environmental conditions similar to those experienced in the Western Cape, in particular in the Mediterranean climate zones of Western Australia (Ludwig and Asseng, 2006) makes this an attractive option for modelling local winter wheat production. APSIM model applications and research are well-reported in contemporary literature with a number of researchers reporting on climate change impact studies (see literature review, Chapter 2). The APSIM model is included in the suite of mechanistic crop models in the Agricultural Model Intercomparison and Improvement Project (AgMIP[6]), an international collaboration which formed recently to assess the state of global agricultural modelling and to understand climate impacts on the agricultural sector (AgMIP, 2011).

One of the main advantages of using a crop modelling approach in the analysis of future scenario datasets and associated statistics, is that the crop model expresses any climate change temperature and precipitation shifts, changes in variability, extremes, dry spells and growing season shifts purely in terms of their *integrated* impact on crop yield (and timing and duration of the modelled growing season). Using wheat yield as the predominant change-field, distils and simplifies the assessment and understanding of the mass of climatic change information by agricultural stakeholders.

The study provided an opportunity to apply two impact modelling approaches with regard to simulating future changes. Most of the literature reports on the manipulation or perturbation of historical daily climate data records by various methods in order to assess possible future yield responses (Section 3.3.2). This methodology (regarded as a sensitivity analysis in this study) has its shortcomings, but in the absence of downscaled, daily time-step, GCM-based data, has been commonly used for impact projections into the future by studying the sensitivity of wheat to changes in temperatures, rainfall and $CO_2$ levels. With the increasing availability and refinement of downscaled daily data output for future GCM scenarios, the validity and usefulness of the sensitivity analysis or baseline perturbation approach as a methodology to assess potential future yield impacts is examined. The perturbation of baseline climate method exposes zonal sensitivities to changed climate or $CO_2$ parameters (or combinations thereof), whilst the approach using

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[6] http://www.agmip.org

downscaled GCM data at a daily time step facilitates the investigation of spatial and temporal changes expected with future climate change, i.e. the likely “pattern” of future change across the province.

## 1.7 Study objectives

Against a background of current high climatic variability, it is evident that the Western Cape is experiencing warming and climate models predict further warming into the future.

Despite the broad expectation of increased wheat yields at higher temperatures (1 - 3°C) at higher latitudes, presented in the synthesis of Easterling et al (2007):

- regional expectations expressed in policy reports or research have either largely avoided the subject of future local winter wheat performance due to lack of information (Midgley et al., 2005; One World Sustainable Investments, 2007) or are unequivocally pessimistic regarding the future of wheat in the region (DEA, 2011; Gbetibouo and Hassan, 2005).
- there are no local process-model based studies on winter wheat upon which to base local assumptions and no local studies indicating the likely spatial variations in winter wheat yields under future conditions.

The Mediterranean climate of the Western Cape is atypical of national or indeed sub-Saharan agricultural conditions. Where winter wheat is indeed included in regional studies (usually aimed at food security “hot spot” analysis) the scale is usually broad, and not intended to infer any detailed assessment of local variation at a local scale (Ericksen et al., 2011; Fraser et al., 2013; Osborne et al., 2013)

In this setting, given the importance of wheat in the provincial context and the highly diverse nature of its agricultural subregions, the study aims to assess whether the pessimistic outlook for the wheat industry by the mid-21st century is valid (e.g. DEA, 2011), given that the estimated projection had to be made in the absence of detailed studies available at the time.  With an understanding of the capabilities (and limitations) of crop modelling, the best downscaled GCM data available (at the time of this study), GIS tools and access to local knowledge, the likely impact of future climate change on local wheat yields at mid 21st century can be addressed.

Within this ambit, the specific objectives to be addressed are:

1. *How sensitive (or resilient) is subregional wheat yield in the Western Cape to the expected changes in temperature, rainfall and $CO_2$ (and combinations of these) and how will these responses vary across the province?*
   Using the approach of perturbing the baseline climate and $CO_2$ parameters for each wheat-producing RHFA (as input to the APSIM crop model) these zonal sensitivities are explored and evaluated.
2. *What are the likely spatial and temporal impacts on wheat yield and production risk across the Western Cape under future GCM-based climatologies for the mid 21st century?*
   In order to investigate zonal responses, the APSIM model is driven by 8 different downscaled GCMs at a daily time step for the period 2046-2065, per RHFA. Analyses of the model outputs contribute to the understanding of
   a. likely changes in geographic distribution of yield across the province.
   b. temporal changes in timing and length of the wheat growing season and the potential importance of choice of season-length cultivars as an adaptive management option.
   c. whether wheat yields are likely to be relatively lower under potentially nitrogen-limited conditions under future climate change .
   d. associated changes in production risk for each zone.
3. *What is the likely influence of increasing atmospheric $CO_2$ in subregional wheat yields in the Western Cape under future climate conditions?*
   Elevated $CO_2$ levels appear to be a critical factor influencing wheat production levels under expected future conditions. Crop responses to climate and $CO_2$ changes are complex and spatially variable and can thus differ considerably between agro-ecological zones. The APSIM model is used to assess the zonal

sensitivities and likely subregional magnitude of impact responses of wheat in the Western Cape to expected future $CO_2$ levels.

Given the reliance on a modelling approach to address these objectives, considerable effort was put into the selection of an appropriate model and the careful parameterisation thereof at an appropriate scale. The propagation of uncertainties through the modelling process is unavoidable, and these are discussed and constrained where possible within the scope of this study. Detailed zonal data were collated and the APSIM model was parameterised per RHFA, in terms of soils, climate, GCM downscaling and local wheat conditions, as described in Chapter 4. Results of the perturbed baseline approach (sensitivity analysis) are given in Chapter 5. Chapter 6 presents the results of the downscaled GCM approach, and includes the outcomes of both the cultivar analysis and risk investigation per zone. The result of the $CO_2$ wheat sensitivity study is addressed in Section 5.8. Chapter 7 draws on all the above results in a synthesis of, and discussion on the likely implications for future (2046-2065) wheat production in each of the wheat producing RHFAs in the Western Cape. The concluding chapter revisits the study objectives and alludes to the associated uncertainties and limitations in this study, whilst making some recommendations for further research.

# Chapter Two: Background – Western Cape wheat production and climate

## 2.1 Introduction

This chapter contains background information on the climatic patterns and trends evident in this study and further information on the zonal characteristics of the RHFAs with regard to their current wheat production system and performance.

## 2.2 Western Cape climate drivers

Although most of South Africa experiences summer rainfall, the south and south-western part of the province (in which most of the province's wheat production takes place) lies in a Mediterranean climate zone. It thus experiences seasonal rainfall distribution that is quite different from the rest of South Africa (Midgley et al., 2005) as shown in Figure 2.1. This results in agricultural production and climate sensitivities that differ considerably from the rest of the country, a potentially significant factor when interpreting country-level climate change impact assessments for South Africa.

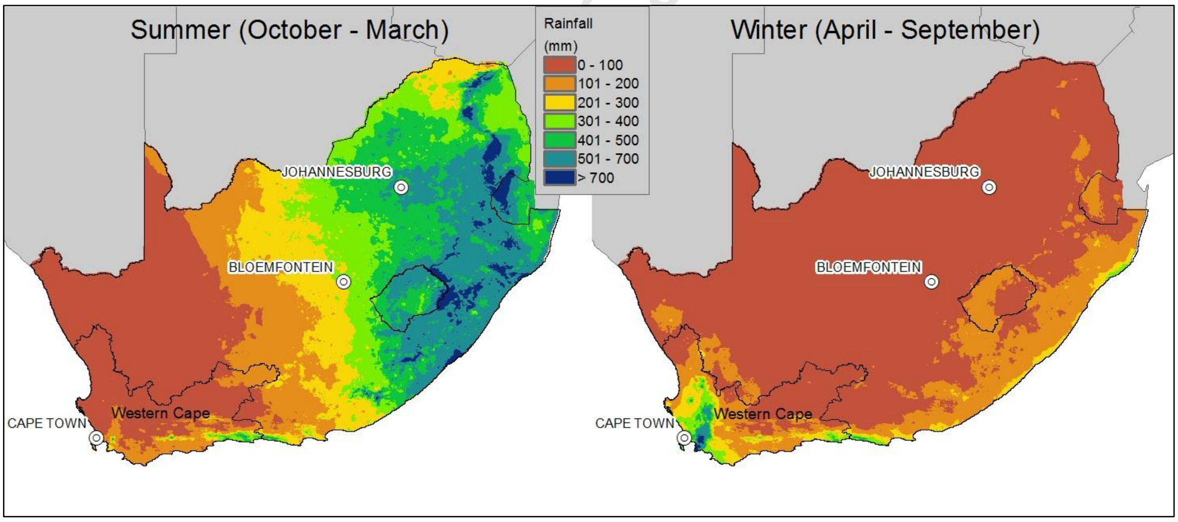

Figure 2.1. Mean seasonal rainfall (mm) for summer and winter over South Africa.

Climatic conditions in South Africa are determined mainly by hemispheric-scale atmospheric circulation, together with effects due to ocean circulation patterns. South Africa is located at sub-tropical mid-latitudes that are subject to subsiding air and high pressures, the result of large-scale 'Hadley cells' that transport surface air from Earth's warmer equatorial regions to sub-tropical latitudes where the air subsides towards the surface. This tends to result, as a general rule, in a dry climate relative to the global average (DEA, 2011).

High pressure cells which stretch across the southern African subcontinent block the passage of the low pressure systems (the co-called westerly waves) that move from west to east between roughly 40° and 50°S during summer. In winter as the high pressure cells shift northwards, these low-pressure systems can also shift northwards, bringing cold fronts to the Western Cape (Tyson and Preston-Whyte, 2000). The eastward movement of these cold front systems is usually followed by the onshore flow of moist air, and post-frontal rain – the dominant rainfall driver in the Western Cape (see Figure 2.2). The winter wheat industry in the region relies heavily on regular rainfall resulting from these systems during winter. The associated rainfall is augmented by a significant contribution of orographic rain due to the extensive mountain ranges in the area. These mountains also act as a barrier creating a drier interior on the lee side of the ranges. There are large variations in the westerly wave and high pressure cell positions during winter and both seasonal and annual rainfall in the region can thus also be subject to this variation creating regular drought conditions (Midgley et al., 2005).

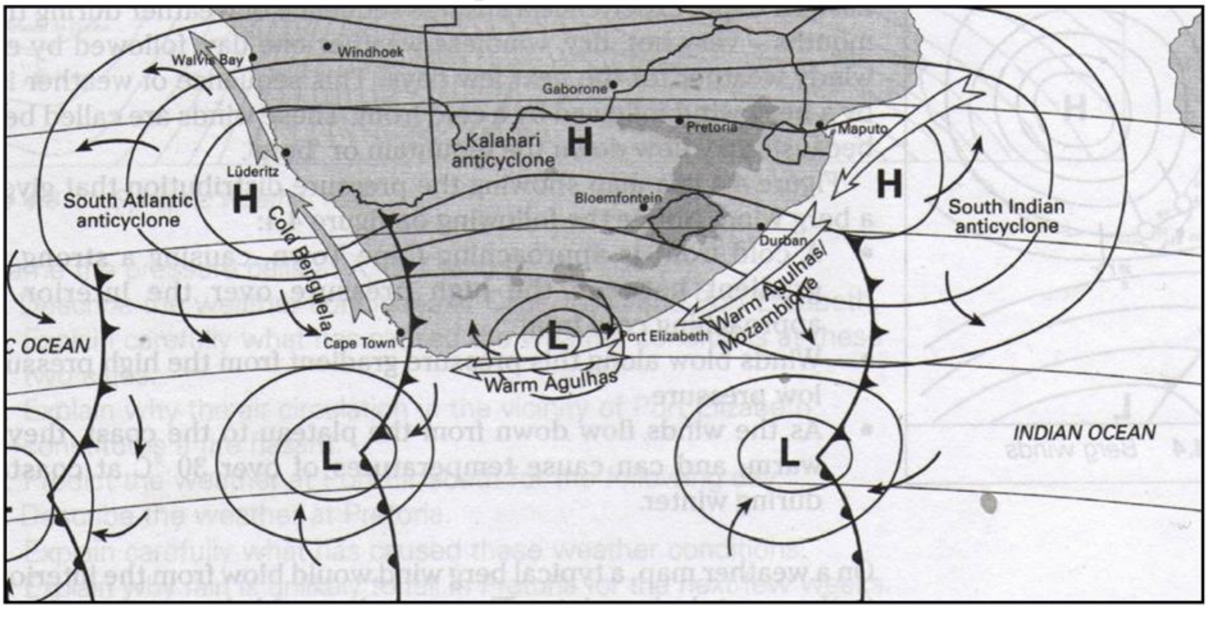

Figure 2.2. A typical winter synoptic condition over South Africa showing the west-east passage of low-pressure cells and associated cold fronts below the band of subtropical high pressure cells (Mindset, 2011).

Rainfall variability is high over much of the country, though somewhat lower in the winter rainfall zones of the west; and this represents a challenge for forecasting weather, and even more so for projecting the impacts of future climate change for rainfall.

Some of the primary large scale circulation changes particularly relevant to the Western Cape, as projected by GCM include (after DEA, 2011)[7]:

- An extension of the Hadley circulation expressed as an increased surface pressure pole-ward of the continent, and increases in the southern margin of the high pressure systems associated with the Hadley cell expansion.
- A decrease in the strength of the prevailing westerly winds south of the continent.
- Shifts in the spatial west–east positioning of the summer rainfall gradient. (The south east part of the Western Cape may thus receive an altered proportion of summer to winter rainfall).
- Increased atmospheric moisture content over the continent, which could translate to potentially more intense precipitation and a likely increase in orographic cloud cover and topographically-induced rainfall.
- Weaker frontal systems to the south, which could translate to weaker penetration of fronts onto the continent, drier conditions in the Western Cape (possibly compensated for by increased orographic rainfall on mountain ranges).

These changes are likely to have a greater impact towards the end of the 21st century. Key climate responses that are affected by topography are likely to be inadequately represented at the GCM grid scale for these regions, including rainfall.

At the scale of the GCM, winter rainfall over the south-west of the province is projected to decrease. It is not possible from GCM projections to determine the position of the boundary between regions with projected increases and decreases in rainfall. Surface air temperature, a more spatially continuous parameter, shows warming everywhere in South Africa, generally increasing from the coast to the interior.

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[7] South Africa's Second National Communication under the United Nations Framework Convention on Climate Change, using the set of GCMs (and subsequent downscalings thereof) used in this thesis.

(The downscaling methodology of the GCM outputs for use in impact models was presented in Section 4.3.4.1, page 78). The downscaled results (presented as maps and tables in Section 6.2 and Appendix II, and precipitation graphs in Appendix III) generally support the broad GCM projections of increased rainfall in the east of the region, whilst they generally moderate the GCM-scale drying projections in the south-west – most probably as a result of orographic effects after statistical downscaling is applied (DEA, 2011).

## 2.3 Trends in historical observed data in the Western Cape

As a background study to this thesis, and in response to numerous queries from agricultural stakeholders in the province, a project was undertaken by the author to investigate existing temperature and precipitation trends within the recent climate record that may be indicative of a changing climate. This project had some aims in common with another local study, thus the two studies merged and were reported on by Hoffman et al. (2011). Data for the climate variables used in this analysis were acquired from a network of climate stations scattered throughout the winter rainfall region of the Western Cape Province. The history of each climate station was determined, with the help of the responsible manager, to assess if the data series could have been affected by external factors such as instrument re-location or fundamental changes in the local environment (e.g. increased urbanisation). All data series were further checked for homogeneity, discontinuities and missing values. Data from 32 climate stations were initially studied but 12 of these were rejected due to the history of the particular climate station, the quality of the data and the period covered by the historical record. Data for the 20 climate stations finally selected for this analysis covered the period 1974-2005.

### 2.3.1 Temperature

There was a significant and relatively steady increase in maximum temperature (Tmax) values between 1974 and 2005 at all but one of the climate stations. Average values for Tmax increased by 0.89 °C at the 20 climate stations over the study period from 23.7 °C/annum to 24.6 °C/annum at an average rate of 0.03±0.009 °C/annum (Figure 2.3a). The trend was also for a significant increase in minimum temperature (Tmin) values at the majority of climate stations in the study area. Average values for Tmin increased by 0.58 °C from 11.1 °C/annum to 11.7 °C/annum at an average rate of 0.019±0.007 °C/annum (see Figure 2.3b).

The analysis confirms both the trend and magnitude of the temperature change reported previously for the Western Cape (Kruger and Shongwe, 2004; Midgley et al., 2005; Wand et al., 2008; Warburton and Schulze, 2005). These changes are generally higher than the increases reported for other parts of the world (IPCC 2007; Wand et al. 2008). Increases in maximum temperatures were greater and more common than increases in minimum temperatures.

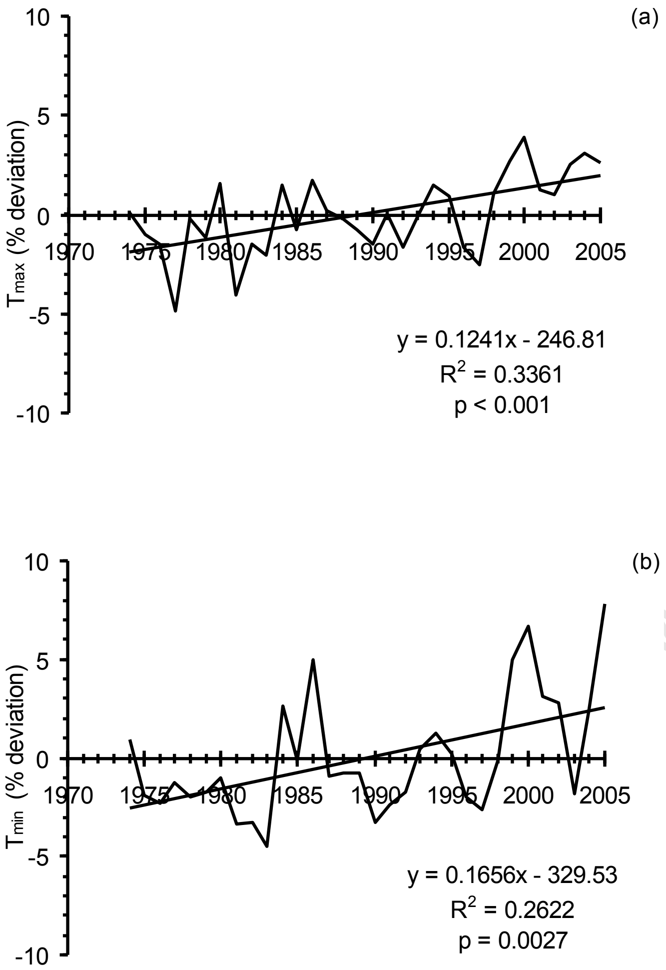

Figure 2.3. Temperature trends for Tmax (a) and Tmin (b) evident in the Western Cape (Hoffman et al., 2011) averaged across the 20 climate stations studied.

### 2.3.2 Precipitation

The study detected no significant changes in rainfall (P) at any of the climate stations over the study period. However, there was considerable inter-annual variability. The average annual rainfall for all stations over the study period was 404 mm/annum. The years 1977 and 1981 were particularly wet when an average of 612 mm and 574 mm respectively was recorded at the 20 climate stations. The years 1978, 1980 and 2004 were the driest on record when an average of 280 mm, 280 mm and 285 mm respectively was recorded at the climate stations during these years.

This study is largely consistent with previous national-scale work by Kruger (2006) but differs slightly from results presented in other studies based on different time-series which found some evidence for localised trends in the province (Midgley et al., 2005; Warburton and Schulze, 2005) - the former reporting a decreasing trend and the latter an increasing trend.

It is evident that, based on the relatively short period of recorded baseline data, no confident statement can be made to support the evidence of strong, unambiguous trends in observed rainfall in the Western Cape during the latter part of the last century. Christensen et al. (quoted by Tadross et al., 2009), suggest that changes in precipitation due to climate change may not be distinguishable from those due to climate variability for 70 or more years.

### 2.3.3 Wind run and evaporation

The Hoffman et al. study (2011) drew attention to the declining wind run trend evident in the Western Cape during the study period 1974 – 2005. The study postulates that this is the primary factor contributing to the manifestation of the "evaporation paradox" in the region. This phenomenon refers to the fact that in many parts of the world, recorded A-pan evaporation records show a decreasing trend in spite of associated increasing trends in surface temperatures.

A recent global review paper by McVicar et al. (2012), found that near-surface terrestrial wind speed is declining in both hemispheres for both tropical and mid-latitudes and that a decreasing trend in measured pan evaporation is evident in the majority of regional studies under review. Midgley et al. (2005) have suggested that the changing temperature gradient between polar and tropical regions might be responsible for this wind phenomenon, but more evidence of this and how it might affect surface winds is still needed

## 2.4 Climate change versus climate variability

In a region with substantial inter annual rainfall variation such as the Western Cape, the question of distinguishing climate change from climate variability is often raised. The IPCC defines climate change as: *a change in the state of the climate that can be identified (e.g., by using statistical tests) by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer* (IPCC, 2007b). In its simplest terms, climate variability can be regarded as a measure of short-term fluctuations about the mean, whilst climate change is concerned about longer-term *shifts*. In essence then, this is a question of time-scales, as there is no reason that climate too should not fluctuate randomly over longer time-scales (Burroughs, 2007). Climate change may occur abruptly or slowly (in relative terms) whilst climate variability may remain constant or change with a change in climate.

From available study material reported by Tyson (1986) it appears that the Western Cape region has exhibited a high level of climate variability since the availability of written records during the 1800s. Some examples of these anomalies during the 19th century extracted from available reports are:

*1825-1829 – predominance of reports of drought and desiccation*
*1830-1833 – flood and good rain reports predominated*
*1834-1843 – drought reports predominate*
*1844-1848 – wetter years*
*1849–1851 – drought reports predominate*
*1852-1860 – wetter years, particularly in the eastern parts*
*1872-1878 – drought reports predominant*
*1881-1885 – predominance of dry conditions*

It thus appears that the climate of the Cape (then the Cape Colony) during the nineteenth century was much like that of the twentieth and twenty-first, with considerable inter-annual rainfall variability and a tendency for the occurrence of extended spells of wet and dry years.

Whilst the paucity of data precludes analysis of trends for individual stations prior to 1910, a number of studies between 1957 and the present have shown little evidence for progressive desiccation at a regional scale (Tyson, 1986) and thus suggests that climate *variability* and not dramatic climate *change* has been the dominant influence in the region during the nineteenth and well into the twentieth century.

## 2.5 Characterisation of the wheat RHFAs used in this study

The character of each RHFA with particular reference to wheat production is briefly discussed in the following paragraphs (the RHFA number refers to the agro-ecological zone numbers used in the RDP source documents). The salient features from the narrative are summarised in Table 2.1, together with April to October average rainfall and area potentially planted to wheat (and other dryland rotation crops).

Agter-Paarl (RHFA 28)

This area is relatively well suited to wheat production, which is the dominant commodity in the zone, closely followed by wine grapes – for which the region is better-known. Good wheat yields can be obtained on the deeper soils in the region but the area suffers from waterlogging in wetter periods on the duplex soils where most of the wheat is produced. Raised beds can be seen on many farms which, when they are in good condition, can largely overcome the drainage problems.

Hoë Reënval Saaigebied (RHFA 17)

Wheat is mainly produced on (relatively) medium-deep soils on a variety of parent materials. A large area of duplex soils occur (where a sandy topsoil or “A horizon” overlays a slow draining, high clay content subsoil). Wheat is well-suited to the area and yields are consistently good. In some of the flatter areas where poorly-drained duplex soils occur, the problem of waterlogging has been overcome in places by the use of ridge & furrow drainage (e.g. in Figure 2.4 below).

Figure 2.4. Typical ridge and furrow or "raised-bed" structures used in the region - water can be seen collecting in the furrow (Photo P. Lombard).

Hermon/Gouda (RHFA 29)

This zone is considered well suited to wheat production, given the high concentration of fairly reliable winter rainfall. The soils can be problematic in terms of drainage, being generally shallow duplex soils with high clay content in the B horizon. Ridge and furrow field structures to facilitate drainage have enabled the use of these poorer soils with good results.

Middel Swartland Saaigebied (RHFA 16)

One of the better wheat production areas (particularly the areas near Moorreesburg) the soils are largely composed of shallow to medium-deep Malmesbury Shale derived soils. Much of the area is overlain by sands originating from the Piketberg (mountain) giving rise to a range of duplex soils and deep sands. Farmers will often focus wheat production on the better soils here, whilst producing mainly fodder oats or pastures on the sandier soils.

Gemengde Boerderygebied (RHFA 18)

The name means “mixed farming area” due to the mix between small grain and wine grape production in this zone. Wine grape production generally occurs on the deeper soils, whilst small grain production is mainly on reasonably well-drained shallower soils, although some duplex soils with poorer drainage may be encountered. Wheat is well-suited to this RHFA and on the better soils some of the best yields in the province can be obtained.

Koringberg/Rooikaroo Saaigebied (RHFA 15)

The zone is fairly well suited to wheat production, but does experience periodic droughts. Its location between the Piketberg mountain and the Atlantic Ocean can lead to a rain-shadow effect under certain synoptic conditions, reducing the effectiveness of north-westerly cold frontal systems. High temperatures and low rainfall during the grain-filling period of September can also impair yields, yet wheat is considered to be well suited to the farming systems in the region. Most of the soils are shallow and heavy textured. Poor rainfall penetration due to soil compaction can be a problem in the region.

Rûens (RHFA 63)

Along with the Swartland this is one of the major wheat production areas of the province. The name Rûens is derived from the Dutch word “rug” meaning “back” as in the backs of cattle, as a result of the rolling landscape. The region is considered well suited to the cropping/livestock enterprises practiced there. Although the region is described in the RDP (Department of Agriculture Western Cape, 1990) as one zone, for the purposes of this study it is split into two (Rûens East and Rûens West). This was considered necessary due to its elongated shape and both the general gradient of declining wheat performance from west to east and decreasing proportion of winter rainfall along the same axis.

Rûens West has a reliable rainfall of which 60 - 75% occurs in winter. Parts of this region are known as the “Golden Rûens” which has the highest potential for wheat production in this subregion. In Rûens East the proportion of *winter* rainfall decreases from west to east, and is subject to more erratic rainfall and periodic droughts.

The undulating landscape results in good drainage and waterlogging is generally not a problem. The soils are generally shallow with little weathering and can have a high stone content (Figure 2.5). Much of the region is on Bokkeveld shales with some deeper soils adjacent to the narrow watercourses. Wheat in the region is usually planted in a rotation system with planted pastures and Canola (*Brassica napus L.*). Lucerne (*Medicago sativa*) is the most common pasture and is able to utilise the summer rainfall effectively in the wetter areas.

Figure 2.5. Typical shallow, rocky wheat soil, Rûens East (Photo M. Wallace).

Bredasdorp-Strandveldvlakte (RHFA 64)

This RHFA is situated on a low-lying coastal plain (the “vlakte” in the Afrikaans name) below 30 m above mean sea level. Rainfall is considered fairly reliable, although drought conditions do occur which together with the very low water storage capacity of the soil can impair production. The soils are mostly shallow, with loamy sand topsoil over marine deposits or residual clay. As a result of the flat topography, surface drainage is poor and waterlogging can occur following heavy rains. Problems due to soil wetness during harvesting operations are also common, leading to reduced yields.

Malgas-Heidelbergvlakte (RHFA 69)

Although rainfall is fairly low in this region it is considered fairly reliable and well distributed, making this a desirable farming region. Although a wide variety of soils occur, they are generally shallow shale or granite-derived soils, fine sandy loam over clay, with relatively low water holding capacity.

Gouritz-Rooirûens (RHFA 72)

Rainfall in this region is fairly low and unreliable, leading to a high risk factor in grain production in this RHFA. As a result wheat production declined from 23.9% of the surface area to less than 10% by 1998. The region is hilly and soils have good internal drainage. The shallow soil and resulting low soil water storage capacity however leads to impairment of yields in drier years.

Kleinberg-Suurrug (RHFA 74)

Rainfall in this RHFA is considered to be fairly reliable and although droughts are rare, a recent lengthy dry spell (2008-2010) has had a negative impact on wheat plantings in the area. Rain in October and November can hamper the harvest process and lead to reduced yields and quality. Transported clay lying on the plateau forms the parent material of a large range of generally shallow duplex soils. Because of the mostly level terrain where wheat is planted and the nature of the soils, waterlogging can present problems during the winter months.

Tulbagh/Wolseley (RHFA 32)

Wheat production mostly occurs in the northern part of this bowl-shaped zone, whilst the southern part is under vegetables, fruit and grapes. The potential is limited by shallow, heavy soils with low water holding capacity and the fact that the rainfall declines sharply from the surrounding mountains to the valley centre.

Graafwater/Sandveld (RHFA 4)

The predominant soil type is a sandstone-derived deep sand, although the best soils in the region for wheat production are the shallow, red, loamy-sands derived from shale. The area surrounding Graafwater has the best potential for wheat in the zone. The soils generally have a poor nutrient status, and it is noted that nitrogen is easily and quickly leached from the soils. A characteristic of this area is the strip-planting of wheat between strips of natural vegetation or Oldman Saltbush (*Atriplex nummularia*), which provide a nutritive wind-break to help prevent wind erosion on the sandy soil (Figure 2.6).

Figure 2.6. Typical strip planting of wheat in the Graafwater area (Photo M. Wallace).

Sandveld Saaigebied (RHFA 14)

Although the soils in this zone are generally sandy with poor nutrient status, the rainfall is concentrated in and well distributed throughout the winter growing season. The RDP for this RHFA reports that this results in very constant, if low yielding wheat production in the region. Wheat is regarded as one of the most drought-resistant grains in this region and is well suited to the small-stock/small grain production systems in the region, with wheat playing an important role in providing summer forage in the form of straw, hay and stubble.

Urionskraal (RHFA 9)

Although isolated and remote, the region closer to the mountain enjoys a higher rainfall than its surrounds. Wheat production, although speculative, can be rewarding in years of good rainfall. Topsoils are chiefly alluvial and colluvial originating from the Table Mountain Sandstone of the surrounding Matzikama mountains and overlying Malmesbury shales. Farmers keep inputs to an absolute minimum, and nitrogen fertilization is minimal. As with most marginal wheat areas, the relationship between small stock farming and wheat production means that wheat production continues to play an important role in the region.

Stockwell (RHFA 45)

Due to the low and variable character of winter rainfall in this small area, wheat production is considered marginal. Many old wheat lands stand neglected or are planted to pastures for livestock production.

Kamanassie (RHFA 57)

The area is highly marginal for wheat production due to the low and variable winter rainfall. Although some areas of medium-deep soils do occur, the high rock component makes cultivation difficult and as a result wheat is planted mainly on shallow shale-derived soils. On some farms only 1 year in 4 delivers an economically justifiable wheat yield! The close relationship with small stock farming however, justifies the continued low-input cultivation of wheat.

Bo-Langkloof (RHFA 56)

The area has a reasonably reliable winter rainfall, yet as a result of increasing input costs and the lower wheat price over the last 15 years the production of wheat has drastically reduced in this region. Many of the old wheat lands are currently used for pasture crops such as oats, medics and lucerne. The area is included in this analysis on account of its production history and the possibility of returning to wheat production should economic or climatic conditions become more favourable.

Hardeveld (RHFA 10)

It is remarkable that wheat is considered an important crop in this harsh environment. Winter rainfall is generally below 120mm and the area is subject to sporadic dry spells and heat waves, although these occur mainly in the summer months. Wheat is considered to be a drought-resistant pasture crop which can yield a viable return in better years as a cash crop. As with other marginal areas is the relationship between wheat and small stock farming that ensures its continued cultivation in this extremely marginal region. In better rainfall years isolated pockets of wheat are found in the midst of semi-desert fynbos.

Gouritz River Valley (RHFA 73)

Winter rainfall is unreliable in the region and wheat production is considered to be risky. The soils mainly consist of deep alluvial sandy and sandy-loam soils, which have reasonable potential but are limited by unreliable rainfall. Wheat production has drastically declined in the region over the last 15 years and is currently fairly insignificant as an enterprise in the region. It is included in the study due to the historical potential of the soils should economic and/or climatic circumstances improve.

Table 2.1. Summary of general RHFA characteristics

| RHFA | Dryland cultivation (ha) | Apr-Oct mean rainfall (mm) | Dominant soil character | Topography |
|---|---|---|---|---|
| Agter-Paarl | 13 327 | 665 | Deeper duplex soils, prone to waterlogging | Rolling gentle topography |
| Bo-Langkloof | 8 544 | 304 | Shallow, shale-derived duplex soils | Gently undulating footslopes |
| Bredasdorp/Strandveldvlakte | 26 636 | 321 | Shallow loamy sand topsoils over clay | Flat coastal plain |
| Gemengde Boerderygebied | 50 009 | 665 | Duplex soils, occasional waterlogging | Undulating - wheat on flatter areas |
| Gourits-Rooiruens | 22 972 | 275 | Shallow, well-drained soils | Rolling landscape |
| Gouritzriviervallei | 3 698 | 247 | Alluvial and sand loam soils | Flatter footslopes |
| Graafwater/Sandveld | 76 272 | 233 | Deep sandstone-derived sands & red loamy sand | Gently undulating |
| Hardeveld | 37 353 | 141 | Shallow sandy loams over granite | Rolling landcape |
| Hermon/Gouda | 18 697 | 597 | Shallow duplex soils, prone to waterlogging | Gently undulating with large flat areas |
| Hoe Reenval Saaigebied | 136 805 | 395 | Sandy topsoil over high-clay, slow draining subsoil | Undulating |
| Kamanassie | 31 780 | 304 | Wheat is on shallow shale-derived soils | Undulating footslopes |
| Kleinberg/Suurrug | 18 852 | 247 | Large range of shallow duplex soil types | Gently undulating to flat |
| Koringberg/Rooi Karoo | 72 082 | 266 | Shallow heavy textured soils, often compacted | Gently undulating to flat |
| Malgas/Heidelbergvlakte | 46 942 | 265 | Shallow sandy loam over clay | Flat plain to gently undulating |
| Middel Swartland Saaigebied | 172 297 | 395 | Medium depth - most wheat on duplex soils | Rolling hills with some flat areas |
| Ruens East | 234 841 | 287 | Shallow shale derived soils, with high stone content | Rolling landscape |
| Ruens West | 168 866 | 349 | Shallow shale derived soils, with high stone content | Rolling landscape |
| Sandveld Saaigebied | 108 715 | 272 | Deeper, sandy soils | Mostly flat coastal plain to gently undulating |
| Stockwell | 1 426 | 201 | Medium depth duplex soils | Rolling landscape |
| Tulbagh/Wolseley | 7 136 | 384 | Shallow heavy soils | Gently undulating valley |
| Urionskraal | 3 412 | 132 | Medium deep alluvial soils | Generally flat footslope "bowl" |

# Chapter Three: Literature review

## 3.1 Climate change

### 3.1.1 Introduction

This literature review examines research literature pertaining to climate change from a broad to a local level and the study of expected impacts at the international and then regional scale with relevance to agriculture, and more specifically to wheat production. No model-based studies on Western Cape wheat production under future climate change were encountered locally, or in the literature. Further references on technical issues are also encountered under the relevant sections in the main text in the following chapters.

### 3.1.2 Climate change: global and regional

Burroughs (2007) provides a concise presentation of contemporary knowledge of climate change, historical climate fluctuations and implications for general society – including some broad, expected agricultural impacts. The book describes the components of the global climate, considers how the many elements of climate combine to define its behaviour, and reviews how climate change is measured. The author discusses how the causes of climate change can be investigated through the evidence of change, and modelled to predict future changes. The author also touches on the complex issue of climate variability as distinct from climate change.

The Intergovernmental Panel on Climate Change (IPCC) was established jointly by the World Meteorological Organization and the United Nations Environment Programme to provide an authoritative international statement of scientific understanding of climate change. The panel produces periodic reports assessing the causes, impacts and possible response strategies to climate change – the most recent assessment report having been published in 2007. The most relevant component of this fourth assessment report to this study is the Contribution of Working Group II on Impacts, Adaptation and Vulnerability to climate change (2007a). Despite some recent controversy regarding the validity of some outcomes (The Guardian, 2010), the majority of evidence in the IPCC report confirms that observed warming of the global system is unequivocal and that further warming can be expected into the 21st century under current emissions scenarios. Even under the most conservative emissions scenarios, $CO_2$ levels are expected to continue rising steeply as indicated in Figure 3.1.

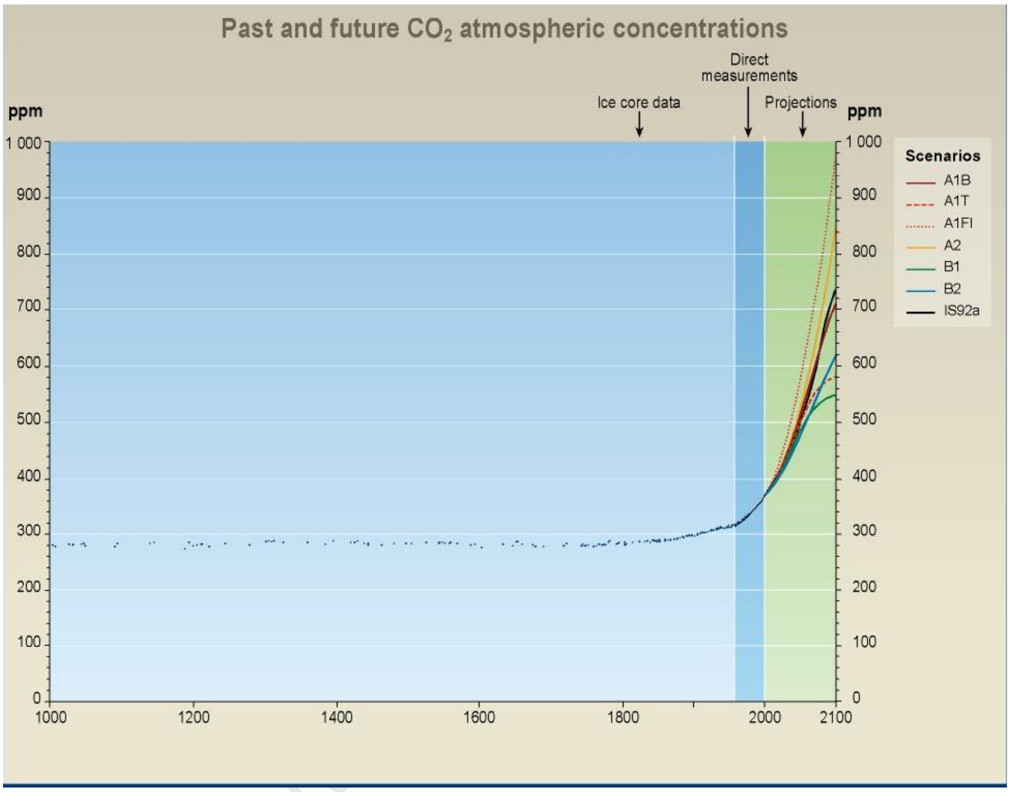

Figure 3.1. Past and projected future $CO_2$ emission concentrations (IPCC, 2007).

Africa is expected to experience particularly dire impacts of climate change. Amongst these are (Boko et al., 2007):

- by 2020, between 75 and 250 million of people are projected to be exposed to increased water stress due to climate change.
- by 2020, in some countries, yields from rain-fed agriculture could be reduced by up to 50%. Agricultural production, including access to food, in many African countries is projected to be severely compromised. This would further adversely affect food security and exacerbate malnutrition.

- towards the end of the 21st century, projected sea level rise will affect low-lying coastal areas with large populations. The cost of adaptation could amount to at least 5 to 10% of Gross Domestic Product (GDP).
- by 2080, an increase of 5 to 8% of arid and semi-arid land in Africa is projected.

Studies quoted in Boko et al, 2007 state that by the 2080s wheat production could have disappeared from Africa. Extreme events such as floods, droughts and heat waves are expected to occur more frequently which could have a major impact on agricultural productivity (Challinor et al., 2007).

Studies on agricultural impacts on Africa generally have generally focused on maize in their assessments, being the major food security crop. South Africa is considered to be among the most vulnerable to negative climate impacts on maize production (Jones and Thornton, 2003; Schlenker and Lobell, 2010; Wolfram and David, 2010).

### 3.1.3 Climate change: local

The Western Cape Provincial Government commissioned a detailed assessment of the Province's vulnerability to the expected impacts of climate change (Midgley et al., 2005). The study suggested a high likelihood that based on climate model evidence as well as prevailing trends that the future of the region would be warmer and drier, with rainfall impacts and trends less clearly identifiable. The study drew from the relatively sparse regional analyses available at the time such as those by Hewitson et al., (2005a) and New (2002).

This initial assessment was followed by a final Climate Change Strategy and Action plan for the Western Cape (One World Sustainable Investments, 2007). The report based its future scenarios on a study undertaken by the Climate Systems Analysis group (CSAG) at the university of Cape Town for the period 2030 – 2045, this being the earliest anchor year to which climate change projections can be realistically scaled back from global climate models. At that juncture, the projections were as follows:

- Precipitation – the most notable change was an indication of drying towards the west of the region, away from the mountains
- Temperature – general warming, with a minimum of +1°C by the late 2030s

A recent study (Hoffman et al., 2011) examined trends in the observed rural data of the Western Cape and found 19 out of the studied 20 climate stations data studied exhibited a clear warming trend. Wind run and A-pan evaporation trends during the study period were also found to be decreasing. As with other studies referred to in Section 2.3.2, no statistical evidence was found for trends in rainfall data in any part of the Western Cape region for the baseline study period.

The IPCC maintains a repository of all the assessment reports and the contributions of the various working groups on their Web site (http://www.ipcc.ch), as well as information on the GCMs used in each assessment. Engelbrecht et al. (2009) discuss the use of a model not used in the IPCC assessments, the Conformal-Cubic Atmospheric Model. Local researchers have made substantial impact in the realm of downscaling these GCM data to be useful in local impact studies, described by Hewitson and Crane (1996a) and Hewitson (2007). The application of scenarios developed with empirical and regional climate model-based downscaling is discussed by Hewitson et al. (2005a). Leary et al. (2009) discuss the state of regional scale climate change research, provide good background and offer some useful caveats in terms of uncertainty and confidence, as do Wilby, et al.,(2004). Ziervogel and Zermoglio (2009) neatly summarise regional downscaling and the application thereof in local impact studies, whilst Wilby et al. (2004) further advise on the responsible assessment of impacts based on scenarios derived from downscaling.

### 3.1.4 Climate change and agriculture

The Fourth Assessment Report of the IPCC deals with agriculture at a generalised global scale (Easterling et al., 2007). Key findings reported are that although increased $CO_2$ levels will have some beneficial effects on yield, these impacts are modified and limited by increased temperatures, particularly at critical growth stages. Accordingly, increased temperatures may also reduce $CO_2$ effects indirectly, by increasing water demand. Rain-fed wheat grown at 450 ppm $CO_2$ demonstrated yield increases with temperature increases of up to 0.8°C, but declines with temperature increases beyond 1.5°C. This thesis intends to assess the applicability of these broad findings to Western Cape conditions.

A number of global studies were referred to in Section 1.3 in which global impacts of climate change are investigated. These studies indicate at a very broad scale where climate change is expected to have positive or negative agricultural impacts. Generally speaking, southern Africa is indicated as a region likely to experience mostly negative impacts under future climate change.

Ericksen et al. (2011) undertook a detailed analysis of to identify areas in the global tropics that are potentially food insecure and are vulnerable to the impacts of future climate change. They noted that although South Africa has a high GDP, there are many people living in poverty – although the situation in the Western Cape is not as severe as the rest of the country. Thresholds of climate change exposure important for agricultural systems were developed, and vulnerability to changing climates was assessed. Wheat was considered to be “hardly grown” in Africa by contrast to other regions, but the Western Cape wheat belt is indeed identifiable in their wheat map. Although, South Africa contained regions of high agricultural sensitivity to climate change and the region showed some potentially “troublesome” areas, the country was not further zoomed in upon as a climate change/food security “hotspot” in the context of this study.

Thornton et al. (2010) conducted a study on crop responses to climate change in East Africa using DSSAT production models, the MarkSim daily weather generator and combinations of two GCMs under two SRES emission scenarios. Although both bean and maize yields overall were expected to decrease by 2050, varied results were presented according to GCMs and SRES scenario used. The study noted the spatial and temporal heterogeneity of results and the importance of high-resolution, localised modelling. In particular, the ultimate aim of this study was to target adaptation options at a community level, for which large, spatially contiguous study domains would be unsuitable.

Thornton et al. (2011) reported on the dire consequences likely to be experienced in sub-Saharan Africa, at a warming of 4°C. The region faces the burden of massive population increases (up to 1 billion on the continent as a whole) by 2050, and it seems unlikely that smallholder farmers, in particular, will have the capacity (and institutional support) to adapt at these levels of warming. The authors call for focused research and improved application of technologies towards understanding critical thresholds in African food production systems.

In terms of baseline data for South Africa, the South African Atlas of Agrohydrology and Climatology (Schulze, 1997) provides a point of reference for many agriculturists in South Africa. The atlas provides printed maps of a variety of climatic and agricultural interest as well as electronic (GIS) data and useful summaries of methodologies. Schulze edited a report on climate change and water resources in South Africa which contains contributions from some leading climate scientists and agriculturists (Schulze, 2005) regarding future climate scenarios and impacts. The same author more recently produced a book comprising a review of recent studies followed by an assessment of the significance of climate change on the South African agricultural scene (Schulze, 2010). Whilst negative impacts are expected for maize in certain northern parts of South Africa, very little could be said in either of these reports regarding the future of the winter wheat industry in the Western Cape, due to the lack of appropriate studies. The same author was instrumental in the development of a refined climatic baseline dataset derived specifically for research exploring eco-hydrological responses to climate change, and was used with appreciation in this study (Schulze and Horan, 2010).

A study by Bradley, et al. (2012), applied the MAXENT to study climate suitability in South Africa at a macro scale for wheat and maize The study explored how crop suitability may shift under climate change, impinging upon currently protected (conservation) areas. The crop distribution model, MAXENT, was chosen in preference to mechanistic, process models such as DSSAT and APSIM due to their highly intensive data requirements and input parameters and the general scarcity of such data in South Africa. One of the co-authors did however embark on a detailed data gathering project and is currently applying the DSSAT model to refine the modelling in this project (Estes, 2011, personal communication), publication of results is pending.

Benhin (2006; 2008) discusses South African agriculture in an attempt to apply a Ricardian modelling approach to assess climate change impacts on agriculture. He assesses three climate scenarios which indicate that temperatures will increase by between 2.3°C and even 9.6°C (by 2100) while precipitation will decrease by between 2 and 8% by 2100. Using these estimates the study predicts that net crop revenues will fall by as much as 90% by 2100 if adaptation measures are not implemented. A study with a similar economic-simulation approach (Gbetibouo and Hassan, 2005) speculated that wheat production in the Western Cape would disappear as winters became warmer over the next 50 years and that crops such as sunflowers and soybeans may become the preferred cash crop of the region[8].

Wheeler et al. (2000) expect in general terms that an increase in mean seasonal temperatures of 2 to 4°C will reduce the yield of wheat - mostly due to shorter crop duration (reduced grain fill period). Variability in temperature is also expected to impact negatively on yield, particularly due to increased brief episodes of hot temperatures.

Although results vary widely, international wheat production in temperate areas appears to generally benefit from projected future climate changes, whilst a study on dry production regions in south-eastern Australia indicates a strong probability of future yield reductions. Table 3.1 summarises various studies on projected changes in wheat yields.

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[8] Soybeans and sunflowers are summer crops, however. Wheat is grown as a *winter* season crop in the Western Cape.

Table 3.1. Summarised results of reported studies on wheat yield projections for the second half of this century.

| Study | Location | Yield Change (%) |
|---|---|---|
| Referred to by Luo et al.(2005): | Great Plains, US | +44 - +82 |
| | Canadian prairies | -40 - +60 |
| | Japan | -41 - +6.3 |
| | Canadian wheat belt | -4 - +8 |
| | France | -30 - +7 |
| | Russia | -19 - +41 |
| | Northeast Queensland, Australia | +9 - +37 |
| | Australian wheat belt | -10 - -35 |
| (Anwar et al., 2007) | South-eastern Australia | -24 - -29 |
| (Eitzinger et al., 2003) | Czech Republic & Austria | +17 - +24 |
| (Eckersten et al., 2001) | Southern Sweden | +10 - +20 |
| (Richter and Semenov, 2005) | England and Wales | +15 - +23 |
| (Gobin, 2010) | Belgium | +7,(but -5 to -12 if potential waterlogging is accounted for) |

One of the important, but relatively uncertain impacts of future climate change, is the potential impact on crop pathogens and the diseases they cause. Juroszek and Tiedemann (2013) recently conducted a review of significant results from work in this field. Whilst no work from southern hemisphere countries was reviewed, there is concern that projections of future wheat yield potential projections may be over- or underestimated if the significant modulating effects from biotic constraints such as diseases are ignored. The authors note a significant lack of simulation studies related to different wheat diseases in different regions and call for a concerted, multidisciplinary effort to address these shortcomings.

Hoffmann (2010) undertook pioneering local work in developing an economically-based farm-system model to optimise diversification whilst limiting risk exposure. The study included some expectations of climate change impacts, but (in the absence of any detailed modelling projections available) these were necessarily based on broad empirical and estimated impacts of expected growing season changes under future climate projections. The estimates ranged from -5% to -70% across the Western Cape – the time-frame was not given. Although his study was based on a sub-sample of RHFAs, the reported adaptation options for wheat farmers in the Western Cape are relevant to the likely impact pathways resulting from this study and are drawn upon further in Section 7.3.

## 3.2 Western Cape agriculture and farming zones

Cartwright (2002) used a climate envelope modelling technique in a study on likely future climate influences on a particular apple cultivar grown in the Western Cape. Apples have a particular requirement for cold exposure for phenological development, whilst heat and sun exposure can negatively impact on fruit quality. The author found that by 2020, due to temperature increases, the areas currently producing export-quality Braeburn apples would begin to decrease and that by 2050, suitable areas would be greatly reduced and limited to patchy microclimates within the Kouebokkeveld area. Likewise, Wand et al, (2008) found the pear industry in the province is also vulnerable to climate change, with negative impacts expected due to reduced chilling units, increasing incidence of sunburn, poor colour development in some blushed cultivars, and higher risk of drought stress.

Barrable, (2005), examined likely climate change effects on land degradation in the Swartland region of the Western Cape. The likely outcome of expected increased temperatures and reduced rainfall in the region was found to be an increase in erosion according to the soil loss model driven by future climate conditions.

A body of valuable and detailed information on Western Cape agricultural conditions – particularly in terms of field crops such as wheat - exists only in unpublished form in ring-bound manuals in the Elsenburg library (Department of Agriculture Western Cape, 1990). Only available in Afrikaans, these volumes originally prepared in the 1970s and subsequently updated in 1990, are known as the “Streeksontwikkelingsplanne” or “Regional Development Plans” (RDPs). A volume exists for each of the old agricultural subregions in the Western Cape – being West Coast, North-West, Boland, South Coast and Central Karoo (these regions have subsequently been superseded by the municipal boundaries in terms of agricultural service regions). Within each of these volumes a chapter is dedicated to each Relatively Homogeneous Farming Area (RHFA), supplying descriptive information on climate, soils, management, production statistics and norms and a comment on resource degradation and sustainability. Although the quality of information varies in terms of detail and current validity between RHFAs, the volumes provide a solid if unwieldy information source on wheat production within the RHFAs in the Western Cape, written by regional experts (extension officers, soil scientists and researchers).

## 3.3 Crop simulation modelling

### 3.3.1 Introduction

A detailed review of the climatic requirements of crop models and the development of crop modelling in close collaboration with the discipline of agrometeorology is provided by Hoogenboom (2000). The author correctly predicted that in the light of climate change and climate variability, reliance on crop modelling by researchers and consultants as well as policy and decision makers would increase. Weather data in the form of historical data or observations made during the current growing season, and short-, medium-, and long-term weather forecasts will play a critical role in impact assessments. The same author with colleague White et al. (2011) and other workers recently conducted an extensive review of crop model papers, concluding that coordinated crop, climate and soil data resources would allow researchers to better focus on underlying science and facilitate comparison between results to improve confidence in outputs. The use of a modular approach within models allows for better comparison and integration amongst model users groups.

The emergence of crop modelling as a mainstream tool in crop science and the philosophy behind the development of such models is addressed by van Ittersum and Donatelli (2003b). The article is written as a preface to a special edition of the European Journal of Agronomy, in which Keating et al. (2003) outline the development of the APSIM model used in this study. APSIM was developed to simulate biophysical process in farming systems, in particular where there is interest in the outcomes of management practice in the face of climatic risk. The paper outlines APSIM's structure and provides details of the concepts behind the different plant, soil and management modules. Reports of APSIM testing in a diverse range of systems and environments are summarised. An extensive citation list for APSIM model testing and application studies is provided in this paper.

### 3.3.2 Wheat and wheat simulation models

Whilst many classical texts exist on wheat and wheat production, the focus in this study was on the vulnerability of wheat to climate change, and more specifically on expected yield impacts on the production of winter wheat in similar conditions to those experienced in the Western Cape. A major portion of this literature thus originates in Australia where similar wheat growing conditions are experienced – particularly in the Mediterranean climate of Western Australia - and where substantial research has been carried out in this field over the past two decades.

A detailed report on the competitiveness of wheat production in the Western Cape (BFAP et al., 2005) sets the economic context for wheat production in the region. The study found that although South African wheat yields are below the international average, the Western Cape competes well in comparison with other low-yield-low-cost wheat producing countries such as Australia, Argentina and Canada. In South Africa the study identifies the areas surrounding Caledon and Moorreesburg as being particularly profitable under the market conditions at the time of writing the report.

Although a study on wheat vulnerability to climate change warming, (Ortiz et al., 2008) makes no mention of South Africa or even Australia, it considers impacts of high temperatures during critical wheat growth stages to reduce grain yield in areas where optimum temperatures already exist. The study also points to the increasing availability of spatially and temporally disaggregated climatic variables data coupled with GIS tools and crop models as key to improved analysis in this field. Daily climate data for future projections (and even complete historical climate) are nonetheless difficult to obtain or develop. There is a temptation to rather use averaged values, yet Nonhebel (1994) found that this method overestimated yields in wet conditions and can underestimate yields in dry conditions by up to 50%.

Workers in the Mediterranean wheat producing area of Spain (Iglesias et al., 2000) tested the CERES-wheat model on seven sites to investigate which climatic variables had the major influence on wheat yield through a sensitivity analysis on temperature, precipitation and $CO_2$ (supplementary irrigation played a major role in their study however, which is not directly applicable to the Western Cape situation). Observed data were then perturbed by the projected anomalies in these parameters to predict future scenarios. The model was deemed successful in simulating wheat conditions in Spain.

Trnka et al. (2004a), used a stochastic weather generator modified by the signals of seven GCMs to generate daily data to conduct site specific yield scenarios for seven test sites in Central Europe. All but one of these seven GCM-based scenarios modelled in CERES-Wheat[9] indicated increased future wheat yields for 3 future time slices (2025, 2050 and 2100).

A study by Luo et al. (2003), coupled the outputs of Global Climate Models with the DSSAT3.5 CERES-Wheat model to explore the potential effects of climate change on South Australia's wheat production for the 2080s with $CO_2$ fertilisation effect taken into account. The AEGIS/WIN module of DSSAT was used to display the resulting impacts in GIS. The study found a general increase in yields due to the $CO_2$ fertilization effect which was more pronounced in the wetter areas.

The same author then switched to the APSIM model, investigating the importance of incorporating a range of climate change perturbations rather than a single scenario (Luo et al., 2005). The study, based in South Australia, found that of the three variables examined (rainfall change, temperature change and increase in atmospheric $CO_2$ concentration) that rainfall change was by far the most influential factor influencing wheat yield in the medium to low rainfall areas. Their approach to estimate wheat yield impacts was to examine the projections of a number of downscaled GCMs and RCMs and perturb the historical climate data accordingly to create probabilistic wheat yield

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[9] The CERES-wheat model was used as an early framework for the APSIM model (Asseng et al., 1998)

simulations in APSIM. In contrast to the preceding study, this work indicates reduced median grain yield by 2080 for all eight locations under study.

A study in Western Australia (van Ittersum et al., 2003a) aimed to explore the complex interactions between $CO_2$, temperature and precipitation and gain more understanding of the complex interactions between water and nitrogen availability, phenological development and climate change factors, in the extremely variable Mediterranean climate of the region. Given the inconsistency of GCM results for this region, the authors opted for a factorial approach in adapting 90 years of historical weather data rather than using downscaled future scenario data to parameterize the APSIM model for future wheat yield projections. Results suggested that elevated $CO_2$ concentration resulted in increased yields, particularly where nitrogen fertilisation was sufficient and conditions were relatively dry. Higher temperatures had non-linear effects, with initial (up to 3°C) benefits on clay soils (less on sandy soils), and then substantial yield declines. If, in addition, precipitation was decreased, financial returns dropped below present levels, particularly in the low precipitation regions. Crop modelling studies in the Czech Republic (Trnka et al., 2004a) and in Western Europe (Nonhebel, 1996) both found temperature increases due to climate change were compensated for, to a large extent, by the $CO_2$ fertilization effect.

A regionalised study was undertaken by Wang et al. (2007), in the Lower Murray basin region of Australia. The study area was divided into homogeneous soil/climate regions for simulation of dryland production systems (including wheat). Baseline (observed) climate data were proportionally modified in terms of precipitation, temperature and $CO_2$ and the APSIM model was used to simulate expected outcomes under these perturbed climate scenario datasets (GCM-modelled outputs were not considered in this study). Future warming and drying scenarios examined in this way were estimated to lead to up to a 41% decrease in crop production.

Wang et al. (2009) undertook a further project in Southeast Australia to assess the impact of changes in $CO_2$ levels, rainfall and temperature. Again the study was based on perturbation of existing rainfall, although a formula was also used to reduce the frequency of small rainfall events and increase the percentage of heavy rainfall events. Their findings for this study were that very slight increases in yield could be expected in the 2050 period, but up to 6% reduction in yields were projected for 2070. Growing seasons reduced by 22 days and 35 days for the projected years respectively. It should be noted that the study site at Wagga Wagga has a water holding capacity of 139 mm and depth of 1.5 m – well above even the best wheat soils in the Western Cape. More recently the same author and his team reported on a study of 11 wheat sites spread across the Murray-Darling Basin using climate scenario data generated by the Ozclim software (http://www.csiro.au/ozclim). The climate scenarios included a wide range of $CO_2$ levels and a range of temperature and precipitation perturbations were modelled in APSIM (Wang et al., 2011). The results showed that responses of wheat yield to future climate are complex and that the regional perspective could provide a more complete picture for future adaptation study. Although a warming and drying trend in climate would lead to reduced yields in some regions, the positive impact of elevated $CO_2$ was found to offset yield losses in others.

In a study in Mid-Lower North of South Australia (Luo et al., 2005b) describes effective use of GIS software to help manage spatial-climate data and spatial-soil data and to present the results. Although there was substantial variability, a median grain yield decrease of between 10 and 40% was estimated under the most likely future scenario.

Ludwig and Asseng (2006) studied how higher temperature, increased $CO_2$ levels and five different rainfall scenarios affected wheat yield in the Mediterranean region of Western Australia. Effects of climate change were simulated with APSIM using perturbed historic weather data. Simulation results showed that there were complex interactions between different aspects of climate change on crop systems. Effects of higher temperatures, elevated $CO_2$ and changed rainfall were usually not linear and differed significantly between soil types and location. Higher $CO_2$ increased yield especially at drier sites while higher temperatures had a positive effect in the cooler and wetter southern part of the region. The authors found that in Mediterranean environments where crops are grown in winter, plant growth is often limited by low temperatures and global warming can, in some cases, have positive effects on crop yields. The main response difference found between soil types was that heavier clay soils were most vulnerable to reduced rainfall while sandy soils were more vulnerable to higher temperatures. They also found varying responses to modelled rainfall increases, with reductions in yield occurring in high rainfall areas under further rainfall increases due to waterlogging and leaching of nutrients.

A crop modelling study in the same region (Ludwig et al., 2009) using the APSIM wheat model in combination with historic climate data showed that simulated wheat yields did not drop in proportion to total growing season rainfall which decreased by 11% during the period. Indeed, actual yields increased during the period. The importance of rainfall *distribution* and the influence of improved technology in assessing future yield change due to climatic influences can thus only be objectively assessed by keeping technological variables such as cultivars and management options constant in the simulation model.

Following closely on this research, Asseng and Pannell (2013) concluded that other technological advances have had much larger effects on wheat yield in the Western Australia region than climate change. These include changes in crop varieties, crop production technologies, fertiliser use, herbicides for weed control, reduced tillage, improved machinery allowing earlier sowing, retention of crop residues and the use of “break” crops, mainly for the management of root diseases. The authors conclude that there is currently no pressing need for farmers in this area to make changes to their farming practices to adapt to long-term climate change. Responding to year-to-year variability remains important, but has not increased in importance. They consider the most important policy response to crop modelling work in the region to be focused research and development to enable farmers to facilitate future adaptation to climate change, and the authors list a number of research priorities. Many of these are likely to have relevance to Western Cape wheat production – given the regional similarities in terms of wheat production.

A European study by Iglesias et al. (2012) used future scenarios constructed from two SRES emission scenarios (A2 and B2) and two GCMs downscaled across Europe to investigate crop impacts for the period 2071 – 2100. Using DSSAT to model crop responses (including wheat) they found a general gradient of increased yield in northern Europe and decreases in southern Europe, attributed largely to changes in the length of the growing season.

A recent study was undertaken in Argentina, using the APSIM model to investigate whether new opportunities for wheat production could develop under recent climate change (Asseng and Pannell, 2013). Although rainfall has increased in their study region, the winter wheat relies on water storage from summer rainfall, and given the sandy, shallow soils in the study region, the resulting (modelled) yields were highly variable and risky. They found that modelled crop response to N fertilisation varied considerably by study site and season. The authors were sufficiently confident that due to the extensive testing of APSIM under a large range of field experiments – including Queensland, where similar "stored-water" situations were encountered – that the lack of local validation and detailed parameterisation of APSIM did not present a limitation for the purposes of their study.

Cho et al. (2012) conducted a study using CERES-Wheat, using 11 RCMs based on HadRM3 and 1 SRES scenario. Yield increases of over 20 % were projected for most of the UK by 2080, although marked spatial variation in responses was evident. They found that applying (modelled) lower amounts of N-fertiliser input improved yields over the UK except in the southwest and Wales. The authors conclude by mentioning some of the uncertainties inherent in their modelling approach, such as the unknown impacts of extreme events, pests and disease and the unknown impacts of potential advances in technology.

Investigating site specific climate change crop responses, Kersebaum and Nendel (2013) applied the HERMES crop model forced by downscaled climate change (SRES A1B scenario) from the ECHAM5 GCM. General yield increases of up to 6.3% were simulated in the presence of increased CO2 levels for study zones across Germany.

In wetter regions in Germany, the elevated temperature led to a modelled increase of nitrogen mineralisation. Weigel and Manderscheid (2012) also found that low N supply increased NUE significantly, but concluded that their present data do not allow sufficient explanation of the variability of the effect between years and N supply. They found no unambiguous evidence that N fertilisation determines the extent of biomass and yield stimulated by elevated CO2.

Finally, back to south-eastern Australia, where Monjardino et al. (2013) undertook a simulation analysis using APSIM to investigate the hypothesis that farmers in low rainfall areas were under-fertilising with regard to N. Their crop model and economic risk analysis suggest that farmers on certain soils in the Mallee region are under-fertilising on up to 80% of their farm lands. They conclude that the use of higher upfront N rates than current district practice on low fertility soils does not substantially increase risk in a highly variable dryland environment and would lead to higher returns in the longer term.

## 3.4 Conclusion

It is evident from the preceding literature that wheat responses to changes in climatic and $CO_2$ influences are site-specific. Whilst the majority of workers found evidence for increasing yields (largely due to $CO_2$ impacts) there was considerable variation between expected outcomes as a consequence of local soil properties and climatic influences (Table 3.2). Even where authors mentioned soil types there was no uniformity of response recorded. It appears that there is no shortcut, formulaic method of predicting localised wheat yield response under climate change.

Table 3.2. Summary of a selection of modelling studies on climate change impacts on wheat, indicating the variation and site specificity of results.

| **Author/Study** | **Place** | **Δ Yield (increase/decrease) for 2050 or closest period** | **Environment** |
|---|---|---|---|
| (Nonhebel, 1996) | Western Europe | No net change | Mixed |
| (Trnka et al., 2004b) | Czech Republic | Increase | 7 sites, deeper soils showed the greatest increase. High spatial diversity of results |
| (Luo et al., 2003) | South Australia | Increase | 8 sites, increases were greater in the (current) wetter areas |
| (Luo et al., 2005b) | Mid-Lower North of South Australia | Decrease | 3 divisions across the region. High spatial variability of results |
| (van Ittersum et al., 2003a) | Western Australia | Increases up to +3°C, decline thereafter | 3 sites. Benefits were greater on heavy clay than sandy soils |
| (Wang et al., 2007) | Australia, Lower Murray Basin | Net increases in wetter scenarios<br>Decreases under drying scenarios | 14 soil profiles defined & 16 climate sites |
| (Wang et al., 2009) | Australia, New South Wales | Slight increases | 11 sites, drier scenarios increased spatial variability |
| (Wang et al., 2011) | Australia, Lower Murray Basin | Increase | Spatial variability highest at current drier sites |
| (Ludwig and Asseng, 2006) | South-western Australian wheat belt | Increase in south<br>Requires >50% $CO_2$ increase for conditional increase in drier north | 3 different soil types<br>Heavy clays more vulnerable to reduced rainfall |
| (Ko et al., 2012) | USA, Great Plains | Decrease | 1 site, 3 cropping systems |
| (Cho et al., 2012) | UK | Increase | UK cereal regions |
| (Kersebaum and Nendel, 2013) | Germany | General increase, but location specific | 22 selected study zones across Germany |

Most often the climate data used to represent future scenarios were based on some manipulation of historic data guided by IPCC emissions scenarios and the broad temperature and precipitation projections provided by GCMs. In a recent analysis of 221 peer-reviewed papers on climate change crop impact modelling, White et al. (2011) found that to obtain daily data for future scenarios the majority of papers adjusted historical daily data with anomaly outputs of the circulation models or used generic effects. The second most reported method used stochastic weather generators such as WGEN or LARS-WG to provide artificial sets of daily data intended to be statistically representative of future climates. The downscaled GCM future scenario data used in this thesis derived by the "weather-typing" method described by Hewitson and Crane (2006) may best be characterised by this second category in that a statistical downscaling approach is followed with stochastically generated daily outputs. Table 3.3 summarises their findings on how future weather scenarios were developed or obtained for crop modelling purposes.

Table 3.3. Review of methods used to prepare modelled future climate variables (after White et al., 2011).

| How future daily climate variables were produced | Number of papers (out of 221) |
|---|---|
| Adjustment to historic data | 141 |
| Weather generator | 68 |
| GCM or RCM used directly | 6 |
| Climate analogue | 3 |
| Not applicable | 3 |

Analogues refer to the technique of using an observed dataset – typically an unusually hot or dry year or sequence of years – to represent future climate scenarios. Six papers reportedly used GCMs or RCM data directly.

As far as South African research is concerned - whilst there are references in the literature to modelling of climate change impacts in the local maize (Crespo et al., 2011; Walker and Schulze, 2008) and sugar industries (Singels et al., 2005), none was encountered in the mainstream literature which dealt specifically with parameterisation of and the application of daily time-step, crop process modelling of Western Cape winter dryland wheat production under future climate, or indeed of the spatial variation in the regional wheat yield baseline.

One of the most significant issues to emerge from the literature study is the positive impact of $CO_2$ levels on wheat yield. $CO_2$ impacts on wheat have been studied experimentally through growth chamber (Qiao et al., 2010; Schütz and Fangmeier, 2001) or – more realistically – Free-Air $CO_2$ Enrichment or FACE experiments (Ainsworth and Long, 2005). The FACE experiments have computer-controlled vertical vent pipes arranged in circular arrays (outdoors), that are programmed to respond to changes in wind speed and direction so as to release $CO_2$ from the upwind pipes to keep the plants within the central portions of the circular arrays continuously supplied with air that is close to the desired $CO_2$ concentration. In a meta-analysis and review, Ainsworth and Long (2005) summarize a number of findings that they compare with findings obtained from other techniques. The study questioned whether perhaps crop models may simulate responses to elevated $CO_2$ too strongly. Tubiello et al. (2007) however showed that simulated responses to $CO_2$ as implemented in the major crop models are indeed consistent with FACE results. Ainsworth et al. (2008b) countered this argument with a different interpretation of FACE results which showed that a number of the crop models used in climate change studies (not including APSIM) had in fact, exceeded FACE results. Studies related to field verification by Asseng et al. (2004) and by Ko et al. (2010) concluded that crop models[10] can be used with reasonable confidence to simulate $CO_2$ impacts on future wheat yield.

A recent meta-analysis of $CO_2$ experimentation results confirms that in water-limited production areas (such as most of the Western Cape) the strong and robust signal for improved water use efficiency under increased atmospheric $CO_2$ will have major positive implications for crop production (Vanuytrecht et al., 2012). Being key to the outcomes of modelling future wheat yields in the Western Cape, the issue of the yield impact of elevated $CO_2$ is discussed further in Chapter 5.8.

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[10] The Asseng et al. study used APSIM, the Ko et al. study used the CERES-Wheat module.

# Chapter Four: Methodology – Parameterisation and application of the APSIM crop model for simulating Western Cape wheat production

## 4.1 Background to climate and soil data availability in SA

Crop modellers in South Africa face considerable challenges in accessing fundamental data sets suited to the requirements of daily time-step models. The demands of models such as the DSSAT and APSIM suites are rigorous in terms of their requirements for "clean", complete, daily weather data and detailed soil physical, hydrological and chemical properties – usually for a number of layers within each soil profile. Soils data already described in this way are available to modellers in certain countries due to funded, collaborative efforts, but none is available for the Western Cape region of South Africa. On a national or provincial basis the only source of regional soil data is the National Land Type Data Inventory, initially developed by the Soils and Irrigation Research Institute – later the Institute for Soils, Climate and Water (ISCW) of the Agricultural Research Council (ARC) during the 1970s and 1980s (ARC-ISCW Land Type Survey Staff, 1972). Whilst these data were not developed with the needs of future crop modellers in mind, they provide the best available data source for a regional crop modelling project.

The majority of climate stations in the wheat farming areas of the Western Cape are administered by the Agricultural Research Council through their Agromet database. Unfortunately very few of the climate stations on record have maintained uninterrupted, complete records (of at least daily precipitation, maximum and minimum temperatures) during the latter part of last century due to a variety of factors including administrative issues during the political changes in South Africa during the 1990s. During the late 1980s the Computing Centre for Water Research was established in Pietermaritzburg with one of its goals being the establishment of a unified, cleaned and patched climate record for the country. Unfortunately the funding was later discontinued, but the legacy of cleaned data was further developed by Prof Roland Schulze (University of KwaZulu-Natal) and colleagues in the Quaternary and later, Quinary catchment hydrology modelling projects (Schulze and Horan, 2010). Courtesy of the latter project, a set of 20 years of cleaned, patched, uninterrupted, observed daily climate data for the entire country was made available and utilised in this study. Whilst a longer term of observed baseline dataset and GCM control data would have been preferred, this was simply not available (Hewitson and Crane, 2006, pg 1323).

## 4.2 Determination of wheat study zones in the Western Cape

One of the objectives of this study is to investigate the *spatial* impacts of climate change on dryland cropping in the Western Cape Province. For this reason, careful consideration was given to the determination of spatial zones within which to realistically parameterise and run the APSIM wheat model. The challenge was to find a spatial unit which was balanced in terms of the density of soil and climate data availability, and relatively homogeneous in terms of farming practices and yield. Local governance in the province – including agricultural planning, administration, policy-making and extension – is now carried out at the local municipal level, providing some "pull" for spatial aggregation at local municipal level. However, politically derived boundaries usually do not coincide with agro-ecological resources, such as soils, local climatic conditions and topography. For this reason the agro-ecological zone approach was chosen for this study.

The Department of Agriculture: Western Cape (WCDA) developed a series of books or manuals known as Regional Development Plans (RDPs) (or "*Streeksontwikkelingsplanne*" in Afrikaans[11]) commencing during the 1970s (Department of Agriculture Western Cape, 1990). A manual was produced for each of 5 subregions of the province and chapters within each manual referred to specific agro-ecological zones known as relatively homogeneous farming areas (RHFAs), shown in Figure 4.1. The boundaries of these RHFAs were determined by regional extension officers and scientists, drawing on a number of unpublished analyses and reports, discussion groups and later, the National Land Type Survey (ARC-ISCW Land Type Survey Staff, 1972) was used to refine the boundaries. Considering the original workers did not have access to GIS, satellite imagery and digital terrain models, the resulting product is a remarkable testimony to the skill and dedication of those agriculturists involved. Subsequent small modifications and error

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[11] The manuals are only available in Afrikaans

corrections have been carried out by the author and co-workers at the Resource Utilisation Institute, WCDA.

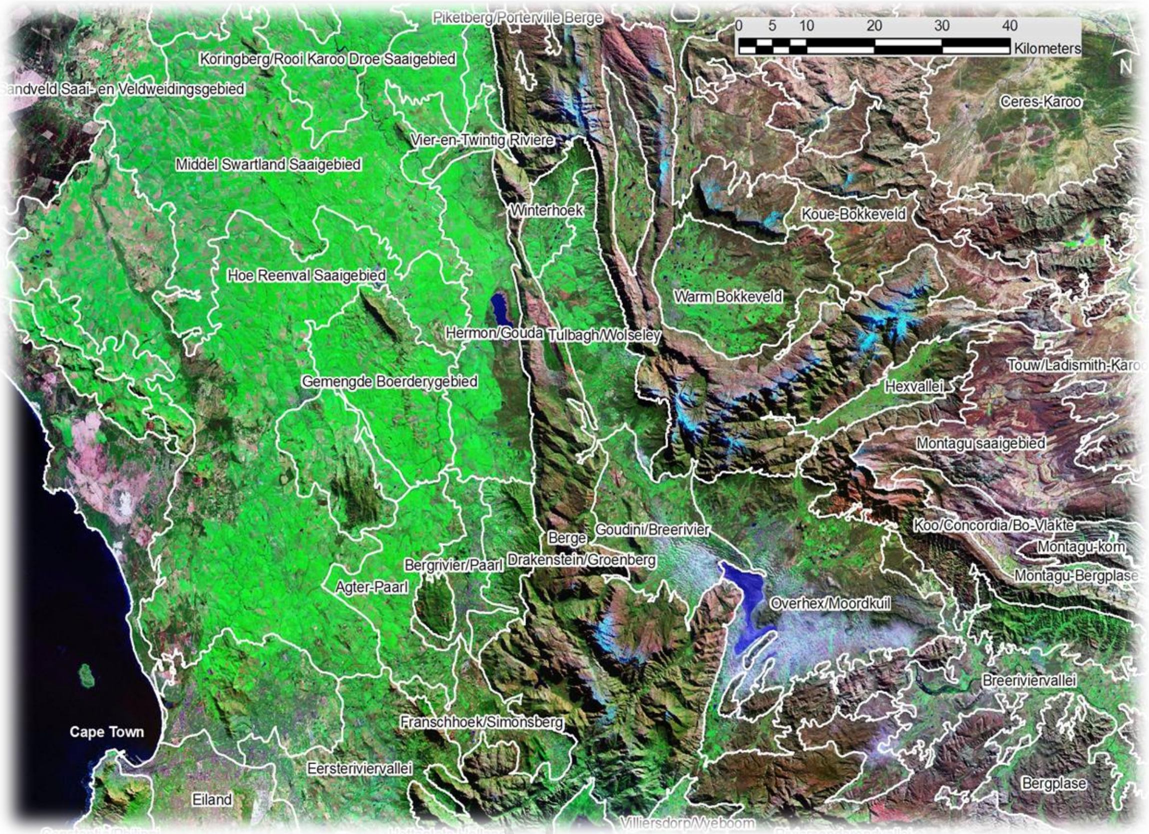

Figure 4.1. An extract of the RHFA boundaries overlaid on Landsat (circa 2000) false colour imagery.

The RHFAs were defined by the following guideline (translated from the Afrikaans)

*A defined region where the main agricultural activities practiced, or which realistically could be practiced, are common to most farm enterprises and within which the pertinent soil patterns and climate factors do not vary sufficiently to influence farming practices and production potential.*

The diversity in climate, soils, topography and water availability in the Western Cape can result in widely differing farming practices occurring in neighbouring RHFAs. To select the zones within which dryland wheat cropping is the dominant enterprise, the following approach was undertaken:

- The National Land Cover Data (NLC2000) (CSIR/ARC, 2003) compiled from Landsat imagery between 2000 to 2003 was used to broadly determine dryland crop areas by spatially merging the *cultivated/temporary/dryland commercial* classes.
- A detailed GIS dataset of all cultivated fields in the Western Cape was obtained courtesy of the National Department of Agriculture. This dataset was accurately digitised from SPOT 5 imagery. Using the "identity" overlay analysis in ArcInfo allowed all field polygons falling outside the "dryland" category to be identified and discarded. An example demonstrating the scale of dryland field mapping is shown in Figure 4.2.

Figure 4.2. An example of the level of detail in field boundary data near the Rûens West RHFA town of Caledon (-34.229°S; 19.428°E).

Each year an aerial survey is undertaken to provide information in support of the National Crop Estimates Committee's decisions on crop areas and anticipated yield per region. This is known as the PICES (Producer

Independent Crop Estimate Survey). The field boundary dataset is captured as a spatial basis for this annual sampling operation.

Figure 4.3. Aerial statistical survey of dryland crop plantings, Rûens East, 2011 (Photo M.Wallace).

- The field boundaries and the NLC2000 data were then intersected with the RHFA boundaries. All dryland cultivated fields within the appropriate NLC2000 dryland classes were selected per RHFA. The following table indicates the best available estimate of dryland areas either currently cropped, or areas potentially suited to this purpose that were previously cultivated (Table 4.1).

Table 4.1. Dryland cultivated areas where wheat is currently cultivated (usually in a rotation system) or was cultivated in previous years.

| **RHFA** | **Dryland cultivation (ha)** |
|---|---|
| Ruens East | 234841 |
| Middel Swartland Saaigebied | 172297 |
| Ruens West | 168866 |
| Hoe Reenval Saaigebied | 136805 |
| Sandveld Saaigebied | 108715 |
| Graafwater/Sandveld | 76272 |
| Koringberg/Rooi Karoo Saaigebied | 72082 |
| Gemengde Boerderygebied | 50009 |
| Malgas/Heidelbergvlakte | 46942 |
| Hardeveld | 37353 |
| Kamanassie | 31780 |
| Bredasdorp/Strandveldvlakte | 26636 |
| Gourits-Rooiruens | 22972 |
| Kleinberg/Suurrug | 18852 |
| Hermon/Gouda | 18697 |
| Agter-Paarl | 13327 |
| Bo-Langkloof | 8544 |
| Tulbagh/Wolseley | 7136 |
| Gouritzriviervallei | 3698 |
| Urionskraal | 3412 |
| Stockwell | 1426 |
| Total | 1260664 |

- Whilst dryland cropping does occur in some of the driest RHFAs, this is considered an opportunistic practice on rare occasions when good rains permit and is often an integral part of a livestock fodder system rather than a regular cash crop. These zones were then checked against the narrative in the RDP manuals and local extension officers were consulted to ensure that dryland cropping was indeed of significance to that RHFA. Wheat is the predominant dryland crop across all the zones

- The final selection includes zones where wheat production is currently considered very marginal. This was done intentionally since although it may be counter-intuitive, the possibility of more favourable future conditions (under climate change) for wheat in current marginal areas should not be overlooked.

## 4.3 Parameterisation of model inputs

### 4.3.1 Introduction

For the analysis, APSIM was configured to be representative of the regional conditions within each study zone: climate and soil data chosen were single-point representations of the average local conditions, while cropping management practices were supplied by local experts and best practice guidelines (ARC-Small Grain Institute, 2010).

### 4.3.2 Soil properties

Spatially explicit estimations of crop yields are limited by the availability of detailed quantitative soil data. Complex crop models such as APSIM have stringent demands in terms of soil parameterisation. The primary source of soils data was the National Land Type Inventory (ARC-ISCW Land Type Survey Staff, 1972). This survey entailed firstly the collation and study of any existing information and maps relevant to the terrain, soil and climate of the area. After an orientation excursion, areas called terrain types were delimited, each displaying a marked uniformity of terrain form. The range of soils in each terrain type was then identified through a reconnaissance survey and areas known as pedosystems, each with uniform terrain and soil pattern, were delineated. Representative or modal profiles were described and sampled for laboratory analysis. A separate map showing the distribution of climate zones was then drawn. This was superimposed on the pedosystem map to arrive at the map of land types, each displaying marked uniformity of terrain, soil pattern and climate. The boundaries were transferred to 1:250 000 maps and an inventory or memoir for each land type was compiled, from which most of the soil data parameters in this study were derived.

Since wheat production in the Western cape is predominantly water-limited, in this study the fundamental soil characteristic to be determined is the Plant Available Water Capacity (PAWC) of the representative soil (Burk and Dalgliesh, 2008). The fundamental input data required to characterise a soil for PAWC for the “SoilWater” module of APSIM are thus:

- Drained upper limit (DUL) or field capacity – the amount of water a soil can hold against gravity.
- Crop lower limit: (LL) or wilting point – the amount of water remaining after a particular crop has extracted all the water available to it from the soil.
- Bulk density (BD) – the density of the soil required to convert measurements of gravimetric water content to volumetric.
- Saturation – the total, maximum water content of a soil before drainage takes place.
- Total porosity – is the percentage of soil volume occupied by voids and is required for the calculation of saturation.

Because these values vary through a profile, and because of the root development of a crop through the growing season, the values are required on a multi-layer basis through the soil profile to adequately model the complex effects of drainage, the impact of limiting soil layers, evaporation, transpiration and root water uptake.

The Land Type memoirs provide largely descriptive information, whereas to adequately describe the pedo-transfer functions within a soil, quantitative measurements are required. Considerable work has been undertaken to interpret the Land Type data in terms of required hydrological and pedo-transfer properties, described in Schulze et al., (1995). Whilst this work was carried out primarily as source data for the ACRU hydrological model, it represents the best and indeed the only readily available source of potentially suitable, local data to adapt for use in APSIM on a regional or zonal basis. Whilst the ACRU model only requires the topsoil and subsoil component for each Land Type, the APSIM model ideally requires 3 or more layer descriptions. The minimum (user-defined) soil parameters required in the model are summarised in Table 4.2. Further to the references provided in the table, Dalgliesh (2008) from the model development team at CSIRO provided substantial support via e-mail.

Table 4.2. Minimum user-defined soil parameter set for APSIM wheat simulation.

| Parameter | Description | Source |
|---|---|---|
| Insoil | Initial soil water for the first modelled season | Based on antecedent moisture regime |
| Cona | Stage 2 evaporation coefficient | (Holzworth et al., 2006; Whitbread, 2009) |
| U | Stage 1 evaporation coefficient | (Holzworth et al., 2006; Whitbread, 2009) |
| Diffuse_const | Constant term in diffusivity calculation | APSIM Lookup table based on texture |
| Diffuse_slope | Slope term used in diffusivity calculation | APSIM Lookup table based on texture |
| Cn2_bare | Bare soil runoff curve number | APSIM Lookup table based on texture |
| Salb | Bare soil albedo | ASPIM Lookup table based on texture |
| Dlayer | The depth of a particle soil layer | (Schulze, 2006) |
| Air_dry | Volumetric air dry per layer | Soil Matters (Dalgliesh and Foale, 2005) |
| DUL | Drained upper limit per layer | (Schulze, 2006) |
| LL15 | Lower limit per layer (15 bar) | (Schulze, 2006) |
| Sat | Saturation per layer | Lookup table based on texture |
| Swcon | Soil water profile drainage coefficient | (Schulze, 2006) |
| BD | Bulk density | (ISRIC, 2008) |
| OC | Organic carbon | (ISRIC, 2008) |
| Ph | Soil Ph | (ISCW, 1986) |
| Fbiom | Microbial biomass | Norms (Whitbread, 2009) |
| Finert | Proportion of initial organic C assumed to be inert | Norms (Whitbread, 2009) |

#### 4.3.2.1 Sources of soil data for the Western Cape

The Western Cape region has a set of archived soil information representative of each RHFA captured by local extension officers and soil scientists between 1970 and 1990 (Department of Agriculture Western Cape, 1990). The documentation includes descriptive data on soil properties within sub-zones of the RHFA known by their Afrikaans name, “hulpbroneenhede” (resource units). Although these resource units were never mapped, many of the archives also describe the spatial extents or proportion of these resource units within each RHFA in the narrative. This information, together with detailed mapping of actual cultivated wheat areas, provided a basis on which to select and spatially weight representative soil data with the corresponding AUTOSOILS-derived pedotransfer parameters (Schulze, 2006) with which to parameterise the APSIM model.

Table 4.3. Zonal soil water holding parameters used in the APSIM model runs.

| RHFA | LL1 | LL2 | DUL1 | DUL2 | Depth (cm) |
|---|---|---|---|---|---|
| Agter-Paarl | 0.15 | 0.21 | 0.23 | 0.28 | 45 |
| Bo-Langkloof | 0.12 | 0.16 | 0.20 | 0.24 | 50 |
| Bredasdorp/Strandveldvlakte | 0.12 | 0.18 | 0.20 | 0.24 | 50 |
| Gemengde Boerderygebied | 0.12 | 0.17 | 0.21 | 0.25 | 70 |
| Gourits-Rooirûens | 0.15 | 0.20 | 0.23 | 0.27 | 65 |
| Gouritzriviervallei | 0.12 | 0.12 | 0.20 | 0.22 | 50 |
| Graafwater/Sandveld | 0.08 | 0.09 | 0.12 | 0.14 | 90 |
| Hardeveld | 0.08 | 0.08 | 0.17 | 0.18 | 55 |
| Hermon/Gouda | 0.14 | 0.21 | 0.23 | 0.28 | 60 |
| Hoë Reënval Saaigebied | 0.10 | 0.16 | 0.20 | 0.24 | 70 |
| Kamanassie | 0.12 | 0.13 | 0.20 | 0.22 | 50 |
| Kleinberg/Suurrug | 0.10 | 0.16 | 0.20 | 0.24 | 55 |
| Koringberg/Rooi Karoo | 0.15 | 0.21 | 0.23 | 0.28 | 60 |
| Malgas/Heidelbergvlakte | 0.17 | 0.20 | 0.24 | 0.27 | 45 |
| Middel Swartland Saaigebied | 0.12 | 0.18 | 0.21 | 0.25 | 75 |
| Rûens East | 0.15 | 0.17 | 0.23 | 0.25 | 45 |
| Rûens West | 0.13 | 0.15 | 0.21 | 0.23 | 55 |
| Sandveld Saai | 0.09 | 0.12 | 0.18 | 0.22 | 90 |
| Stockwell | 0.13 | 0.16 | 0.22 | 0.24 | 60 |
| Tulbagh/Wolseley | 0.13 | 0.16 | 0.22 | 0.24 | 50 |
| Urionskraal | 0.14 | 0.20 | 0.22 | 0.27 | 70 |

To derive representative pedotransfer values per RHFA, a spatially area-weighted average of potential cultivated wheat area (derived from the digitised field boundaries), per Landtype was calculated using the zonal statistics functions in the Spatial Analyst module in ArcInfo GIS. These weighted AUTOSOILS-derived values were then compared to the RDP narrative on representative soil descriptions per RHFA. In the few cases where discrepancies were evident, the AUTOSOILS-derived values were adjusted and tested step-wise (as the only changed model parameter) closer to the RDP description of the dominant soil. Given the absence of locally parameterised soils, Dalgliesh[12] and Whitbread[13], both of the CSIRO and involved with the development of APSIM, were most helpful in advising on realistic

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[12] Personal communication (2008), Dr Neal Dalgliesh, Farming Systems Researcher, CSIRO

[13] Personal communication, (2009), Dr Anthony Whitbread, Farming Systems Scientist, CSIRO

methodologies to infer values for the required APSIM parameters from sparse available data.

The final pedo-transfer values used in APSIM are shown in Table 4.3. Further information on the area-weighting method and the range of water-holding capacity values for each RHFA are presented in Appendix VII.

### 4.3.3 Management practices

The APSIM model allows the user to modify a number of management decisions. Based on existing practices a number of modelled planting rules were developed. It must be noted that some of these "rules" may not always reflect practical on-farm constraints, such as the determination of a sowing date. For optimum germination a farmer should ideally wait for some rainfall before sowing – yet in reality many farmers both in the Swartland and the Rûens have predetermined planting date "windows" based as much on their machinery or other on-farm resource limitations as on the expected onset of rainy conditions. The model can thus be instructed to plant within a certain window:
"*If* there is >10mm rainfall within a 2 day period after 21 April *then* plant, *else* must plant by the latest 31 May".

Factors such as cultivar choice, row spacing, sowing density, planting depth are based on production guidelines for the winter rainfall area (ARC-Small Grain Institute, 2010). Since the primary intention of this study is to determine yield impacts resulting from climatic change, the provision of fertilizer nutrition is set to be non-limiting and is reset each year, to avoid any modelled nutrient depletion or long-term degradation of the soil resource. In the absence of parameterised South African cultivars, the cultivar choice was based on season-length and yield characteristics of the widely used SST027 South African cultivar, closely approximated by the parameterisation for the Janz cultivar provided in the APSIM wheat module as a mid-late maturing variety (ARC-Small Grain Institute, 2010; Luo et al., 2005). For the cultivar sensitivity study in Section 6.5, the longer-season Batavia and early-maturing Hartog cultivars were also used (Wang et al., 2009).

### 4.3.4 Weather input files

Whilst South Africa has a wealth of recorded weather data compared to most other African countries, there are remarkably few rural weather stations with uninterrupted, complete rainfall, temperature and solar data through an entire climatology of 30 years or more. With the political changes and subsequent changes in agricultural research infrastructure in the mid-90s, many stations simply ceased to record data (Schulze, 2011 personal communication). Daily time-step crop models require a clean unbroken dataset with a recording for each day for each input parameter. In the absence of such daily observational records, some studies make use of simulated daily weather data using a well-tested weather generator, based on long-term climatic data[14] (Jones and Thornton, 2000; Jones and Thornton, 2013).

The minimum weather data required by the APSIM model is a set of daily precipitation, maximum and minimum temperatures and solar radiation. Quality controlled, cleaned and patched temperature and precipitation (observed) data were available for the period 1979 to 1999 through the Quinary Catchment data set (Schulze and Horan, 2010) for each described quinary catchment. For each SRES A2 GCM model data, the downscaled data are generated at a daily time step for the period 2046 to 2065 using the methodology described by Hewitson and Crane (2006). Since measured solar radiation data are scarce in South Africa – particularly continuous data as required in a modelling environment (Singels et al., 2010) - the solar radiation parameter was calculated for each day using the Heargreaves and Samani model modified by Annandale et al., as evaluated and reported on in Ball et al. (2004).

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[14] See also IPCC website for a description of these: <http://www.ipcc-data.org/ddc_weather_generators.html>

The statistical downscaling of the GCM data (see Section 1.2.4) was undertaken by the Climate Systems Analysis Group (CSAG) of the University of Cape Town (and made available courtesy of Dr Lyndon Estes, Princeton University, US, who funded this particular downscaling during 2010 for his project). In each case the A2 SRES scenario output was used (IPCC Working Group III, 2000) of the models shown in Table 4.4.

Table 4.4. The A2 SRES GCM ensemble downscaled by CSAG and used in this study with the NCEP data used to drive the downscaling methodology.

| **Model** | **Abbreviation*** | **Description** |
|---|---|---|
| NCEP/NCAR Reanalysis | ncep | The National Centres for Environmental Prediction (NCEP) and National Centre for Atmospheric Research (NCAR) Reanalysis Project |
| CCMA CGCM3.1 | cgcm3_1 | Canadian Centre for Climate Modeling and Analysis, the third generation coupled global climate model (CGCM3.1 Model, T47) |
| MPI _ECHAM5 | echam5 | Max Planck Institute for Meteorology, Germany, ECHAM5 / MPI OM |
| MRI_CGCM2.3 | mri_cgcm2_3 | Meteorological Research Institute, Japan Meteorological Agency, Japan |
| MIUB_Echo_G | echo_g | Meteorological Institute of the University of Bonn, Germany |
| CNRM_CM3 | cnrm_cm3 | Meteo-France, *Centre National de Recherches Meteorologiques*, the third version of the ocean-atmosphere model (CM3 Model) |
| CSIRO_MK3.5 | csiro3_5 | CSIRO Atmospheric Research, Australia, MK3.5 Model |
| IPSL_CM4 | ipsl_cm4 | IPSL/LMD/LSCE, France, CM4V1 Model |
| GFDL_CM2.1 | gfdl2_1 | NOAA Geophysical Fluid Dynamics Laboratory, coupled climate model |

*the abbreviation used in this study in graphs, maps and tables

Considerable effort was required to transform the data from the GCM-derived output format to the exacting requirements of the APSIM climate module. Some of the GCM output is supplied in 360 day years whilst others ignore leap years and output 365 day years perpetually. APSIM requires calendar-correct input, thus the data had to be appropriately distributed into a full 365 day calendar or leap year.

Taking note of the *caveats* reported by White et al., (2011) in terms of applying contemporaneous baseline and future $CO_2$ levels in crop impact modelling, a conservative 500 ppm $CO_2$ level is used in APSIM for the future scenarios between 2046 and 2065. This is in line with the lower levels of projections estimated by the IPCC for the SRES A2 scenario (see Figure 3.1). The baseline was set to 350 ppm which appropriately represented the baseline data modelling period between 1979 and 1999 (IPCC, 2007b). Further details on the procedure are presented in 4.4.4.2.

#### 4.3.4.1 GCM downscaling methodology

The empirical downscaling methodology used to derive the data used in this study takes model output from GCMs, and uses a method based on a type of artificial neural networks known as self-organizing maps (SOM), calculated on a daily basis to relate GCM-scale data to local climate dynamics (Hewitson and Crane, 1996a; Hewitson and Crane, 2006). The methodology is based on the premise that local-scale climate is in some measure a response to larger, synoptic-scale forcing. Essentially, using observational data, SOMs characterise the atmospheric circulation on a localised domain around a target location. A probability density function (PDF) is generated for the local weather conditions associated with each synoptic state at the target location. The downscaling process then takes the GCM data and matches it to the closest SOM characterisation of the atmospheric states, and for each matching circulation state in the GCM data, randomly selects weather (e.g. precipitation) values from the associated PDF, in the manner of a stochastic weather generator. Thus in a relatively computationally-inexpensive manner, the relationship between the synoptic-scale and local climates is used to derive a plausible local climatic response to the GCM forcing. In the mountainous Western Cape, topography has an important influence on local climate. The downscaling methodology incorporates these local forcings by including appropriate parameters in the predictor variables (Hewitson and Crane, 2006).

The GCM downscaling methodology used daily mean atmospheric fields constructed from 6-hourly NCEP reanalysis data for 1979 to 2002. Only post-1979 data were used, as the advent of satellite data for the reanalysis significantly improved the quality of the reanalysis for the Southern Hemisphere after 1979. While 24 years of NCEP reanalysis data are available to develop the SOMs, the available precipitation data set ends in 1999 (Hewitson and Crane, 2006), which is why this study by necessity uses a 20 year baseline data period, as opposed to the preferable 30-year baseline climatology.

Typically the process of downscaling takes data from the resolution of the GCM cell, usually about 300km, to a spatial scale of approximately 25km, or to point/climate station scale. The rationale for producing downscaled data is usually the need for climate information at a finer spatial and temporal scale than GCMs currently deliver, for impact assessments. For example, computing runoff or running crop models requires daily data at catchment or station scale with appropriate spatial variability. Data at this level of detail is certainly required to address sub-regional or zonal differences in expected climate change impacts at local scale.

It is important to note, however, that the increased resolution obtained by downscaling does not necessarily translate to increased confidence in the regional scenario (Wilby et al., 2004) and the same caveats apply as with the source GCM. In other words, the downscaling techniques propagate the uncertainty inherent in the GCM.

In terms of accounting for local forcings, land use and land cover changes cannot be captured by empirical downscaling techniques. The degree to which land cover changes can feedback to impact local climate represents an uncertainty in the climate projections similar to that posed by future levels of greenhouse gas emissions (Hewitson and Crane 2006).

Empirical downscaling implicitly assumes that the observational data from which the relationship is derived, encompasses the required information for future cross-scale relationships. In other words, it implies that for a given region, the same synoptic–scale states will be present in the future, and that climate change will manifest itself as changes in the persistence and frequency of the larger-scale events. This is the problem of stationarity, and cannot be verified until after the fact. In mitigation, the authors consider that appropriate selection of atmospheric variables that fully encompass the physics of large scale forcings, should ensure that the transfer function remains relevant into the future. The authors also warn against using predictor relationships that are purely correlative, and where there is no clear physical process linkage – for example, the El Nino southern oscillation teleconnection that induces drought in parts of southern Africa. It is unlikely that these teleconnection relationships will be maintained in future climates.

The authors also consider it unlikely that there is a “best” downscaling algorithm, and that the optimum technique is likely to be application and region specific. Each model and each downscaling thereof will inevitably introduce its own biases. There may therefore, not be much gained by an in depth comparison study (in any attempt to quantify relative uncertainties) and the user community may be best served by a clear articulation of the benefits and limitations of any particular downscaled product (Hewitson and Crane 2006).

Mapped outcomes of the downscaled rainfall and temperatures are in Appendix II, with projected rainfall graphs in Appendix III. Further uncertainties, limitations and possible mitigations associated with the downscaling methodology are discussed in Section 4.5.2.

#### 4.3.4.2 The GCM ensemble approach

*"Uncertainty is unavoidable in work of this nature, but in itself does not preclude confidence in scientific results"* (Leary et al., 2009).

It should be borne in mind that although GCM model projections are inherently uncertain, the results may disagree because future changes are within the natural variability (Deser et al., 2012). Such natural fluctuations in climate should be expected to occur, and these will augment or reduce the magnitude of climate change due to anthropogenic forcing in many parts of the world. Issues regarding the treatment of uncertainty are highly topical of late and are well reported on in recent literature (Mastrandrea et al., 2011; Morgan and Mellon, 2011; Moss, 2011; Yohe and Oppenheimer, 2011) and the language of climate change writing is under examination by advisors to the IPCC to help communicate the "confidence" we can have in modelled results more uniformly and transparently.

In this study the recommended multi-GCM model approach is followed (CSAG, 2006; Wilby et al., 2004) with the degree of agreement between the different downscaled GCM-based yield models in terms of sign of change taken as a primary indicator of confidence in the expected yield changes per zone. The median yield (anomaly) per APSIM run ensemble "envelope" of results is provided for quantitative purposes, together with the 1st and 3rd quartiles.

It should be noted that the control period of each GCM does not represent observed climate, but the broad scale climate as simulated by the particular GCM, and should only represent a particular location (in this case RHFA zone) in a mean sense (CSAG, 2006). Additionally it is not valid to assume that a data set that has an accurate control climate will have a more accurate future projected climate. To avoid model bias, the modelled yield anomaly is calculated (*future – control*) for each GCM-forced yield for comparison with observed yields. Wilby et al. (2004) and CSAG (2006) further recommend an envelope of projections forced by a wide range of GCMs. Selecting one or two GCMs based on any criteria will not necessarily produce a more scientifically robust analysis, and a wide spread in future projections should not be reduced by removing models arbitrarily from the analysis. In the final analysis the 2nd quartile (or median) value together with the 1st and 3rd quartile of results within the change “envelope” are presented, which in effect moderate the effects of positive and negative outliers. These outliers may still represent plausible futures until superseded by new data and their impacts are still present in the mean and standard deviation results.

During the course of this study it became evident that a thorough consideration of the uncertainty “cascade” is essential to the interpretation of final results. Section 4.5 provides further discussion on inherent uncertainties and mitigation measures in the modelling approaches followed in this study.

## 4.4 APSIM crop model outputs

### 4.4.1 Introduction

Once the required parameters and correctly formatted data are in place the model can be run for a particular sensitivity analysis, control or future scenario. The error trapping algorithms are activated if any data inputs are outside acceptable norms or if required data are missing or incorrectly formatted. The model writes output from each model run to a text file – combinations of which can be analysed within the APSIM framework or imported into third-party software for further analysis. A typical ensemble run, per scenario, per representative zonal parameterisation, for the 8 downscaled GCM-based models (each with a control and future scenario) plus the observed and NCEP data, will produce 18 data files per scenario per zone (thus 378 model runs per scenario over all 21 zones). A typical output is shown in Figure 4.4.

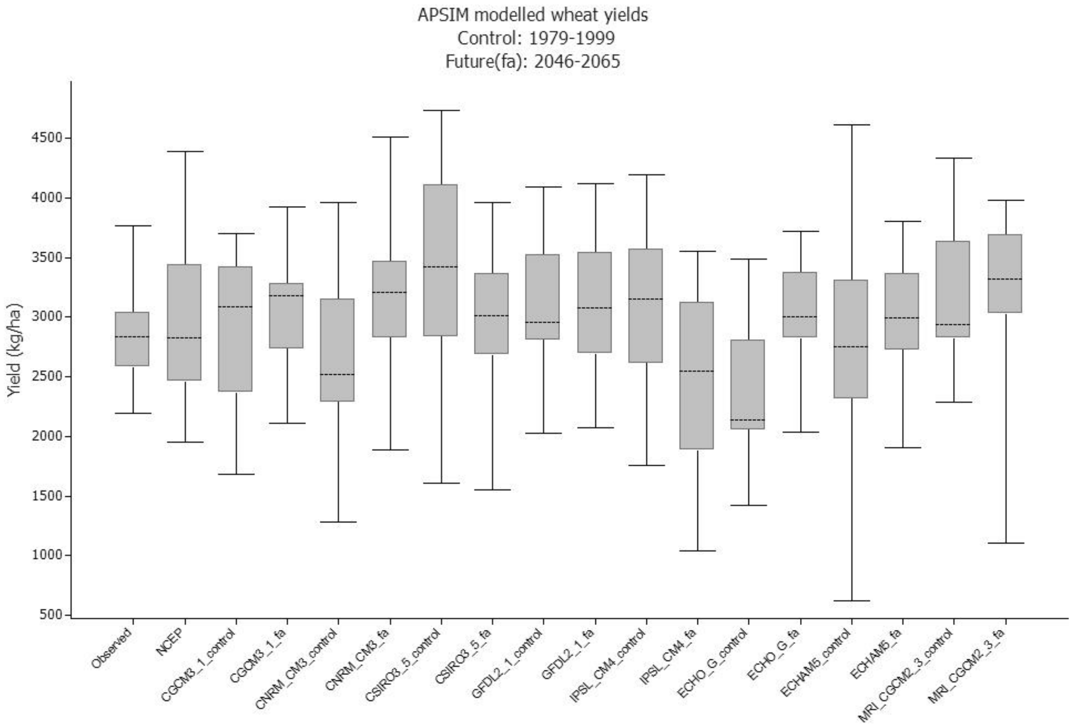

Figure 4.4. Graphed output from a typical APSIM ensemble future scenario. The observed data, NCEP re-analysis data and each downscaled model's control and future are shown on the x-axis.

### 4.4.2 APSIM crop model performance

The process of model parameterisation per zone is laborious, but once completed the model appeared to perform well when driven by the observed baseline data for the period 1979 to 1999 (Table 4.5). Georeferenced, time-series yield data are extremely difficult to obtain in South Africa – possibly as a consequence of the ongoing debate regarding a proposed farm-potential based taxation (South African Treasury, 1998). Some historical yield data were kindly provided by the farmer's co-operative in Swellendam[15]. The highly aggregated data based on grain delivery from their service area between Swellendam and the Heidelberg area compared quite favourably with APSIM-modelled yield (Rûens East RHFA) for the same period, with a correlation coefficient of 0.64 (see Figure 4.5).

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[15] Courtesy of Mr Jannie Bruwer, Agronomist, SSK, Swellendam

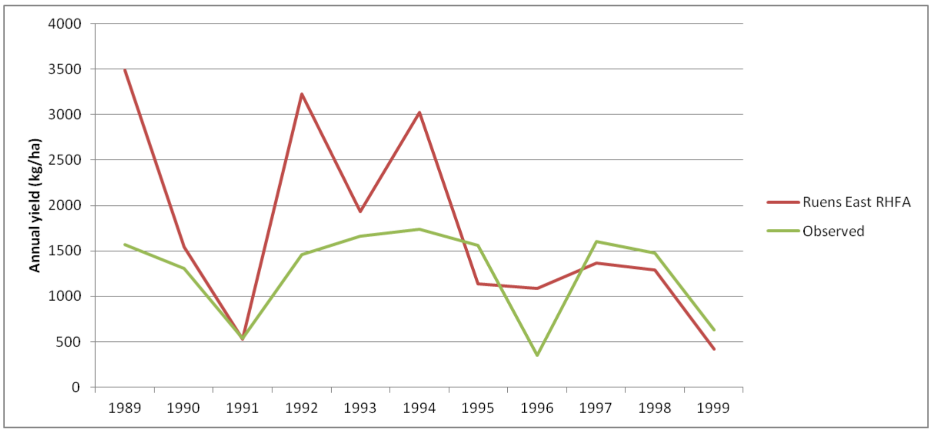

Figure 4.5. Graph showing aggregated "observed" data from a regional co-operative versus APSIM modelled yields for approximately the same region.

The Department of Agriculture Western Cape (1990) produced a series of Regional Development Plans (RDPs) in which expert consultation was undertaken to produce achievable target “norms” for each RHFA which were obtainable in better years and under optimal management. The spatial distribution variation across the 21 zones was very well simulated, with a high correlation co-efficient (0.87) between these reported RDP value (Department of Agriculture Western Cape, 1990) and the modelled yield (Figure 4.6). Four of the 21 RHFA zones did not have reported norms in their RDP document and yield norms were estimated based on neighbouring RHFA values or local knowledge. (In cases where the “>” sign was used in the RDP norm without closure of the range, the bounding value at the next 0.5 t/ha was assumed.)

Table 4.5. Reported RDP target norms, corrected (simplified) values derived production norm values for comparison with modelled yields, and APSIM modelled baseline values (1979 - 1999).

| **RHFA** | **Reported RDP norm** (t/ha/annum) | **"Adjusted" norm value** (t/ha/annum) | **Modelled Yield (1979-1999)** (t/ha/annum) |
|---|---|---|---|
| Agter-Paarl | > 2.0 | 2.5 | 2.86 |
| Bo-Langkloof | Not given | 1.5* | 1.92 |
| Bredasdorp/Strandveldvlakte | 1.5 – 2.5 | 2.5 | 2.70 |
| Gemengde Boerderygebied | > 2.5 | 3.0 | 3.68 |
| Gourits-Rooirûens | 1.0 – 1.5 | 1.5 | 1.99 |
| Gouritzriviervallei | Not given | 1.4* | 1.89 |
| Graafwater/Sandveld | < 1.0 | 1.0 | 1.10 |
| Hardeveld | Not given | 0.8* | 0.43 |
| Hermon/Gouda | > 2.5 | 3.0 | 3.14 |
| Hoë Reënval Saaigebied | > 2.5 | 3.0 | 3.44 |
| Kamanassie | Not given | 1.0* | 1.39 |
| Kleinberg/Suurrug | 1.5 | 1.5 | 1.78 |
| Koringberg/Rooi Karoo | < 2.0 | 2.0 | 1.84 |
| Malgas/Heidelbergvlakte | 1.5 - 2 | 2.0 | 1.74 |
| Middel Swartland Saaigebied | > 2.5 | 3.0 | 3.44 |
| Rûens East | 2.0 | 2.0 | 1.91 |
| Rûens West | 3.0 | 3.0 | 3.05 |
| Sandveld Saai | <1.4 | 1.4 | 1.67 |
| Stockwell | 1.2 | 1.2 | 1.16 |
| Tulbagh/Wolseley | 1.2 -1.4 | 1.4 | 2.86 |
| Urionskraal | 0.75 | 0.75 | 0.64 |

* Estimated value

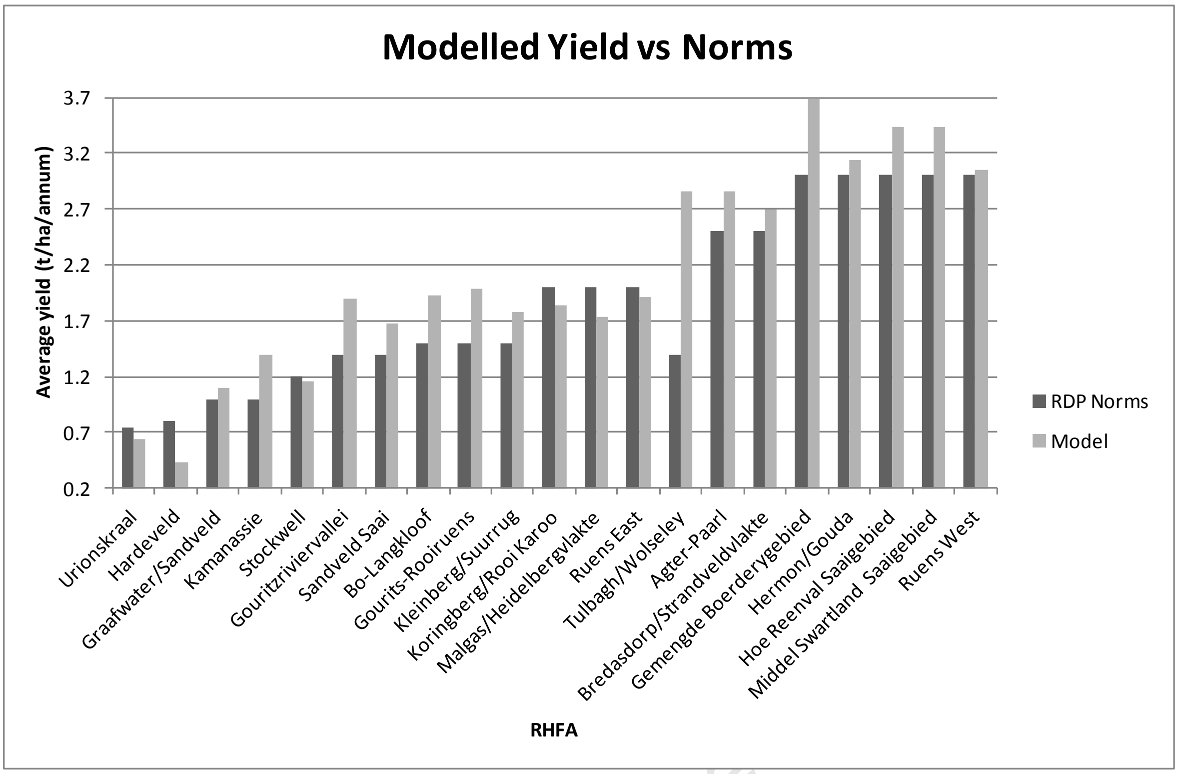

Figure 4.6. Long-term average modelled yield versus RHFA target norms.

The RDP norm values used are based on 1990 studies, providing a good representation of the mid-baseline period 1979 to 1999. In most cases modelled yields were slightly higher than RDP norms per zone. This is expected as:

1. In the simulations, nutritional parameters are generally non-limiting, in order to isolate impacts due to climate and $CO_2$ changes. In the real world, economics would prevail regarding management inputs.
2. The common practice of withholding seed by farmers, which may slightly reduce recorded yields per hectare per region made available to the expert groups.
3. Yield reductions due to wind damage, mechanical issues and harvest delays due to wet field conditions are not replicated in the model. For example in the flat areas of the Bredasdorp Plain, harvesting operations are strongly dictated by soil moisture – even heavy dewfalls hamper field operations leading to delays in harvest.
4. Negative influences of pest, diseases and weed competition are not modelled.

### 4.4.3 APSIM crop model performance: The application of MODIS vegetation indices to estimate spatial yield distribution

To help overcome the shortfall in objective yield data at RHFA level, the use of remote sensing products was explored as a proxy for yield data indicating spatial variation of long-term average wheat yields in the Western Cape. The high correlation between satellite-derived peak NDVI and final wheat yield (with reported $r^2$ values ranging from 0.73 to 0.95) have been well utilised by a number of researchers involved in spatial modelling of wheat yield, for a number of years (Aase and Siddoway, 1981; Becker-Reshef et al., 2010; Moriondo et al., 2007; Potgieter, 2009). Recent improvements in sensor technology and data availability, such as the high-quality daily vegetation products from NASA's MODIS data, have made this an attractive option for estimating wheat yield variation in the Western Cape.

Although relatively coarse, the 250 m resolution MODIS data have been shown to be highly suited to wheat yield estimation, particularly where an accurately mapped crop "mask" is available (Becker-Reshef et al., 2010; Potgieter, 2009) as is the case in the Western Cape (mentioned in Section 4.2). Two MODIS vegetation index products are available – the more traditional MODIS NDVI (Normalised Difference Vegetation Index) and the newer MODIS EVI (Enhanced Vegetation Index) product[16] which is considered to perform slightly better for wheat analysis (Potgieter, 2009).

Since the correlation between final grain yield and the chosen vegetation index is highest at peak NDVI/EVI, usually at wheat anthesis, a preliminary analysis was undertaken to determine the timing of this phenomenon in the Western Cape, which resulted in the mid-August time-series of imagery being averaged from 2000 to 2012 at peak NDVI & EVI. The zonal statistics function of ArcGIS Spatial Analyst was used to average the "masked" wheat fields only across RHFAs. Over the 12 years this gave an indication of wheat production variation across the Western Cape. It was beyond the scope here to determine which index performed better (NDVI versus EVI), since the problem was a lack

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[16] The 16-Day L3 Global 250m NDVI and EVI products are freely downloadable from NASA for non-commercial use at <http://reverb.echo.nasa.gov/reverb/>

of objective observed yields available in the first place. The average of both these (NDVI & EVI) 12-year averaged time-series data shows promising correlation ($r^2 > 0.8$) with both the APSIM modelled and expert "target norm" values across the 21 RHFAs. The temptation to construct a simple regression (against modelled data) and present the NDVI/EVI results as kg/ha/annum was avoided[17], and the "raw" vegetation index values are used, plotted for illustrative purposes on the secondary axis of (Figure 4.7). In the absence of further observed field data, and in light of the high correlation between the vegetation index measure of biomass and the literature supporting good correlation with yield at peak NDVI/EVI, the method provides some reassurance that spatial variation across the province is being sensibly modelled.

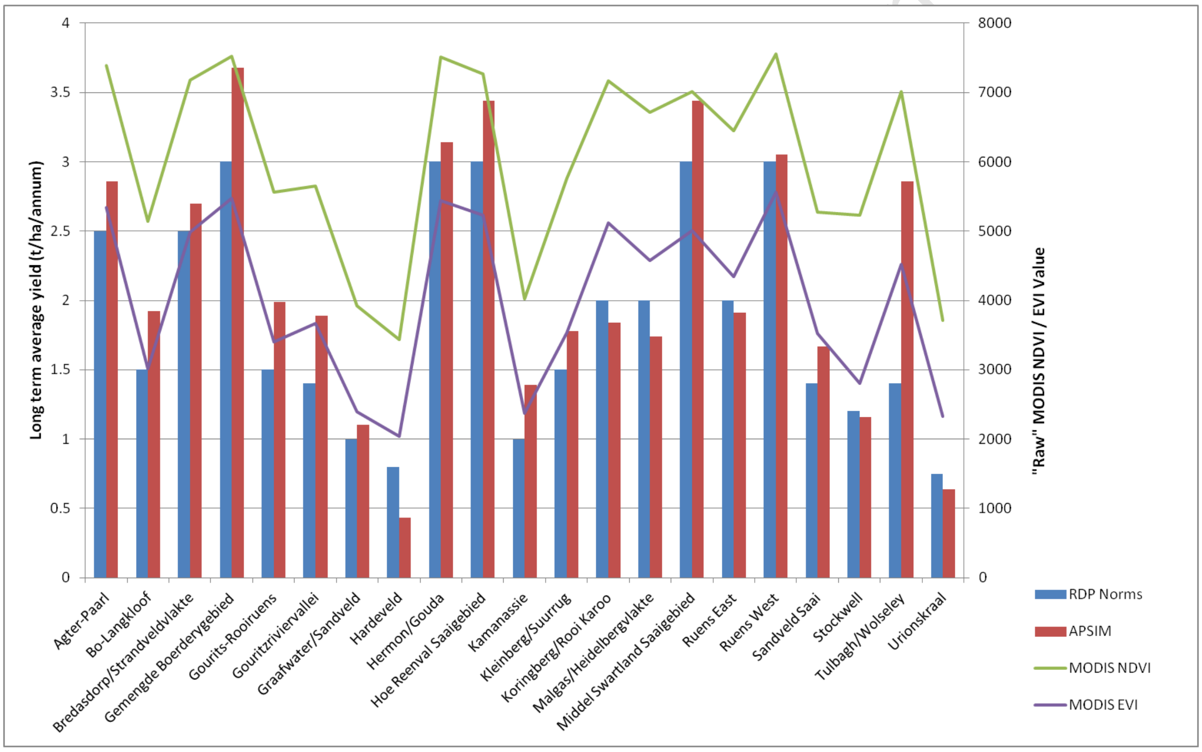

Figure 4.7. Graph illustrating RDP yield norms and modelled APSIM values (primary Y-axis, showing t/ha/annum) and MODIS NDVI and EVI values for 2000 to 2012 at mid-August (secondary Y-axis, units are the "raw" values obtained from the NDVI/EVI image processing).

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[17] Field survey data sample points will be used to construct this regression as and when they become available, from a WCDA project of the author, currently in progress.

### 4.4.4 The two modelling approaches executed in APSIM

#### 4.4.4.1 The perturbed baseline crop sensitivity analysis per zone

A perturbation is applied to each observed (daily) baseline dataset for each of the study sites, with no explicit input from any GCM defined future. The methodology is undertaken as a contextual, background study to investigate the sensitivity or resilience of a particular zone in response to changes in temperature, rainfall and $CO_2$. This adds to the understanding of a particular zone's response to a modelled climate change and in particular, the important impact of elevated $CO_2$ in concert with other perturbations can be investigated.

#### 4.4.4.2 Crop modelling forced by the downscaled multi-GCM daily data per zone

This methodology is based on using the best available downscaled multi-GCM data for the future period 2046-2065 to drive the APSIM model at a daily time-step. Wheat yield results are modelled for each GCM's future and control. (1979 – 1999) The yields are averaged over the period and the resulting anomaly between control and future for each GCM is calculated. To control model bias in the weather records introduced by the GCMs and their downscaling, future yields are represented by adding this anomaly to the value obtained for the simulation forced by observed data. The full ensemble of GCMs controls and future is modelled in this way for each zone and the resulting "envelope" of outcome anomalies is graphed and inspected. For each envelope, the 1st, 2nd (median) and 3rd quartiles, mean and standard deviation statistics are calculated from the resulting yield anomalies. The modelling process was repeated for each of three season-length cultivars to further assess temporal issues and likely influence of cultivar choice.

#### 4.4.4.3 Spatial analysis of modelled results

The results of each set of model runs were imported into ArcInfo GIS. Each of the modelled output scenarios was joined as an attribute table to the shapefile of the corresponding RHFA zones to facilitate thematic visualisation and spatial analysis of the results.

## 4.5 Uncertainty and limitations of the modelling approach

### 4.5.1 Introduction

A study of this nature requires responsible consideration of the source of uncertainties throughout the process (the so-called “cascade of uncertainties”) and how these can impact upon the processes of GCM modelling, downscaling, parameterisation of models and structural uncertainty within the crop model itself. Furthermore it should be stated that the study addressed direct impacts of climate change and increasing $CO_2$ on wheat development and yield (Olesen et al., 2011), whilst a number of the indirect impact pathways (e.g. pest and disease impacts, crop damage resulting from climate extremes and environmental degradation) are not considered.

Whilst uncertainties cannot be excluded when modelling complex systems, a conservative approach was followed to mitigate uncertainty where possible, and with corresponding use of probabilistic terminology in both narrative and graphic output. It is necessary to convert the deterministic outcomes of the downscaled GCM-modelled yield into probabilistic outcomes for responsible communication of the results. Johnston (2008) discusses the problems that decision makers have with the interpretation of probabilistic climate forecasts. His study showed that probability reporting is widely misunderstood amongst the target group (in agriculture). The responsibility is largely on the impact research community to ensure that results are responsibly reported, using appropriate language. It should be clearly communicated that the projected impact *is* probabilistic and is the result of conservative and responsible application of tools and data at the time with references given for decision makers who wish to delve deeper into methodology. Distinction must be made between the speculative and the well-established (Moss, 2011). The “uncertainty language” of climate change is currently under review by the IPCC, with a number of references to this provided in Section 4.3.4.2.

### 4.5.2 The cascade of uncertainties relevant to this study

The processing and reporting of uncertainties in ensemble-based agro-climatic modelling is still in its developmental phase and was the subject of 2 leading climate and agricultural journals' special issues in recent years[18]. Challinor et al. (2013) consider that new frameworks are needed to properly quantify uncertainty in agro-climate modelling. Recent developments in agro-climatic model intercomparison, such as the AgMIP project, should help to facilitate such frameworks (Rosenzweig et al., 2013). Von Storch and Zwiers (2013) warn against attempts to quantify uncertainty in the absence of such comparative frameworks, and recommends that a descriptive approach be followed. Figure 4.8 indicates the highlighted sources and propagations of uncertainties (and the mitigation steps that were implemented in this study) as discussed either here, or elsewhere in the thesis.

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[18] *Agricultural and Forest Meteorology*, Climate ensembles for crop modelling, Volume 170, March 2013; and *Climatic Change*, Special Issue: Guidance for Characterizing and Communicating Uncertainty and Confidence in the IPCC, October 2011.

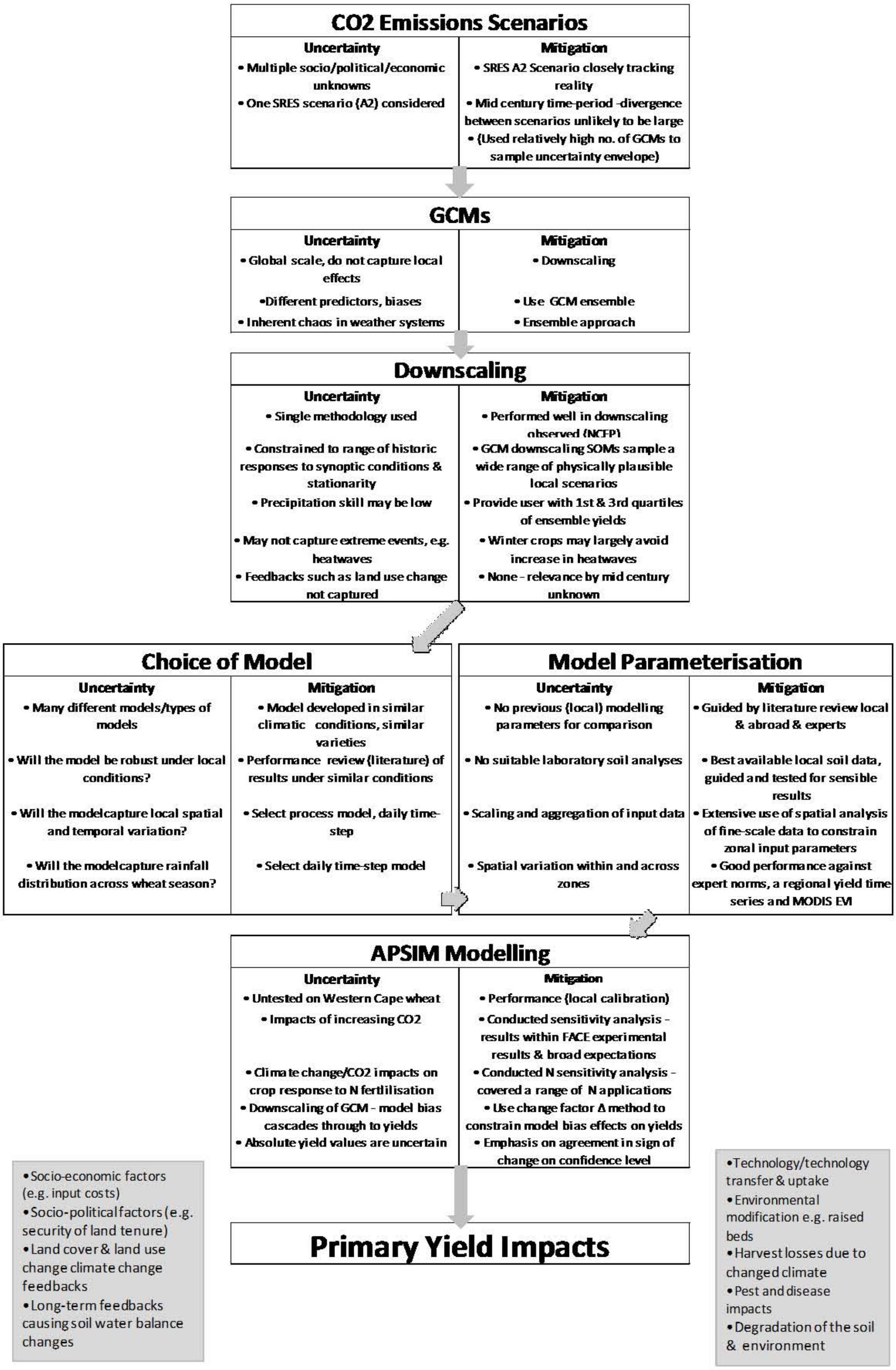

Figure 4.8. The cascade of uncertainties as encountered in this modelling study. The grey blocks indicate some external uncertainties not part of this modelling process, which are likely to have an (unknown) impact on future yields.

The uncertainties likely to have the major impact in the outcomes of GCM-based crop impact study are those inherent in the application of $CO_2$ emissions scenarios to force GCMs and the skill of the GCMs themselves (Hawkins et al., 2013).

Downscaling may fail to capture the effects of local topographic forcing, or the synoptic relationships upon which they are largely based (stationarity) may not hold under future climate circulation patterns. A limitation of this study is the analysis of yield impacts resulting from only one “family” or suite of downscaled GCMs. Although the applied technique of downscaling from atmospheric fields is considered robust for South African conditions (DEA, 2011) a potential weakness exists in that it cannot project weather conditions outside the envelope of previously experienced weather. The fact that wheat is produced in the winter months in the Western Cape may mitigate to some extent, against impacts resulting from the likely increased incidence of heat waves, which are usually in summer months. Recent downscaling methods and tools developed by other institutions e.g. such as those currently under development by the CSIR (Engelbrecht et al., 2009); and MarkSimGCM, described by Jones and Thornton (2013) may reveal some alternative insights into plausible future yield outcomes in local agro-climatic modelling. The choice of one SRES (A2) emissions scenario in this study may also be considered a limitation, but given that it closely tracks recent emissions levels which are unlikely to diverge to a great extent by mid 21st century (DEA, 2011) this seems reasonable, when a relatively large ensemble of 8 downscaled GCMs were used to sample the envelope of uncertainty.

The downscaled GCM ensemble for the study period 2046 – 2065 projected generally (relatively) beneficial future rainfall regimes for most of the southern and south-eastern parts of the Western Cape. Given the high modelled sensitivity of much of the region to reduced rainfall under warmer conditions, a downward deviation in precipitation projected by other downscaling techniques may result in considerably less favourable projections for a number of the RHFAs in these regions. Crop damage resulting from climate extremes is not modelled. A study on the impact of heatwaves on Mediterranean winter wheat yield showed simulated heatwaves to be of minor significance in the region compared with the impacts of heatwaves on typical summer crops (Moriondo et al., 2011). Further research would be required to test this hypothesis locally on winter wheat; particularly given that current climate projections may not capture the expected future increase in climate extremes.

Whilst the choice of an appropriate wheat model to be used in this project was thoroughly researched and deemed appropriate for the scale of the study, the use of a single, mechanistic crop model also implies a possible limitation. It is fairly rare in agro-climatic modelling that different models, e.g. mechanistic and empirical, or a crop-model ensemble (to help constrain uncertainty) are used (Challinor et al., 2013). The problem has been recognised by the international agricultural impact modelling community, leading to the recent establishment of the Agricultural Model Intercomparison and Improvement Project (AgMIP) (Rosenzweig et al., 2013). AgMIP will facilitate a distributed climate-scenario crop simulation exercise for model intercomparison on both historical and future climate change conditions with participation of multiple crop modelling groups around the world – including APSIM. Accordingly, the input parameters will be standardised and outputs of various crop models will be comparable. This would be beneficial in the Western Cape of South Africa, as the crop modelling approach used in this thesis stands in relative isolation in the local wheat research milieu. A recent local study reported on a workshop attended by some leading agronomists in the region, that delegates had no knowledge of any model that could simulate South African winter wheat production based on physiological and physical parameters (Hoffmann, 2010). The "culture" and awareness of crop modelling and models have largely disappeared from the Western Cape technical and research community.

Despite these challenges, the APSIM model itself is indeed a well tested, process-based model, calibrated and validated in a wide range of environments. With due care taken to parameterise the model appropriately for local conditions, the results must be considered to have a plausible basis. Likewise the GCM downscaling methodology and resulting data used to force APSIM is founded in physical responses to atmospheric conditions. Notwithstanding the issue of stationarity mentioned above, it could be speculated that the fact that it draws from a probability density function of historical weather responses, also contributes to some physical plausibility for the mid 21st century.

Certain factors likely to influence future production are not currently modelled. Earlier narrative has discussed the problem of infield harvesting in wet conditions in the RHFAs on coastal plains (Bredasdorp and Malgas/Heidelbergvlakte), which are not accounted for in the modelling. This may lead to significant losses as these areas are projected to become wetter by mid-21st century. Structures such as raised-beds may be required to alleviate the problem, as in flatter parts of the Swartland. Potential long-term degradation of the soil resource is not modelled, but hopefully if current minimum-tillage and soil conservation initiatives gather momentum, this situation will not realise. Effects of potential future land use and land cover changes may also induce climate feedbacks which are not accounted for in the downscaled GCM models. Likewise, some long-term (potentially beneficial) feedbacks may arise from additional leaf area development under $CO_2$ enrichment which may reduce soil evaporation and improve the soil water balance (Hoffman et al., 2011; Hoffman et al., 2009b; Reyenga et al., 1999b).

Uncertainty in terms of changes in the impacts of wheat diseases and pathogens are addressed by Juroszek and Tiedemann (2013), who in a review of existing, fragmented studies found no clear signal or consensus on likely yield impacts and recommend further research. The methodologies reported on were mostly speculative and indicative of varied disease impacts under future climate change – both positive and negative. None of the reviewed studies was undertaken in Africa. Likewise there seems to be little literature to provide any guidance to the significance of the impact of insect and other pests under changed conditions. Changes in temperature and moisture regimes are expected to have some changes on insect life-cycles, but likely impacts – particularly in the light of future technology advances in crop protection - are not clear.

We can state with some confidence that advances in technology have played the major role in wheat yield increases in the past (e.g. in terms of wheat cultivars, farming systems, improved and increased fertiliser use, weed control, crop protection and reduced tillage amongst others (Asseng and Pannell, 2013)). The authors conclude that even in the study region of Western Australia, already experiencing climate-change induced drying, there is no pressing need for farmers to make changes to their farming practices, but to continue with systems that mitigate year-to-year variability. Climate change indeed poses some opportunities for plant breeders to maximise benefits of increased $CO_2$, to adapt cultivars to optimise temporal changes in growing seasons and to develop cultivars adapted to warmer conditions. It is likely that by mid 21st century we will be facing unforeseen challenges in wheat production, but at the same time, given the rate of technology advances, we may be equipped to manage some of these challenges.

Socio-economic and political issues may have concerted effects on realisation of modelled future wheat production and yields. Strategic decisions on wheat imports, local food security strategies, insecurity of land tenure due to land redistribution and land reform, biofuels strategies, future economic conditions affecting wheat price versus input costs, trade policy related to tariffs and subsidies and conservation policy can all play a role on future wheat production in the South African context. Their impacts may occur at varying scales, both geographically and quantitatively, and are possibly not worth speculating further upon, decades in advance.

It seems fitting to close this chapter on a more positive (in one sense) note on climate change projections. During 1990, climate scientists from around the world wrote the First Assessment Report of the IPCC, that contained a projection of the global mean temperature trend over the 1990 – 2030 period. Currently as we are past halfway through that period, the GCM projections seem accurate (Frame and Stone, 2013). Measured increases in global mean temperatures and $CO_2$ levels are evidently tracking increasingly within central projections of the IPCC third and fourth assessments over the last five years (Rahmstorf et al., 2012). Whilst local variability will continue to obfuscate future projections due to the inherent chaos in weather systems (Deser et al., 2012), at least the physical science and broad climate change signal at a global scale level seems to be narrowing the envelope of uncertainties.

# Chapter Five: Perturbed baseline sensitivity analysis results

## 5.1 Introduction

The sensitivity analysis examines the modelled long-term yield response of wheat to the following perturbations of the baseline data for the control period 1979 to 1999:

- a temperature increase of 1°C and of 2°C respectively.
- a 10% increase and a 10% decrease in rainfall respectively.
- a temperature increase of 2°C with a 10% increase in rainfall and $CO_2$ levels elevated to 500 ppm.
- a temperature increase of 2°C with a 10% decrease in rainfall and $CO_2$ levels elevated to 500 ppm.
- a temperature increase of 2°C, unchanged rainfall and $CO_2$ levels at 500 ppm.

Given the strong evidence for future warming, and the reported synergies between warming and elevated $CO_2$ impacts on wheat (Ainsworth and Long, 2005; Idso and Idso, 1994), modelling meaningful yield responses to (climate change induced) temperature increase and precipitation changes should include the concomitant elevation of $CO_2$ levels to a value representative of the future study period. The single factor scenarios at baseline $CO_2$ levels are presented simply to assist in the understanding of the zonal yield responses.

## 5.2 Physiological responses to climate change factors as simulated in APSIM

The different impacts of climate change do not act independently but all interact with each other. To develop climate change adaptation strategies, it is important to develop an understanding of the interactions between different aspects of climate change and how these may vary with location. Whilst individual effects of higher temperatures, elevated $CO_2$ and rainfall changes are relatively well known, few studies have examined the less well understood interaction between these different effects (Ludwig and Asseng, 2006) and how these may vary spatially, at a local level.

### 5.2.1 General

APSIM calculates potential daily biomass production based on light interception and radiation-use efficiency. Suboptimal temperatures, water- and N-deficits can reduce the potential growth. The rate of advance of rooting depth is a function of air temperature, crop water stress, and soil water content in the soil layer with the deepest roots. Radiation use efficiency (RUE) in the context of this discussion refers to the net above ground biomass accumulation per unit intercepted radiation integrated over a specified period (Reyenga et al., 1999a).

### 5.2.2 Temperature impacts

Air temperature in the model affects several modelled processes including leaf area, growth, photosynthesis, senescence, root depth elongation and phenology. Increasing temperatures accelerate phenological development which results in a shorter growth period (Asseng et al., 2004). In rain-fed Mediterranean environments in favourable conditions, this may increase or decrease yields due to the avoidance or aggravation of terminal drought during grain filling – particularly under elevated $CO_2$ conditions (van Ittersum et al., 2003 Wang et al., 2009). Towards the end of the growing season, as evaporative demand increases rapidly due to falling relative humidity, increasing radiation and temperatures, and under decreasing rainfall, the consequence (especially in the shallow Western Cape soils) is marked post-anthesis water shortage (Asseng et al., 2008). There is an additional variation in modelled yields as the result of two temperature-driven mechanisms. Firstly, the occurrence of heat-stress events during grain filling accelerates crop senescence and reduces grain yields, and secondly, increases in crop evapotranspiration arising from increased maximum temperatures during vegetative growth reduce the availability of soil moisture later in the season, and can induce significant yield losses from water shortage during grain filling (Asseng et al., 2011). This phenomenon seemed to play a role in a number of RHFAs in the shallow soils of the Western Cape, particularly as high nitrogen levels at application promote early vigour, large canopy growth and thus higher evapotranspiration. The model temperature thresholds are presented by Keating et al, (2003).

### 5.2.3 Water impacts

Potential water demand is a function of transpiration efficiency and vapour pressure deficit (Monteith, 1988). Vertical soil water movement is simulated using a multilayered soil model primarily using a cascading approach, with movement both up and down also occurring by diffusive flow. Water (deficit) stress reduces tillering, leaf area index (LAI) and photosynthesis, and enhances senescence – modelled in APSIM (Asseng et al., 2011). Water stress (Fw) is calculated as a fraction of available soil water in the root zone. Levels and thresholds of Fw also determine the rates of leaf growth, tillering, photosynthesis and root depth elongation. Waterlogging resulting from a perched water table can be simulated by adjusting flow parameters (swcon and mwcon) which penalise growth by enabling soil layers to become saturated for extended periods of time (Keating et al., 2003; Ludwig and Asseng, 2006).

### 5.2.4 $CO_2$ impacts

Generally, higher levels of atmospheric $CO_2$ increase wheat production due to higher rates of photosynthesis (and thus RUE) and increased water use efficiency. Elevated $CO_2$ has two main effects on crop physiological development. It increases the intercellular $CO_2$ concentration leading to increased net photosynthesis rates and at the same time reduces stomatal conductance, resulting in reduced transpiration. The reduction in stomatal conductance with increasing $CO_2$ levels is well documented (Asseng et al., 2004; Reyenga et al., 1999a).

In APSIM, to model these implications of elevated $CO_2$ the RUE was scaled by the ratio of light-limited photosynthetic response at enhanced $CO_2$ compared with current (when the model was developed, 350 ppm). The methodology and formula are presented in Ludwig and Asseng (2006).

While the increased net photosynthesis rates directly affect RUE, the increased net photosynthesis under reduced crop transpiration also has an impact on transpiration efficiency (TE) (Asseng et al., 2004). TE was linearly scaled when $CO_2$ increases from 350 to 700 ppm (van Ittersum et al., 2003a). Water stress, N stress and temperature all influence modelled RUE and TE indirectly through their effects on photosynthesis.

Certain long-term feedback effects may exist, which are not accounted for in the model. In dry years, the additional leaf area development under high $CO_2$ may reduce soil evaporation slightly thus increasing soil moisture and allowing increased transpiration over the ambient $CO_2$ regime (Reyenga et al., 1999a).

### 5.2.5 Combined impacts

Where precipitation remains constant and the yield increase under the combined change of temperature and $CO_2$ concentration is generally lower than the *sum* of yield changes under individual increase in temperature and $CO_2$, the results may be due to the “haying off” effect. Higher $CO_2$ concentration and higher temperature in concert, enhance early crop growth and more crop water use during the early growth stages, therefore aggravate the terminal drought (van Herwaarden et al. 1998; Asseng et al. 2004). Yield reductions would also occur if critical temperature thresholds – particularly during grain filling - were exceeded.

These complex interactions also suggest that the response of crop growth to the same climate change scenario would vary significantly between locations and adaptation strategies need to be spatially explicit (Wang et al., 2009). This was indeed evident (see Table 5.4 where the deeper soil, higher rainfall areas (Gemengde Boerderygebied, Hoe Reenval Saaigebiedengde, Agter-Paarl) showed positive responses to the concerted impacts compared to some of the poorer production RHFAs such as Bo-Langkloof and Stockwell which showed negative responses (see also Section 5.6).

A hierarchy of growth factors determines the effects of growth conditions on crop growth in the model. If water and nitrogen are non-limiting, radiation and RUE determine crop growth. If water is limiting, TE and water availability determine crop growth, while combinations of radiation, RUE, soil water, TE and nitrogen availability explain crop growth if nitrogen is also limiting (Ludwig and Asseng, 2006). Initially the APSIM model was run with high N applications in this thesis, to focus only on the climate change-induced impacts of changing soil water balance, TE and RUE. An analysis of future yield scenarios (downscaled GCM ensemble) under different N-application levels subsequently provided an opportunity to further explore simulation in a nitrogen-limited environment (see Section 6.6).

The results of APSIM model testing in literature found the model capable of simulating, in principle, a range of experiments with combinations of rising temperatures, various levels and periods of water stress, elevated atmospheric $CO_2$ and changing N supply (Asseng et al., 2004; Wang et al., 2009). Effects of higher temperatures, elevated $CO_2$ and changed rainfall were in general not linear and differed significantly between locations (Ludwig and Asseng, 2006)

## 5.3 Crop responses to temperature increases per RHFA

Table 5.1 and Figure 5.1 present results for the APSIM wheat model runs driven by the perturbed baseline daily climate data for each zone. Observed daily temperatures were perturbed by 1°C and 2°C for each set of RHFA model runs.

Table 5.1. Modelled zonal yield responses to single factor perturbations of baseline temperature of +1 and +2°C respectively ( baseline period 1979 – 1999).

| RHFA | Baseline (kg/ha/annum) | Yield anomalies Δ Yield +1 °C (%) | Δ Yield +2 °C (%) |
|---|---|---|---|
| Agter-Paarl | 2861 | 0.2 | -4.6 |
| Bo-Langkloof | 1918 | -10.3 | -19.8 |
| Bredasdorp/Strandveldvlakte | 2709 | -9.0 | -20.7 |
| Gemengde Boerderygebied | 3681 | -1.2 | -10.0 |
| Gourits-Rooiruens | 1990 | -10.3 | -17.9 |
| Gouritzriviervallei | 1897 | -9.5 | -17.8 |
| Graafwater/Sandveld | 1104 | -2.9 | -10.2 |
| Hardeveld | 429 | -0.8 | -2.2 |
| Hermon/Gouda | 3145 | -1.6 | -11.2 |
| Hoe Reenval Saaigebied | 3443 | -8.2 | -18.1 |
| Kamanassie | 1395 | -11.8 | -16.4 |
| Kleinberg/Suurrug | 1781 | -10.9 | -18.4 |
| Koringberg/Rooi Karoo Saaigebied | 1841 | -7.4 | -15.2 |
| Malgas/Heidelbergvlakte | 1741 | -8.9 | -19.4 |
| Middel Swartland Saaigebied | 3442 | -6.1 | -16.3 |
| Ruens East | 1911 | -6.7 | -15.7 |
| Ruens West | 3051 | -8.8 | -17.3 |
| Sandveld Saaigebied | 1676 | 6.7 | 8.7 |
| Stockwell | 1161 | -9.1 | -16.5 |
| Tulbagh/Wolseley | 2896 | -0.3 | -3.7 |
| Urionskraal | 635 | 0.2 | -3.1 |
|  | Average | -5.5 | -12.7 |
|  | 90th percentile | 0.2 | -3.1 |
|  | 10th percentile | -10.3 | -19.4 |
|  | Median | -7.4 | -16.3 |
|  | Max | 6.7 | 8.7 |
|  | Min | -11.8 | -20.7 |
|  | Range | 18.4 | 29.4 |

The range of the yield decreases are broadly consistent with the rates of yield decline with increasing temperature from various studies reported on by Semenov et al.,(2012). The zones showing the greatest negative yield responses to the +2°C perturbation were the Bredasdorp/Strandveldvlakte, Bo-Langkloof and Malgas/Heidelbergvlakte RHFAs. All of these zones are in the south or south-east of the province. The zones to the north and east of the province generally exhibited a lower sensitivity to the temperature perturbation with the Sandveld Saaigebied actually showing increased yields and the

Hardeveld, Urionskraal and Tulbagh/Wolseley RHFA showing only slight reductions under warmer conditions. Figure 5.2 presents the spatial impact of these temperature perturbations on the province’s wheat RHFAs.

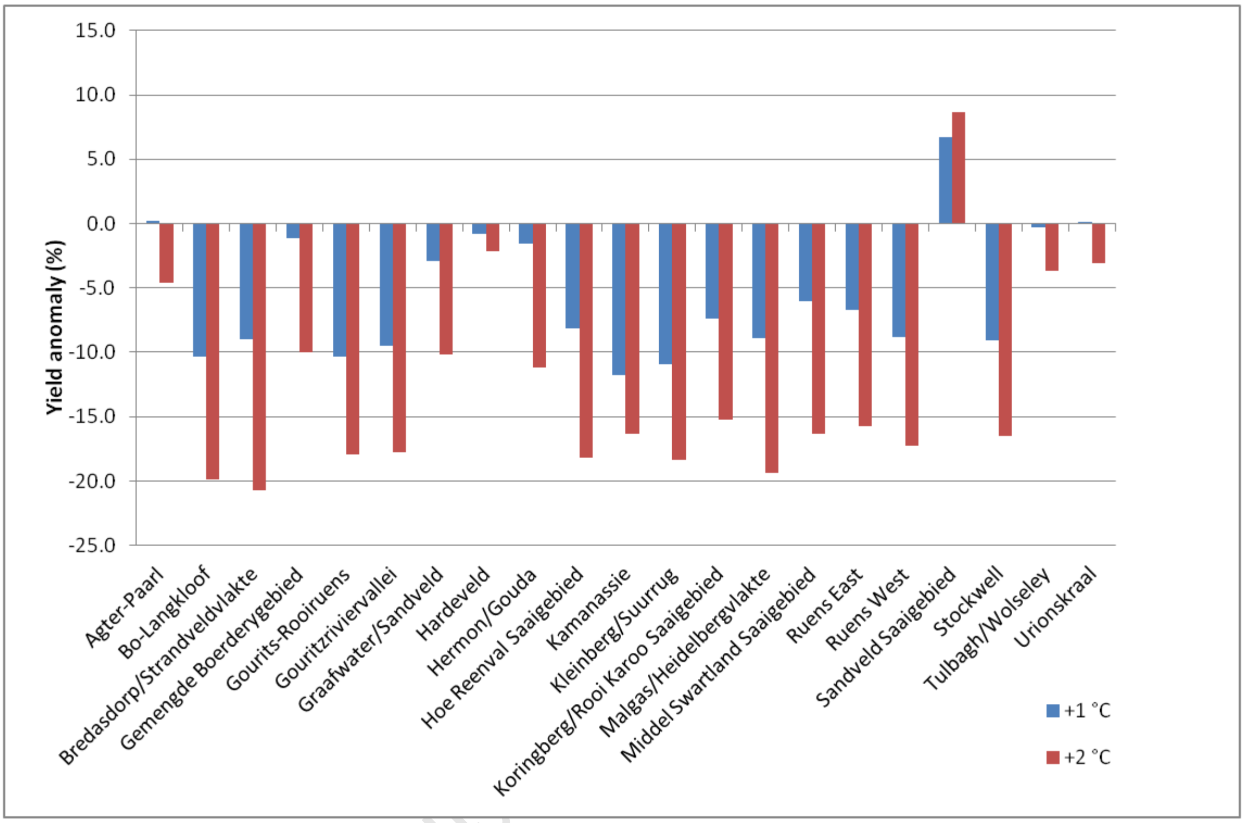

Figure 5.1. Modelled zonal yield responses to single factor perturbations of baseline temperature of +1 and +2°C respectively (baseline period 1979 – 1999).

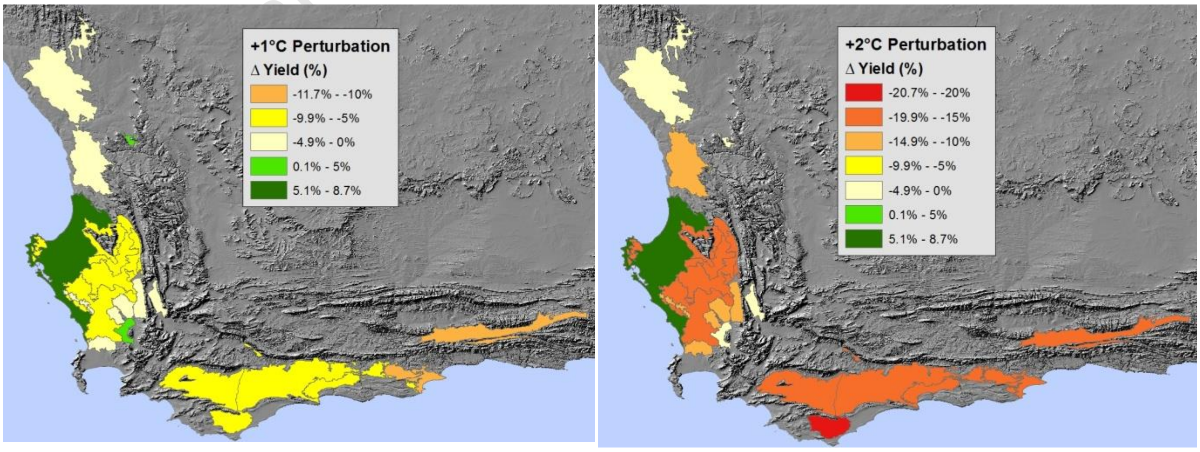

Figure 5.2. Modelled yield response to a +1 and +2°C perturbation of baseline temperature respectively ( baseline period 1979 – 1999).

## 5.4 Crop responses to rainfall perturbations per RHFA

The baseline climate per RHFA was modified by perturbing the observed rainfall by -10% and +10% respectively and the results used to drive the APSIM wheat model. Resulting impacts on zonal yields are presented in Table 5.2 and Figure 5.3.

Table 5.2. Modelled zonal yield responses to single factor perturbations of baseline rainfall of -10% and +10% respectively (baseline period 1979 – 1999).

| RHFA | Baseline (kg/ha/annum) | Yield anomalies Δ Yield -10% (%) | Yield anomalies Δ Yield +10% (%) |
|---|---|---|---|
| Agter-Paarl | 2861 | 0.9 | -2.9 |
| Bo-Langkloof | 1918 | -9.2 | 12.2 |
| Bredasdorp/Strandveldvlakte | 2709 | -28.5 | 12.1 |
| Gemengde Boerderygebied | 3681 | 2.5 | -3.1 |
| Gourits-Rooiruens | 1990 | -13.6 | 9.2 |
| Gouritzriviervallei | 1897 | -7.5 | 5.8 |
| Graafwater/Sandveld | 1104 | -19.7 | 22.4 |
| Hardeveld | 429 | -34.3 | 38.5 |
| Hermon/Gouda | 3145 | 3.3 | -2.9 |
| Hoe Reenval Saaigebied | 3443 | 1.4 | -3.5 |
| Kamanassie | 1395 | -11.2 | 12.3 |
| Kleinberg/Suurrug | 1781 | -13.4 | 12.6 |
| Koringberg/Rooi Karoo Saaigebied | 1841 | -21.5 | 15.6 |
| Malgas/Heidelbergvlakte | 1741 | -19.9 | 17.3 |
| Middel Swartland Saaigebied | 3442 | 0.8 | -2.3 |
| Ruens East | 1911 | -14.1 | 14.0 |
| Ruens West | 3051 | -10.9 | 2.3 |
| Sandveld Saaigebied | 1676 | -0.5 | -4.6 |
| Stockwell | 1161 | -20.1 | 18.2 |
| Tulbagh/Wolseley | 2896 | 0.0 | -2.4 |
| Urionskraal | 635 | -28.8 | 33.7 |
|  | Average | -11.6 | 9.7 |
|  | 90th percentile | 1.4 | 22.4 |
|  | 10th percentile | -28.5 | -3.1 |
|  | Median | -11.2 | 12.1 |
|  | Max | 3.3 | 38.5 |
|  | Min | -34.3 | -4.6 |
|  | Range | 37.6 | 43.1 |

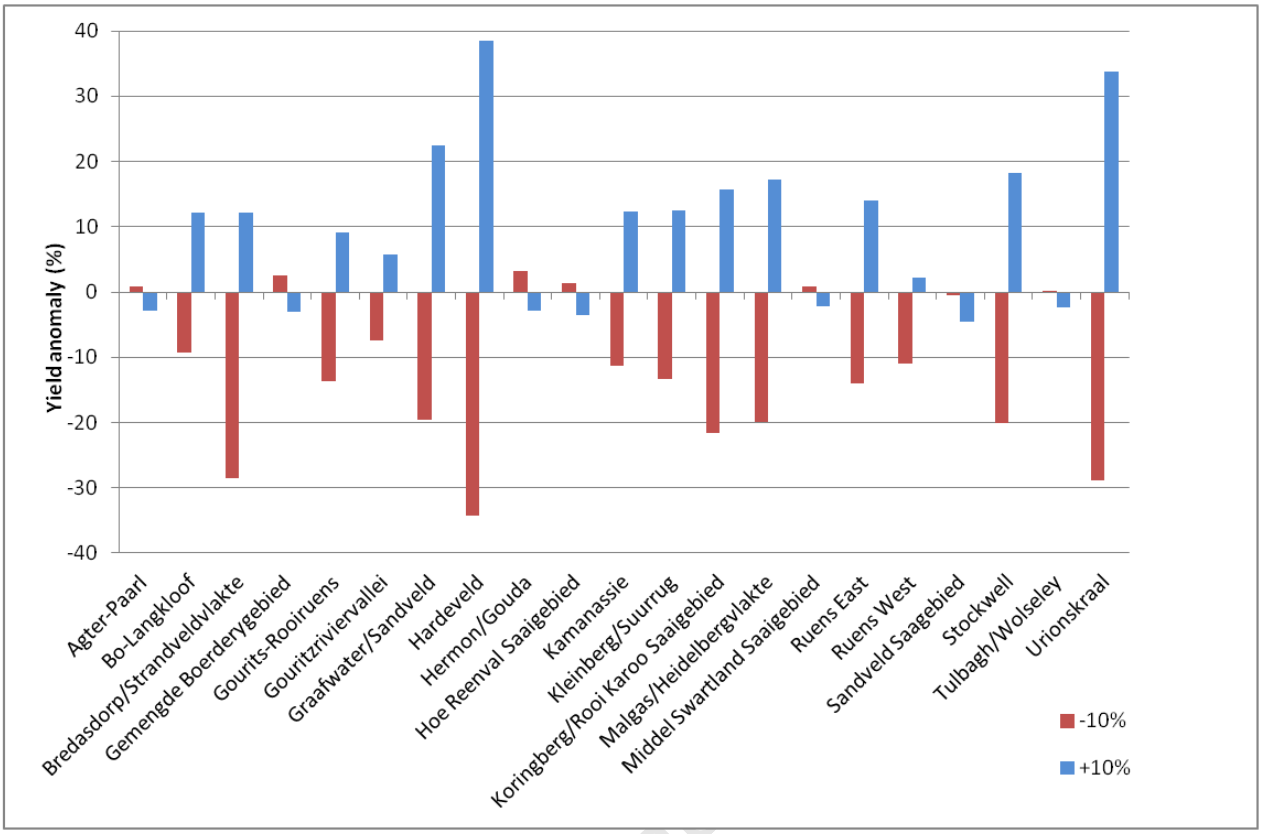

Figure 5.3. Modelled zonal yield responses to single factor perturbations of baseline rainfall of -10% and +10% respectively (baseline period 1979 – 1999).

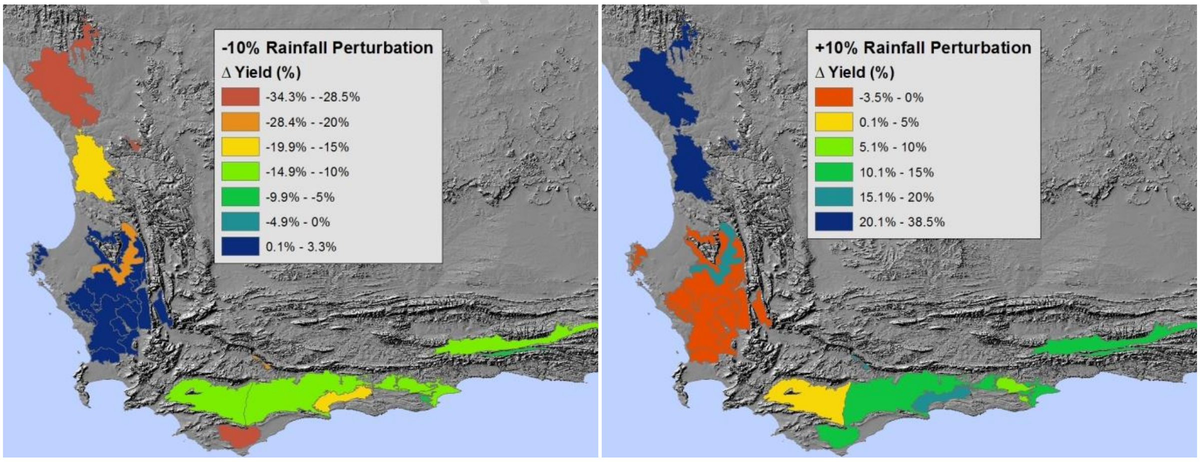

Figure 5.4. Modelled zonal yield responses to single factor perturbations of baseline rainfall of -10% and +10% respectively (baseline period 1979 – 1999).

Yield responses to the reduced rainfall perturbation were generally positive in the Swartland RHFAs where waterlogging conditions in the higher-clay soils can impair yields. Similar responses on duplex soils was reported by Ludwig and Asseng (2006). The exception (in the Swartland) was the Koringberg/Rooi Karoo, which showed a high sensitivity to reduced rainfall, in contrast with its neighbours. The remaining areas showed reduced yield under modelled drier conditions, with the Bredasdorp/Strandveldvlakte and the dry areas of Hardeveld and Urionskraal showing the largest yield reductions under drier conditions.

Accordingly, the Swartland zones did not respond favourably to increased rainfall with the exception of Koringberg/Rooi Karoo. The most favourable yield responses under wetter conditions were evident in the Hardeveld and Urionskraal RHFAs.

## 5.5 Crop responses to combined perturbations per RHFA at elevated $CO_2$ levels

Complex, non-linear interactions exist between $CO_2$, temperature and rainfall effects on wheat growth (van Ittersum et al., 2003a) and see Section 5.2.5. The results of three sensitivity analyses (Table 5.3 and Figure 5.5) were derived by driving the APSIM wheat model with a combined-factor, perturbed, daily baseline climate. In all three cases, temperatures were increased by 2°C, $CO_2$ levels were all set to 500 ppm, whilst rainfall was modified as follows for each of the 3 model runs per zone respectively:

- rainfall decreased by 10%
- rainfall unchanged
- rainfall increased by 10%

It was clear from the results that $CO_2$ elevation played a role in substantially mitigating against losses due to temperature increases. Whilst the median yield anomaly across all zones for the single factor +2°C perturbation was -16.3% (see Table 5.1), the corresponding median value, where $CO_2$ was elevated to 500 ppm (unchanged rainfall), improved to 1.5% (see Table 5.3). Even under an unaltered rainfall regime and hotter conditions, yields in the Urionskraal and Hardeveld appear to benefit the most from increased $CO_2$ levels.

Again, rainfall increases had negative yield impacts on some of the Swartland zones. Under warmer conditions, modelled waterlogging conditions are reduced and these negative impacts were thus correspondingly smaller in each case.

Table 5.3. Modelled zonal crop responses to combined factor perturbations (increase of 2°C, $CO_2$ elevated to 500 ppm and rainfall perturbed as indicated in column header). (Baseline period 1979 – 1999)

| **RHFA** | Baseline (kg/ha/annum) | Yield anomalies | | |
|---|---|---|---|---|
| | | Rainfall -10% | Rainfall unchanged | Rainfall +10% |
| | | (%) | (%) | (%) |
| Agter-Paarl | 2861 | 3.9 | 3.6 | 0.4 |
| Bo-Langkloof | 1918 | -13.4 | -5.8 | 4.1 |
| Bredasdorp/Strandveldvlakte | 2709 | -28.3 | 1.5 | 12.3 |
| Gemengde Boerderygebied | 3681 | 4.6 | 4.0 | 0.9 |
| Gourits-Rooiruens | 1990 | -12.1 | -1.3 | 7.6 |
| Gouritzriviervallei | 1897 | -12.2 | -1.4 | 7.9 |
| Graafwater/Sandveld | 1104 | -12.1 | 8.2 | 31.8 |
| Hardeveld | 429 | -22.8 | 16.8 | 60.8 |
| Hermon/Gouda | 3145 | 6.0 | 4.0 | 1.1 |
| Hoe Reenval Saaigebied | 3443 | 1.3 | 0.9 | -1.5 |
| Kamanassie | 1395 | -10.1 | -3.7 | 8.4 |
| Kleinberg/Suurrug | 1781 | -16.4 | -4.1 | 6.3 |
| Koringberg/Rooi Karoo Saaigebied | 1841 | -14.0 | 2.2 | 16.1 |
| Malgas/Heidelbergvlakte | 1741 | -16.9 | 0.1 | 15.2 |
| Middel Swartland Saaigebied | 3442 | 1.2 | 0.1 | -1.8 |
| Ruens East | 1911 | -7.7 | 4.3 | 16.4 |
| Ruens West | 3051 | -9.1 | -1.1 | 1.9 |
| Sandveld Saaigebied | 1676 | 7.3 | 9.2 | 4.8 |
| Stockwell | 1161 | -20.6 | 0.5 | 21.9 |
| Tulbagh/Wolseley | 2896 | 6.6 | 6.3 | 5.1 |
| Urionskraal | 635 | -19.2 | 14.5 | 53.9 |
| | Average | -8.8 | 2.8 | 13.0 |
| | 90th percentile | 6.0 | 9.2 | 31.8 |
| | 10th percentile | -20.6 | -3.7 | 0.4 |
| | Median | -12.1 | 1.5 | 7.6 |
| | Max | 7.3 | 16.8 | 60.8 |
| | Min | -28.3 | -5.8 | -1.8 |
| | Range | 35.6 | 22.6 | 62.6 |

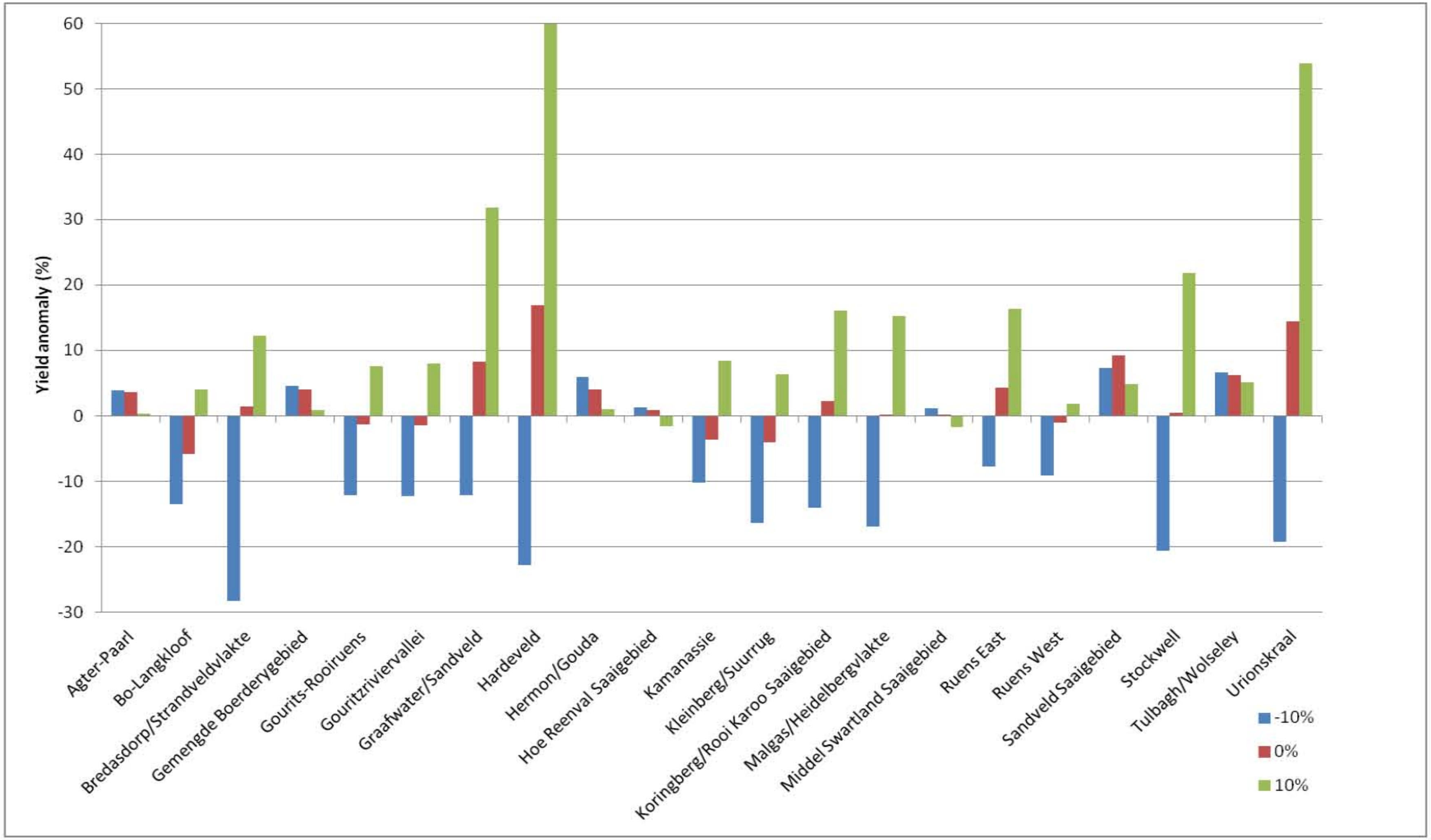

Figure 5.5. Modelled zonal crop responses to combined perturbations (increase of 2°C, $CO_2$ elevated to 500 ppm and rainfall perturbed from the 1979 -1999 baseline as indicated in the legend).

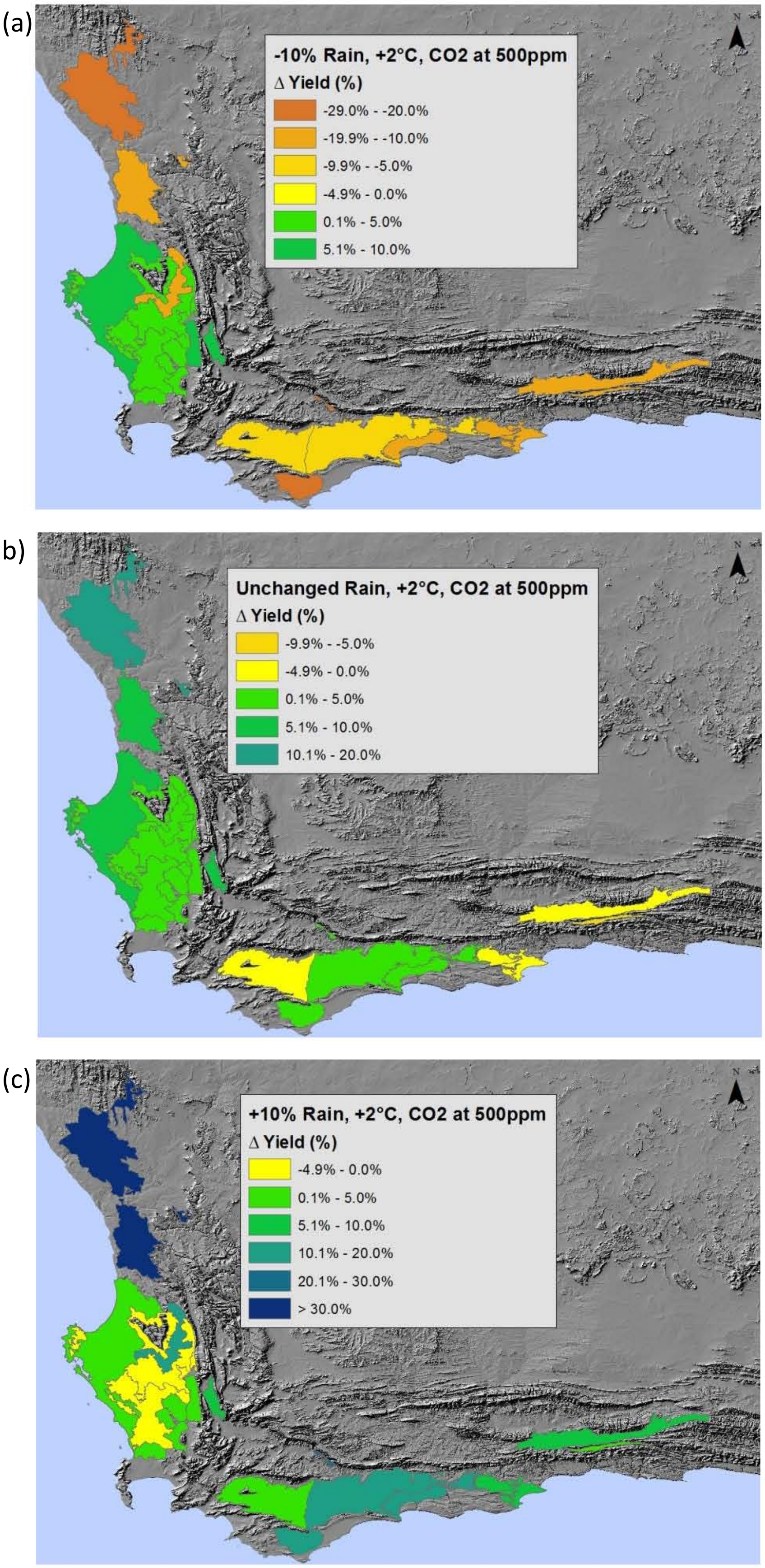

Figure 5.6. Modelled yield responses to perturbations of baseline climate data of +2°C, $CO_2$ set at 500 ppm and three rainfall scenarios (a) rainfall decreases by 10%, (b) rainfall unchanged from baseline (1979 – 1999) and (c) rainfall increases by 10%.

## 5.6 Comparing concerted versus additive modelled yield impacts

Comparing the differences between the additive single parameter perturbations and their modelled combined or concerted impacts allows some further exploration of the combined impacts mentioned in Section 5.2.5 (see Table 5.4).

Table 5.4. Comparison between added single-factor perturbations and their combined effect at 3 rainfall perturbations. Positive values are in green, negative values in red. The 150 ppm is the difference between baseline (350 ppm) and the perturbation at 500 ppm.

| | Baseline yield (kg/ha/annum) | Rainfall unchanged | | | + 10% Rainfall | | | - 10% Rainfall | | | SD of Yield impact diff (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Added 2°C+150ppm CO2 (Δ kg/ha/annum) | Concerted 2°C&150ppm CO2 (Δ kg/ha/annum) | Concerted Yield impact difference (%) | Added 2°C+150ppm CO2 (Δ kg/ha/annum) | Concerted 2°C&150ppm CO2 (Δ kg/ha/annum) | Concerted Yield impact difference (%) | Added 2°C+150ppm CO2 (Δ kg/ha/annum) | Concerted 2°C&150ppm CO2 (Δ kg/ha/annum) | Concerted Yield impact difference (%) | |
| Agter-Paarl | 2861 | 41 | 104 | 2 | -42 | 11 | 2 | 66 | 111 | 2 | 0.3 |
| Bo-Langkloof | 1918 | 14 | -112 | -7 | 247 | 78 | -9 | -163 | -257 | -5 | 1.6 |
| Bredasdorp/Strandveldvlakte | 2709 | 14 | 40 | 1 | 343 | 332 | 0 | -759 | -766 | 0 | 0.6 |
| Gemengde Boerderygebied | 3681 | -180 | 148 | 9 | -292 | 32 | 9 | -87 | 169 | 7 | 0.9 |
| Gourits-Rooiruens | 1990 | 18 | -25 | -2 | 201 | 152 | -2 | -253 | -241 | 1 | 1.4 |
| Gouritzriviervallei | 1897 | -70 | -26 | 2 | 39 | 151 | 6 | -212 | -231 | -1 | 2.8 |
| Graafwater/Sandveld | 1104 | 120 | 91 | -3 | 367 | 351 | -1 | -97 | -133 | -3 | 0.8 |
| Hardeveld | 429 | 76 | 72 | -1 | 241 | 261 | 5 | -72 | -98 | -6 | **4.4** |
| Hermon/Gouda | 3145 | -118 | 126 | 8 | -208 | 34 | 8 | -15 | 189 | 6 | 0.6 |
| Hoe Reenval Saaigebied | 3443 | -264 | 30 | 9 | -385 | -52 | 10 | -217 | 44 | 8 | 0.9 |
| Kamanassie | 1395 | 14 | -51 | -5 | 186 | 118 | -5 | -143 | -141 | 0 | 2.3 |
| Kleinberg/Suurrug | 1781 | 27 | -73 | -6 | 251 | 113 | -8 | -211 | -292 | -5 | 1.3 |
| Koringberg/Rooi Karoo | 1841 | 105 | 41 | -3 | 392 | 296 | -5 | -292 | -257 | 2 | 3.0 |
| Malgas/Heidelbergvlakte | 1741 | 121 | 2 | -7 | 422 | 265 | -9 | -226 | -294 | -4 | 2.1 |
| Middel Swartland Saaigebied | 3442 | -156 | 4 | 5 | -234 | -61 | 5 | -127 | 41 | 5 | 0.1 |
| Ruens East | 1911 | 178 | 82 | -5 | 446 | 313 | -7 | -91 | -147 | -3 | 1.6 |
| Ruens West | 3051 | -181 | -33 | 5 | -111 | 58 | 6 | -514 | -278 | 8 | 1.2 |
| Sandveld Saaigebied | 1676 | 23 | 155 | 8 | -53 | 81 | 8 | 15 | 122 | 6 | 0.7 |
| Stockwell | 1161 | 145 | 5 | -12 | 356 | 254 | -9 | -88 | -240 | -13 | 1.8 |
| Tulbagh/Wolseley | 2896 | 138 | 182 | 2 | 70 | 147 | 3 | 139 | 190 | 2 | 0.5 |
| Urionskraal | 635 | 97 | 92 | -1 | 312 | 343 | 5 | -86 | -122 | -6 | **4.3** |

The modelled concerted influence generally modified the added single perturbation impacts of the same factors by a factor between -10% and +10%, except for Stockwell, where the changed response reached -13%. The highest standard deviation between concerted and added responses at the 3 rainfall levels were in the highly marginal, dry areas of Hardeveld and Urionskraal. In both zones the concerted simulations at higher rainfall, higher $CO_2$ and increased temperature most likely allowed the wheat to make better use of the high levels of nitrogen early in the season, whilst in the drier regime, haying-off impact would occur as the crop depleted soil moisture earlier, thus exacerbating the terminal drought. The higher-clay, ("wetter") duplex soils of the Swartland zones (e.g. Hoe Reenval Saaigebied, Hermon/Gouda) generally showed a greater concerted response under all regimes, compared with the additive single perturbation impacts. Rûens West fares better than its Rûens East neighbour in the concerted scenarios, likely a result of the accelerated growth moving the ripening period forward and thus avoiding terminal drought (rainfall in Rûens East tends to increase during October due to the influence of the greater summer rainfall component). Under constant (high application) nitrogen levels, these localised, and non-linear responses appear to be largely a consequence of the following modelled interactions (Asseng et al., 2004; Wang et al., 2009):

- concerted impacts greater than additive impacts suggest that temperature increase interactions reduce the negative impact of water deficit stress on crop growth, by accelerating phenology and shifting the grain filling period forward and away from terminal drought, or
- yield increases under the combined change of temperature and $CO_2$ concentration are lower than the sum of yield changes under individual increase in temperature and $CO_2$ due to the enhanced “haying off” effect (van Herwaarden et al., 1998). Higher $CO_2$ concentration and higher temperature (under high nitrogen conditions) enhance early crop growth and increase crop water use during the early growth stages, thereby aggravating the terminal drought.

Discussion of the sensitivity single factor and combined yield responses is presented in the following results per RHFA.

## 5.7 Sensitivity analysis per RHFA

### 5.7.1 Primary wheat zones

#### Agter-Paarl

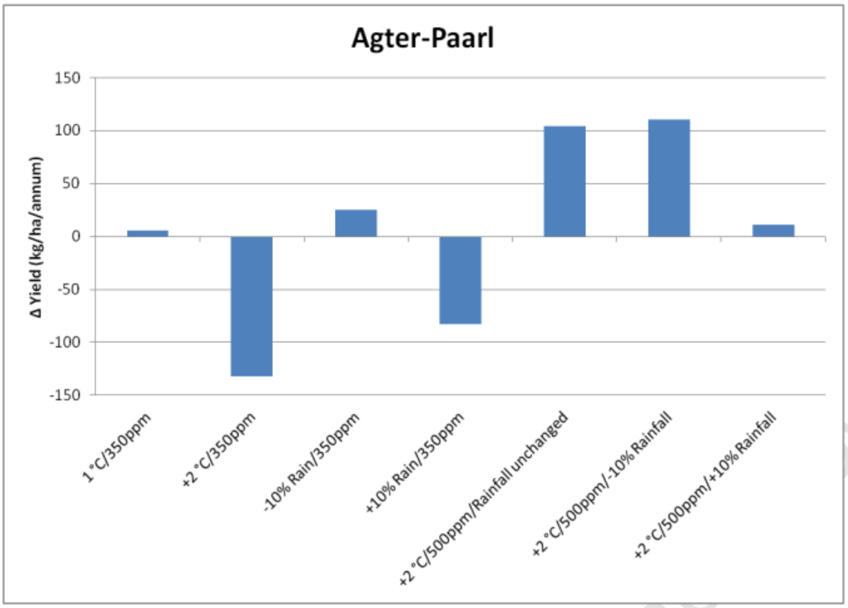

Figure 5.7. Sensitivity analysis for the Agter-Paarl RHFA.

A slight increase in yield results from a 1°C increase in temperature, but any further temperature increase has a limiting effect. The simulated single factor 10% reduction in rainfall has a *beneficial* effect. The area is subject to waterlogging problems during wet winters which explains this phenomenon here and in some of the neighbouring RHFAs where the model simulates yield reductions resulting from plant stresses under waterlogged conditions[19].

In reality, much of the wheat, particularly on areas of flatter topography, is cultivated in extensive raised beds or ridge-and-furrow field structures to facilitate drainage (see Figure 2.4). This existing adaptation method is likely to reduce the modelled negative impact of increasing moisture in many parts of the RHFA where these structures are created or maintained. In the combined perturbation scenario for this zone, increasing

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[19] The ability of APSIM to model this waterlogged or "perched water table" effect in duplex soils was made possible by the introduction of a parameter (mwcon) which controls the rate of water moving through macropores from the upper soil layer when the layers below are saturated, described in Asseng et al., (1998) and Ludwig and Asseng (2006).

carbon levels to 500 ppm, more than compensated for yield losses due to the 2 degree temperature increase at all three levels of perturbed rainfall in the combined scenarios.

Hoë Reënval Saaigebied

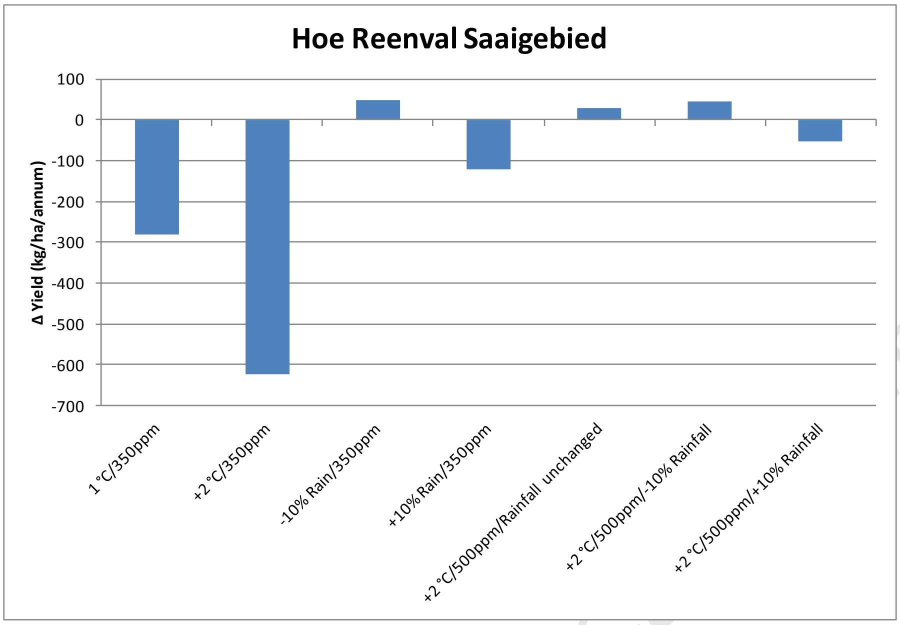


Figure 5.8. Sensitivity analysis for the Hoe Reenval Saaigebied.

This zone showed a clear negative response to temperature increases, whilst the reduced rainfall was slightly beneficial as with Agter-Paarl, due to the resulting reduction in plant stress waterlogging conditions. The combined parameter perturbation scenarios for this zone resulted in positive yield responses for the decreased and unchanged rainfall, whereas the combined scenario with increased rainfall produced a slight modelled yield reduction. This zone showed one of the highest sensitivities in terms of the moderating impacts of increased $CO_2$ and temperature on the large negative impact of the 2°C temperature increase (see Table 5.4), likely as a result of rapid crop development under sufficient soil moisture conditions leading to earlier ripening and avoidance of the terminal drought during the ripening phase (Wang et al., 2009).

Hermon/Gouda

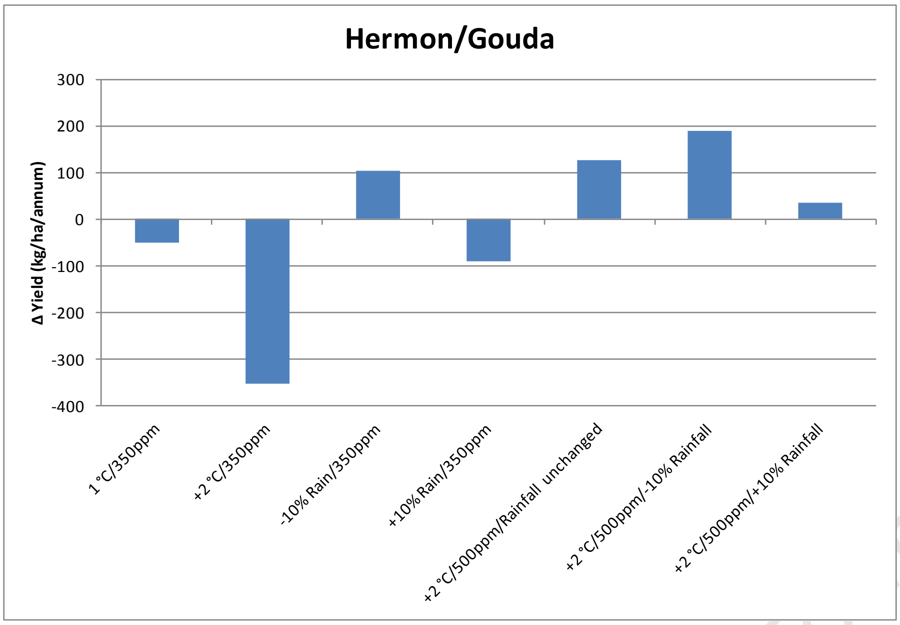


Figure 5.9. Sensitivity analysis for Hermon/Gouda RHFA

This zone showed a negative response to temperature increases, whilst the reduced rainfall was again slightly beneficial as would be expected in an area that suffers waterlogging conditions during wet periods. As with Agter-Paarl there are many areas where structures such as raised beds have been developed to improve field drainage. The combined scenarios produced an overall slight increase in yields in all cases.

In common with its neighbour, Hoe Reenval Saaigebied, Hermon/Gouda showed one of the highest sensitivities in terms of the moderating impacts of increased $CO_2$ and temperature on the large negative impact of the 2°C temperature increase (see Table 5.4).

Middel Swartland Saaigebied

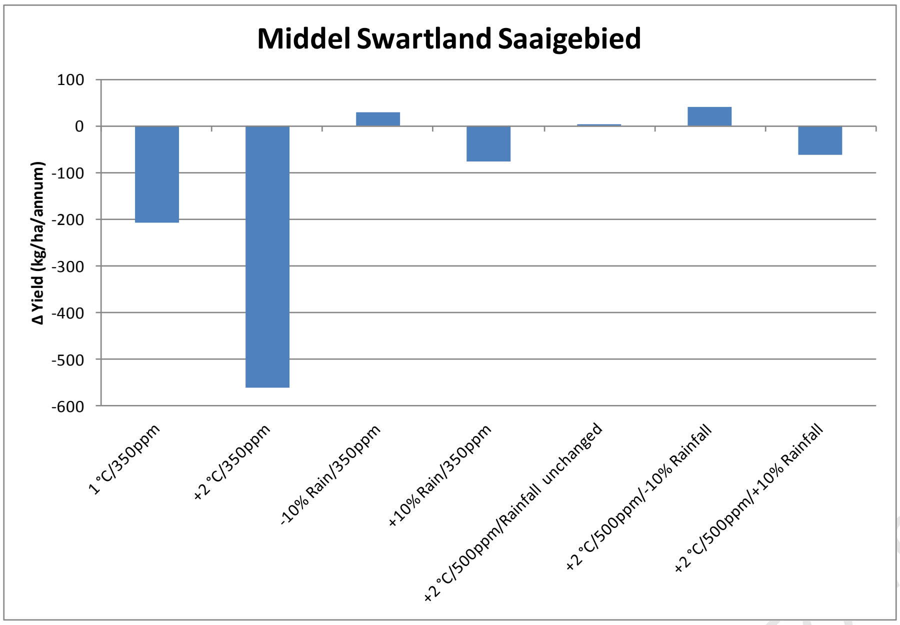


Figure 5.10. Sesitivity analysis for Middel Swartland Saaigebied

This zone showed a high sensitivity to the 2°C temperature increase from 1°C to 2°C. The impact of increased atmospheric carbon levels did however compensate for the negative impacts of this increase. As with its neighbouring RHFAs with problematic drainage in wet conditions, the zone showed a small positive response to the 10% rainfall decrease. The combined perturbations produced very small changes to baseline yield, being negative only in the combined scenario with *increased* rainfall - again a consequence of the duplex soils in the region which are appropriately modelled to be prone to waterlogging.

Gemengde Boerderygebied

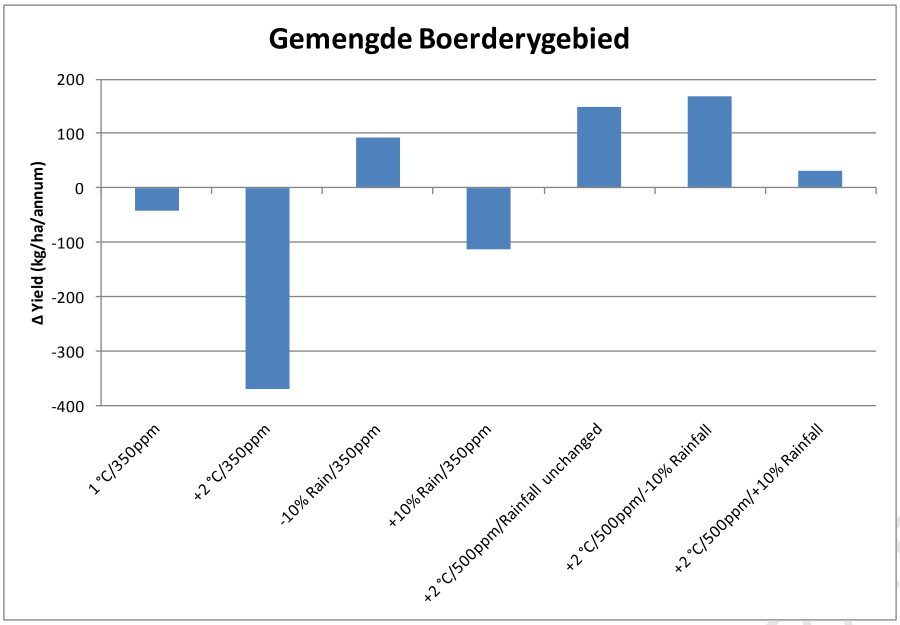


Figure 5.11. Sensitivity analysis for Gemengde Boerderygebied

This zone showed strong negative responses to average temperature increases above 1°C, whilst the reduced (single factor) rainfall was marginally beneficial as with other Swartland zones where soil drainage can be problematic particularly on the high clay content duplex soils common in the area. The combined scenarios with elevated $CO_2$ produced relatively small increases in yield in all cases, demonstrating the strongly beneficial influence of $CO_2$ in compensating for negative impacts due to increased temperatures.

As with its Swartland neighbours Hoe Reenval Saaigebied and Hermon/Gouda, Gemengde Boerderygebied demonstrated one of the highest sensitivities in terms of the moderating impacts of a concerted increased $CO_2$ and temperature on the large negative impact of the 2°C temperature increase (see Table 5.4).

Koringberg/Rooikaroo Saaigebied

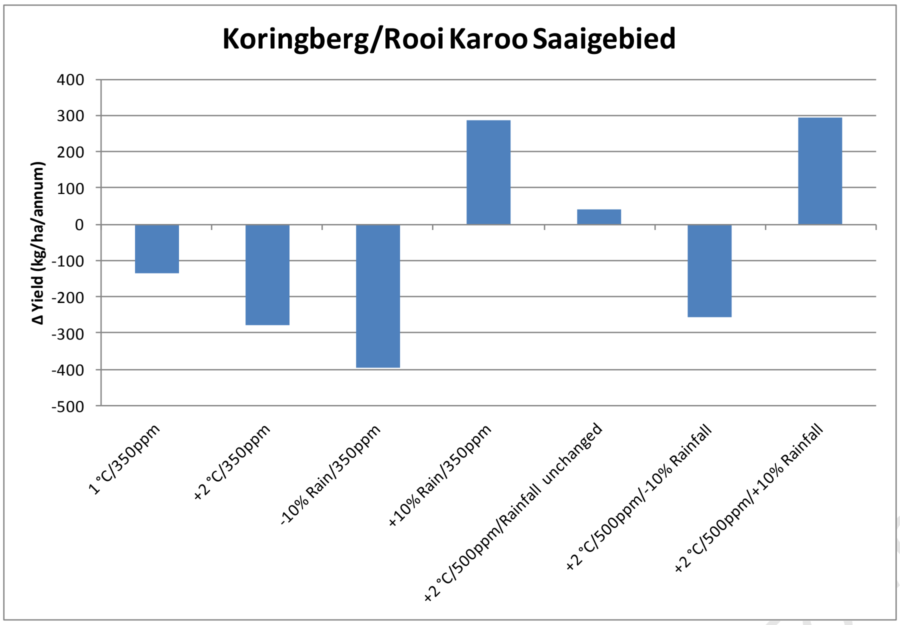


Figure 5.12. Sensitivity analysis for Koringberg/Rooikaroo Saaigebied.

Whilst the preceding RHFAs can all be considered relatively reliable wheat areas, the Koringberg/Rooikaroo is subject to considerable variations due to periodic drought conditions and low soil water holding capacity resulting from shallow soils. Increased temperature and reduced rainfall perturbations of the baseline demonstrated substantial sensitivity of in yield impacts in this zone. In an already drought-prone RHFA, any further reduction of the baseline precipitation has a strongly negative impact. In the combined perturbations the elevated $CO_2$ levels compensated for heat stresses except in the case where rainfall was reduced, which resulted in a 14% reduction in yield. In an economic study on a sample of grain subregions, Hoffmann (2010) considered this RHFA to be particularly vulnerable due to the risky performance of wheat, compared to other Swartland zones.

Rûens West

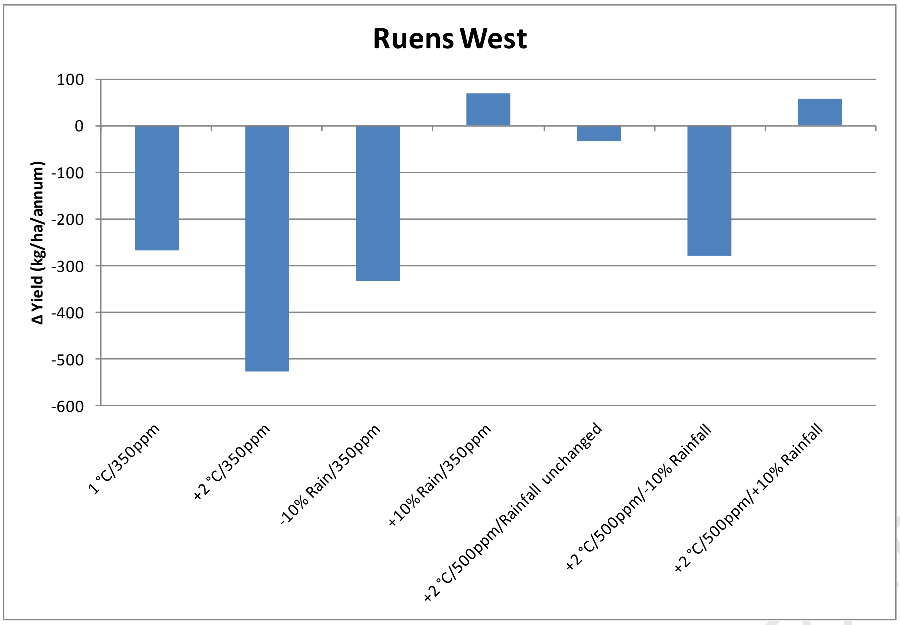


Figure 5.13. Sensitivity analysis for Rûens West

The zone exhibited a fairly high level of sensitivity to the single factor reduced rainfall and increased temperature perturbations, with increased carbon levels failing to compensate fully for losses due to increased temperature and reduced rainfall, but almost restoring the baseline yield where rainfall is unchanged. Yields are likely to increase under increased rainfall regimes. This high production potential area relies strongly on its regular rainfall and a moderate temperature regime to maintain adequate moisture levels in the generally shallow soils. The region appears to benefit slightly from the accelerated phenology modelled under combined increased temperature and increased $CO_2$, helping to move the grain-filling period into the wetter part of the season.

Rûens East

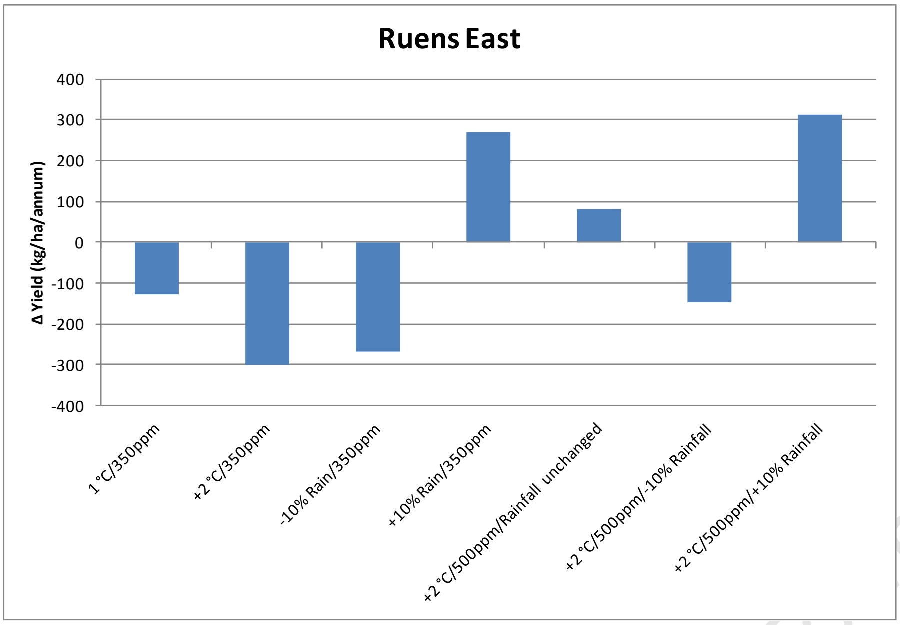


Figure 5.14. Sensitivity analysis for Rûens East

Increased temperatures and decreased rainfall resulted in negative yield impacts. The combined perturbations indicated that increased carbon levels would fail to compensate for losses due to increased temperature and reduced rainfall. Yields under increased rainfall are modelled to increase by 300kg/ha/annum (16.4% of baseline) however. This moderate production area is subject to periodic droughts as the relatively low rainfall is distributed through the whole year, and not predominantly in the winter months as it is further west. The soils are shallow, often with a high stone content. Any further drying would indeed be expected to result in plant stress.

Bredasdorp-Strandveldvlakte

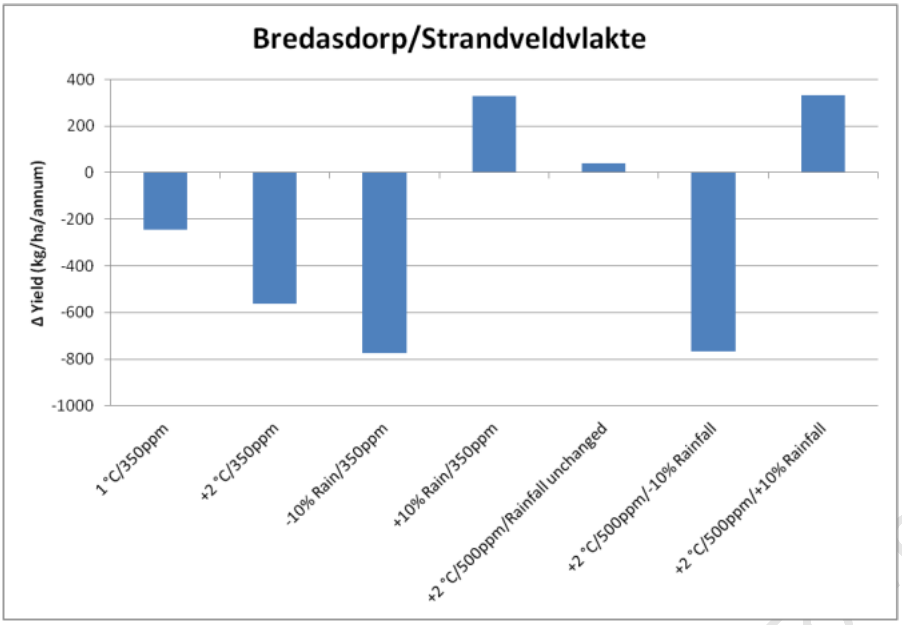


Figure 5.15. Sensitivity analysis for Bredasdorp/Strandveldvlakte

All perturbations where temperatures were increased and rainfall was decreased, resulted in substantial yield reductions. The area showed a very high sensitivity to a reduction in rainfall which would be expected given the reported low water holding capacity of the soil in this zone. The RHFA also exhibits high sensitivity to temperature increases, with a 2°C increase also resulting in a modelled loss of nearly 600kg/ha/annum. Under the combined perturbation conditions the effects of elevated $CO_2$ compensated for these negative impacts, except where rainfall was reduced. This is an extremely flat area and increases in rainfall are likely to impact upon harvesting machinery access.

Interestingly this zone showed the least difference between the added single factor perturbations of temperature, $CO_2$ and rainfall, and their concerted simulation (see Table 5.4).

Malgas-Heidelberg Plain

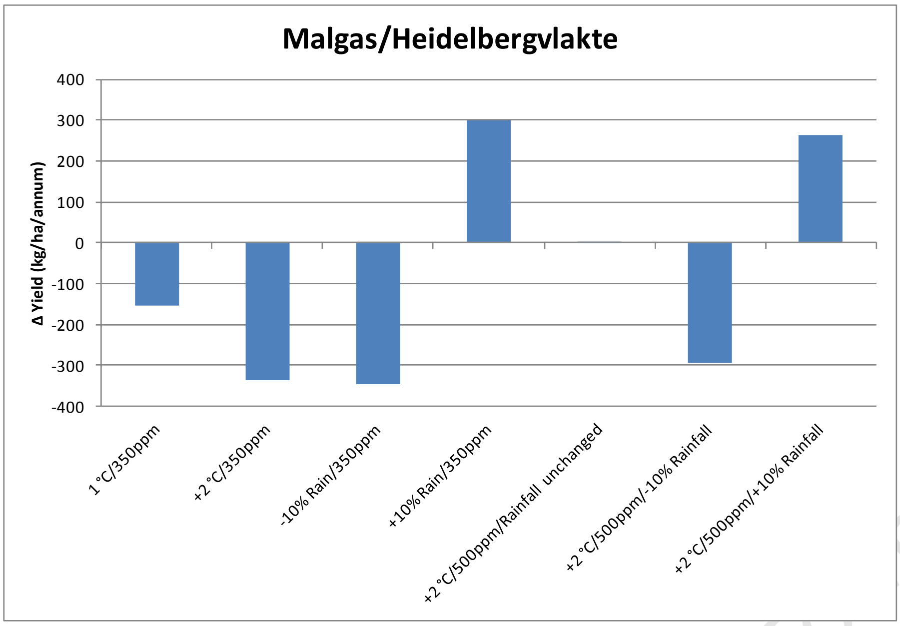


Figure 5.16. Sensitivity analysis for Malgas/Heidelbergvlakte.

The area exhibits a high sensitivity to a reduction in rainfall. Elevated $CO_2$ levels did however compensate for temperature-induced losses, provided the rainfall did not decline. The soils are known to have a low water holding capacity and rely heavily on well distributed rainfall through the growing season.

### 5.7.2 Secondary wheat zones

The graphic output for the secondary wheat zones is presented in Appendix V. Currently very low-production areas such as the Urionskraal and the Hardeveld showed strongly positive yield responses in sensitivity scenarios where rainfall increases as would be expected for these extremely moisture-limited zones. In both cases, unchanged rainfall in a warmer environment with elevated $CO_2$ actually resulted in yield increases due to the $CO_2$ effects consistent with the physiological impacts of elevated $CO_2$ in reducing moisture loss (see Section 5.2.4). These beneficial impacts are nonetheless low in terms of kilograms or tons per hectare, given the very low baseline yields evident in these areas.

Most of the western secondary wheat zones showed a high level of sensitivity to simulated rainfall decreases, with the Hardeveld, Urionskraal and Graafwater/Sandveld indicating reductions in modelled yield response, even when combined with elevated $CO_2$ in the perturbation scenarios.

Eastern secondary wheat zones such as Kleinberg-Suurrug, Kamanassie and Stockwell all exhibited sensitivity to the reduced rainfall perturbation scenario, with $CO_2$ impacts unable to compensate for yield losses due to warming.

Interestingly two of the western zones showed positive responses to (single factor) increases in temperatures, particularly the Sandveld Saaigebied. This is possibly a result of the west coast's landscape exposure to cold winter Atlantic breezes in the historical data which may have a suppressing effect on modelled (and observed) baseline yields.

The Tulbagh/Wolseley RHFA's response is noteworthy in that it showed very little sensitivity to temperature and rainfall single factor perturbations and also to the combination of increased temperature and precipitation. A resilient zone – the combined perturbations at all 3 rainfall levels led to improved yields – in particular, where rainfall was *reduced* by 10%.

## 5.8 The impact of elevated atmospheric $CO_2$ levels on modelled crop yield results

### 5.8.1 Introduction

During the literature review preceding this study (presented in Chapter 2) it became evident that the effects of $CO_2$ elevation were likely to have a significant impact on projected (modelled) future yield outcomes. The primary effects on plants of rising $CO_2$ have been documented and include (Ainsworth and Long, 2005; Wall, 2001):

- Reduction in stomatal conductance which reduces transpiration.
- Improved water-use efficiency.
- Higher rates of photosynthesis resulting in increased net assimilation in wheat leaves and ears.
- Increased light-use efficiency.

- Elevated $CO_2$ increases the ability of wheat plants to extract available soil water and nutrients (considered a *secondary* effect).

It also became evident during the crop modelling sensitivity analysis presented in Chapter Four that this impact had a wide range and was regionally specific.

### 5.8.2 Modelled $CO_2$ impacts

In the sensitivity analysis based on perturbation of baseline climate, in all RHFAs, the impact of elevating $CO_2$ levels (from 350 ppm to 500 ppm) in APSIM had a positive effect on wheat yield under warming of 2°C (summarised in Table 5.5 and mapped in Figure 5.17). These responses ranged from a low of 0.6% in the Sandveld Saaigebied to a high of 22.2% in the Bredasdorp/Strandveldvlakte RHFA.

Table 5.5. The modelled yield response to $CO_2$ elevation from 350 ppm to 500 ppm under a constant + 2°C perturbation of baseline temperature (rainfall unchanged from baseline). The Δ Yield column shows the difference between yield at 350 ppm and at 500 ppm expressed as a percentage of the baseline yield.

| **RHFA** | Baseline (kg/ha/annum) | Δ Yield +2 °C 350ppm CO2 (kg/ha/annum) | Δ Yield +2 °C 500ppm CO2 (kg/ha/annum) | Δ Yield % |
|---|---|---|---|---|
| Agter-Paarl | 2861 | -132 | 104 | 8.2 |
| Bo-Langkloof | 1918 | -380 | -112 | 14.0 |
| Bredasdorp/Strandveldvlakte | 2709 | -561 | 40 | 22.2 |
| Gemengde Boerderygebied | 3681 | -369 | 148 | 14.0 |
| Gourits-Rooiruens | 1990 | -357 | -25 | 16.7 |
| Gouritzriviervallei | 1897 | -337 | -26 | 16.4 |
| Graafwater/Sandveld | 1104 | -112 | 91 | 18.4 |
| Hardeveld | 429 | -9 | 72 | 19.0 |
| Hermon/Gouda | 3145 | -352 | 126 | 15.2 |
| Hoe Reenval Saaigebied | 3443 | -625 | 30 | 19.0 |
| Kamanassie | 1395 | -228 | -51 | 12.7 |
| Kleinberg/Suurrug | 1781 | -328 | -73 | 14.3 |
| Koringberg/Rooi Karoo Saaigebied | 1841 | -280 | 41 | 17.4 |
| Malgas/Heidelbergvlakte | 1741 | -338 | 2 | 19.5 |
| Middel Swartland Saaigebied | 3442 | -562 | 4 | 16.4 |
| Ruens East | 1911 | -300 | 82 | 20.0 |
| Ruens West | 3051 | -527 | -33 | 16.2 |
| Sandveld Saaigebied | 1676 | 145 | 155 | 0.6 |
| Stockwell | 1161 | -192 | 5 | 16.9 |
| Tulbagh/Wolseley | 2896 | -107 | 182 | 10.0 |
| Urionskraal | 635 | -20 | 92 | 17.6 |
| | Ave | -284 | 41 | 15.5 |
| | 90th percentile | -20 | 148 | 19.5 |
| | 10th percentile | -561 | -51 | 10.0 |
| | Median | -328 | 40 | 16.4 |
| | Max | 145 | 182 | 22.2 |
| | Min | -625 | -112 | 0.6 |
| | Range | 770 | 294 | 21.6 |

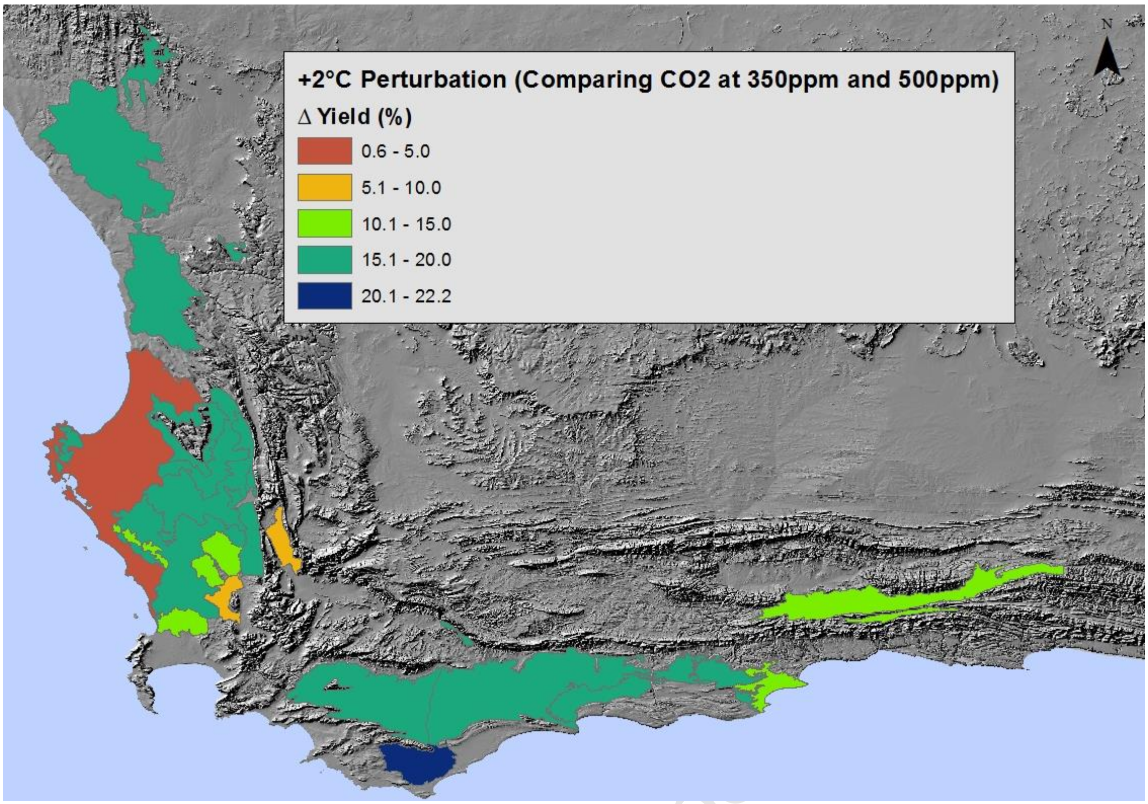


Figure 5.17. The modelled yield response to $CO_2$ elevation from 350 ppm to 500 ppm under + 2°C perturbation of baseline temperature.

Upon further sensitivity modelling it was evident that the single factor perturbations of temperature and reduced rainfall do indeed present cumulative effects when combined (Section 5.6). Figure 5.18 demonstrates this effect by graphing sensitivity results of the zone showing the greatest response to $CO_2$ elevation, the Bredasdorp/Strandveldvlakte RHFA (Figure 5.17). In a sensitivity analysis on this zone, the combined impact of the temperature increase AND rainfall decrease resulted in a yield reduction of 1200kg/ha/annum. Elevating $CO_2$ levels from 350 to 500 ppm reduced the impact of this by 400kg or 15% of the baseline yield for that zone. (This is not an expected future outcome in the RHFA, merely an example to illustrate $CO_2$ impacts – and also demonstrates the utility of the sensitivity analysis approach).

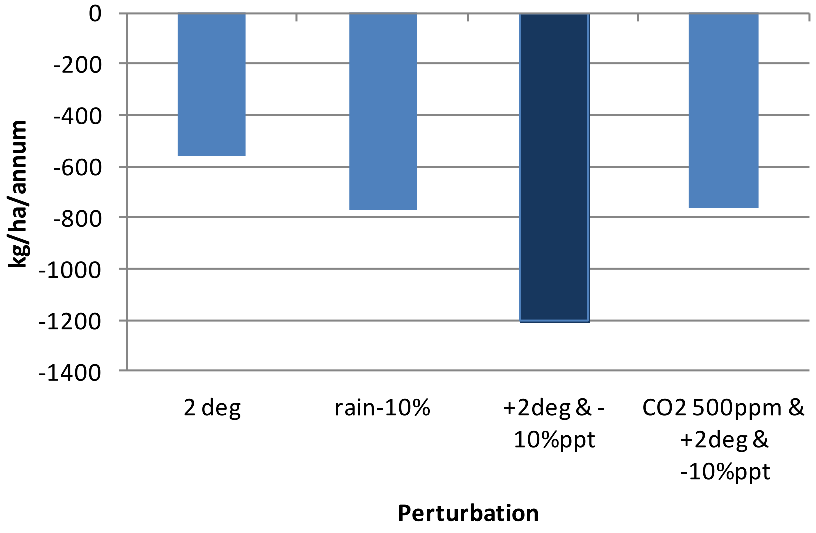


Figure 5.18. Bredasdorp/Strandveldvlakte modelled perturbations including the combined effect of increased temperature AND a 10% decrease in rainfall without (in the darker colour) and with elevated $CO_2$.

As demonstrated, the results become locally specific when increased temperature and $CO_2$ are modelled in combination. The meta-analysis of Ainsworth and Long (2005) illustrates the complex synergism that exists between concomitant increases in atmospheric $CO_2$ concentration and temperature. These results are consistent with results obtained and presented in the review of (non-FACE) studies conducted by Idso and Idso (1994). This highlights the importance of a zonally-specific downscaled modelling approach to ensure that local temperature and moisture regimes (and the expression of these factors through the soil water balance) and climate threshold impacts may be examined.

To examine the impacts that these concerted effects (temperature, rainfall and $CO_2$) have under the downscaled GCM modelled future scenarios, the entire suite of GCMs per RHFA were modelled with the $CO_2$ concentration set to 400 ppm for the future period (2046 – 2065). Comparing this with previous 500 ppm modelling, facilitated a zonal yield sensitivity analysis, based on projected (downscaled GCM) climate data per RHFA in which $CO_2$ values only were perturbed. The selection of 400 ppm is merely to facilitate a convenient 100 ppm $CO_2$ increment, yet it also represents the value which the IPCC expected us to imminently approach (IPCC Working Group III, 2000) and indeed we seem to have reached.

Table 5.6. Comparison between median future (2046-2065) downscaled GCM-forced yield anomalies at $CO_2$ concentrations of 400 ppm and 500 ppm (control period 1979 – 1999).

| **RHFA** | Baseline | CO2 at 500 ppm | CO2 at 400 ppm | Δ Yield | Δ Yield |
|---|---|---|---|---|---|
| | (kg/ha/annum) | (kg/ha/annum) | | (kg/ha/annum) | % |
| Hardeveld | 429 | 60.4 | 32.0 | 28.3 | 6.6 |
| Urionskraal | 641 | 23.1 | -12.0 | 35.2 | 5.5 |
| Kamanassie | 1395 | 167.4 | 100.8 | 66.5 | 4.8 |
| Sandveld Saaigebied | 1676 | 109.6 | 36.7 | 72.9 | 4.3 |
| Graafwater/Sandveld | 1104 | 84.9 | -3.1 | 88.1 | 8.0 |
| Stockwell | 1126 | 294.7 | 199.5 | 95.2 | 8.5 |
| Koringberg/Rooi Karoo Saaigebied | 1841 | 132.7 | 19.2 | 113.4 | 6.2 |
| Agter-Paarl | 2861 | 70.8 | -46.0 | 116.7 | 4.1 |
| Malgas/Heidelbergvlakte | 1741 | 196.2 | -5.4 | 201.6 | 11.6 |
| Kleinberg/Suurrug | 1781 | 317.7 | 116.0 | 201.6 | 11.3 |
| Ruens East | 1911 | 393.3 | 159.3 | 234.0 | 12.2 |
| Gourits-Rooiruens | 1990 | 188.2 | -50.6 | 238.8 | 12.0 |
| Gouritzriviervallei | 1897 | 207.3 | -36.4 | 243.7 | 12.9 |
| Bo-Langkloof | 1918 | 177.9 | -98.3 | 276.2 | 14.4 |
| Ruens West | 3051 | 379.3 | 81.1 | 298.2 | 9.8 |
| Gemengde Boerderygebied | 3681 | -18.8 | -321.2 | 302.5 | 8.2 |
| Hermon/Gouda | 3145 | -77.8 | -427.2 | 349.4 | 11.1 |
| Bredasdorp/Strandveldvlakte | 2709 | 452.8 | 102.3 | 350.5 | 12.9 |
| Tulbagh/Wolseley | 2896 | 92.3 | -269.8 | 362.1 | 12.5 |
| Hoe Reenval Saaigebied | 3443 | -96.0 | -533.7 | 437.6 | 12.7 |
| Middel Swartland Saaigebied | 3442 | 28.0 | -439.6 | 467.6 | 13.6 |

| | | |
|---|---|---|
| Average | 218 | 10 |
| 90th percentile | 362 | 13 |
| 10th percentile | 67 | 5 |
| Median | 234 | 11 |
| Max | 468 | 14 |
| Min | 28 | 4 |
| Range | 439 | 10 |

Table 5.6 and Figure 5.19 present the differences between the projected climate change yield anomalies calculated under $CO_2$ levels of 500 ppm and 400 ppm respectively. The RHFAs are arranged in order of increasing difference between the anomalies modelled for the two $CO_2$ levels in terms of kilograms of yield per hectare per year.

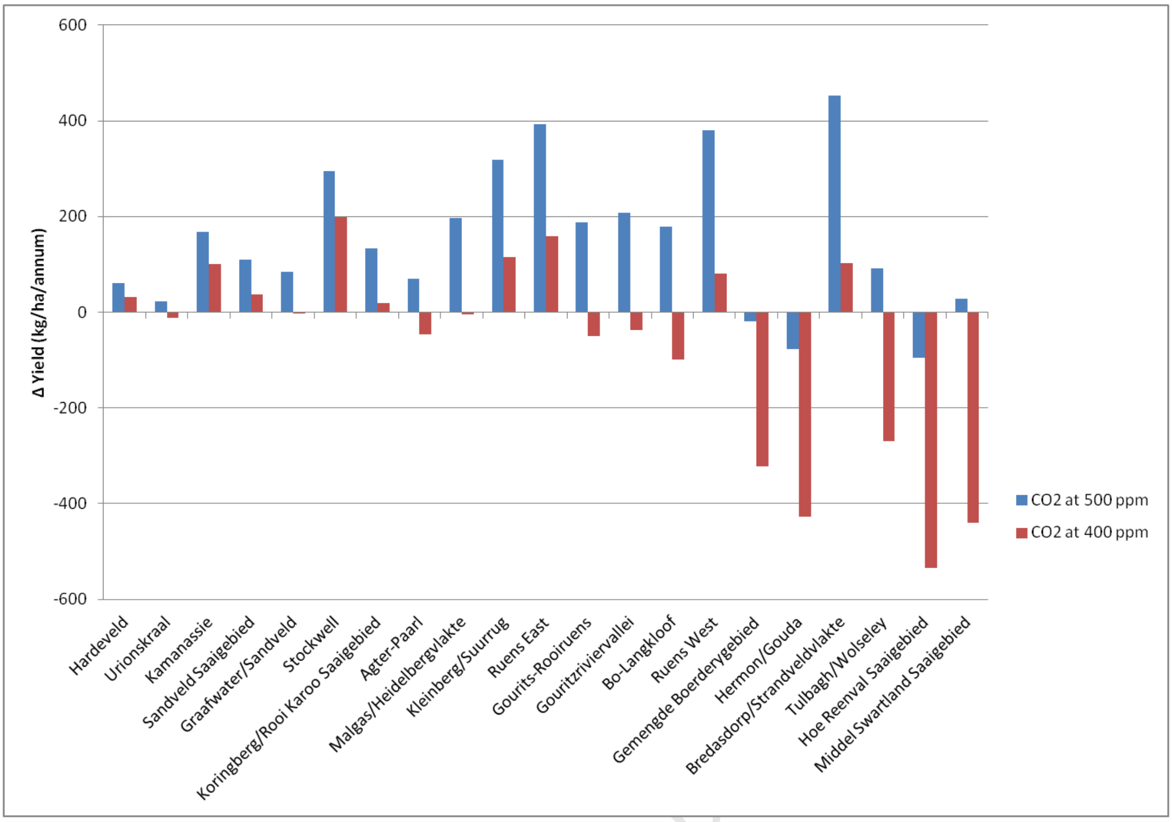


Figure 5.19. Comparison between median future (2046-2065) downscaled GCM-forced yield anomalies at $CO_2$ concentrations of 400  ppm and 500  ppm respectively.

The spatial implications are immediately apparent (in Figure 5.20) in that a number of the Swartland RHFAs exhibit a *strongly* negative (median) yield response when modelled at a $CO_2$ concentration of 400 ppm, indicating high sensitivity to $CO_2$ levels.  The likelihood for *positive* yield changes at 400 ppm also declines sharply for the Swartland, when compared with the 500 ppm median scenario as shown in Figure 5.21.

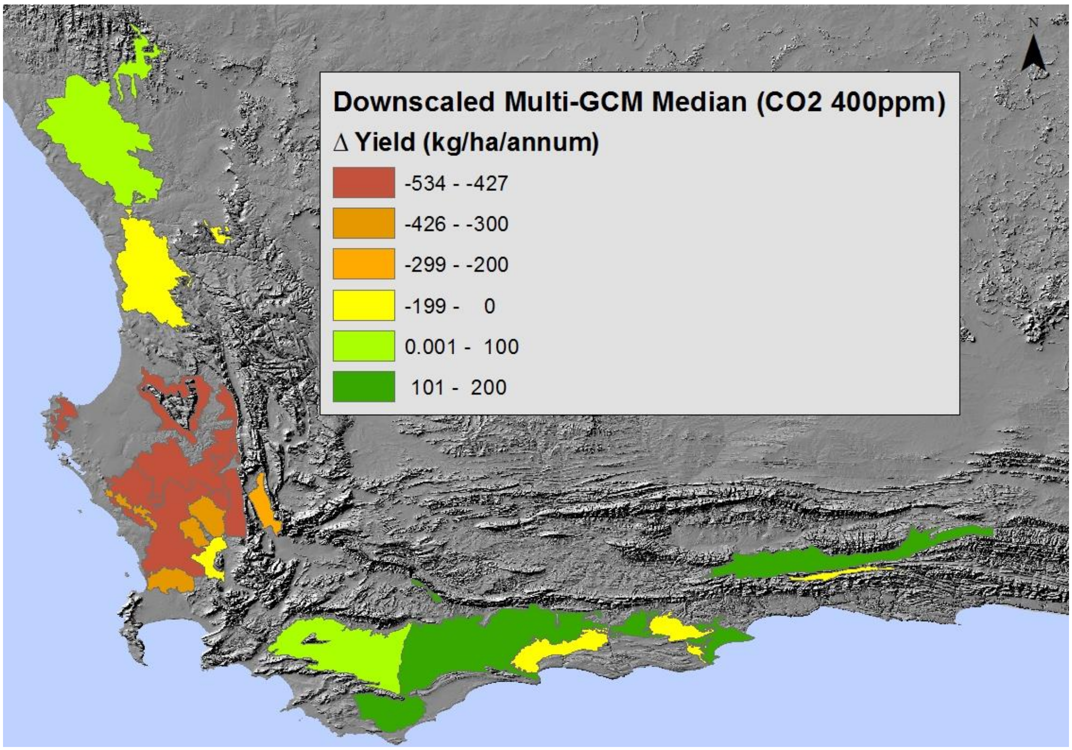
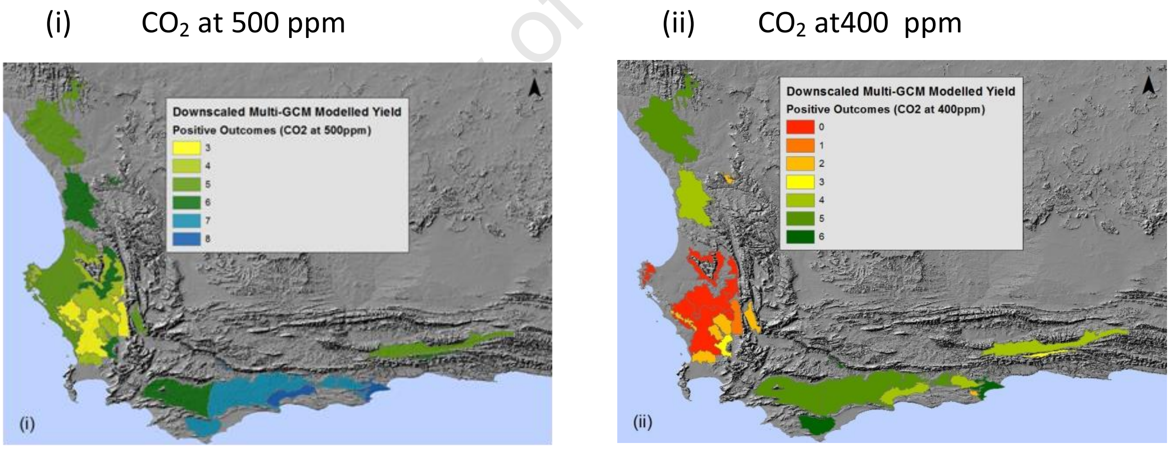


Figure 5.20. Modelled median future (2046-2065) downscaled GCM-forced yield anomalies modelled at $CO_2$ concentrations of 400 ppm (intended for zonal $CO_2$ sensitivity analysis) see Figure 6.15. for the 500 ppm scenario (Q2).


(i) $CO_2$ at 500 ppm

(ii) $CO_2$ at400 ppm

Figure 5.21. Number of modelled future (2046-2065) downscaled GCM-forced yield scenarios with positive outcomes when $CO_2$ is set to (i) 500 ppm and positive outcomes under a downscaled GCM-forced sensitivity analysis scenario in which the $CO_2$ concentration is reduced to (ii) 400 ppm.

### 5.8.3 Modelled response to further increases in $CO_2$

A simple sensitivity analysis was undertaken in APSIM to investigate the modelled wheat response to further increases in $CO_2$ levels. From the data in Table 5.6, three RHFAs were chosen for further investigation. RHFAs selected were those at the 10th, 50th and 90th percentiles of the (perturbed baseline) modelled yield responses to $CO_2$ elevation; being the Tulbagh/Wolseley, Middel Swartland and Malgas/Heidelbergvlakte respectively (Figure 5.22). Baseline temperatures, both maximum and minimum, were perturbed by +2°C and $CO_2$ levels from 450 ppm to 700 ppm were modelled at 50 ppm increments. The results are presented in Figure 5.22.

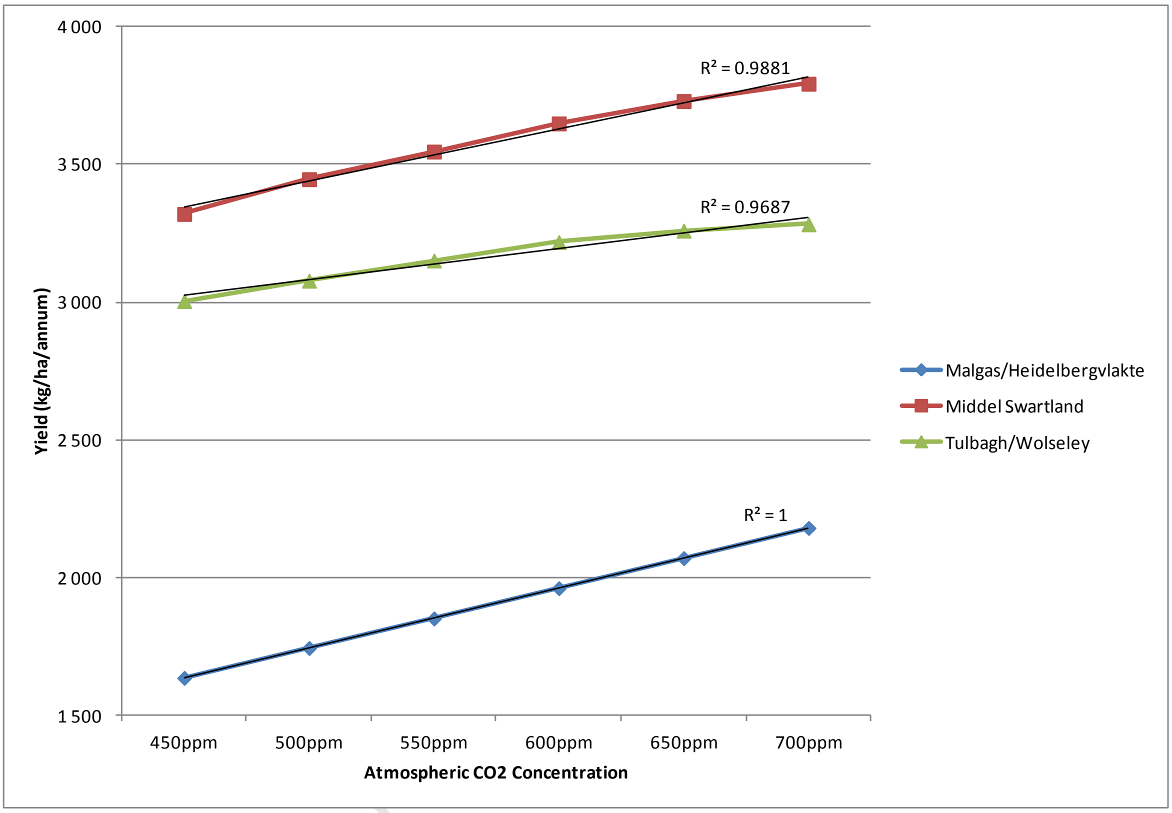


Figure 5.22. Modelled yield response to increases in $CO_2$ levels (at a temperature perturbation of +2°C of baseline).

In the case of Malgas/Heidelbergvlakte (which was at the 90th percentile of crop sensitivity analysis response to increased $CO_2$ levels) the yield response to $CO_2$ elevation was linear. The remaining 2 RHFAs showed near linear responses, with a slight flattening of the curve becoming evident above 650 ppm. Similar linear responses at these $CO_2$ levels were noted by researchers in the UK, using the Ceres-Wheat model (Cho et al., 2012) and in Australia (van Ittersum et al., 2003a). Tubiello et al.,(2007) reported that a number of crop models perform satisfactorily against the FACE experiments, although this was the cause of some vigorous debate (Ainsworth et al., 2008b). Recent model intercomparison work did show some marked differences in different models' response to $CO_2$ fertilisation (AgMIP, 2012), although the APSIM result was within FACE parameters.

In reality, elevation of $CO_2$ levels to these levels is likely to be accompanied by further increases in temperatures and modification of other weather variables. Associated crop stresses are likely to moderate this linear response and for this reason the issue of crop $CO_2$ response must be noted as a source of uncertainty in assessing future modelled yield projections.

### 5.8.4 Discussion

In a future, warmer Western Cape where climate variability and periodic droughts are still expected to continue, the expected elevated $CO_2$ levels of the future appear to play a major role towards compensating, either partially or in full, for both increased temperatures and for projected drier regimes - particularly in the Swartland. The dire situation for the Swartland indicated in Figure 5.21(ii) is unlikely to be realised given the current global trend in $CO_2$ enrichment. The scenario nonetheless illustrates the critical role that atmospheric $CO_2$ enrichment is expected to play in the continued regional sustainability of wheat production. The APSIM model for wheat has been well tested in a variety of relevant environments and over a range of artificially generated $CO_2$ field conditions (Asseng et al., 2004) where it has been found to perform satisfactorily within certain limitations. Nonetheless, the above work is based on simulation, which implies inherent uncertainties. Further discussion on this is presented in Section 4.5.

# Chapter Six: Downscaled GCM-forced model results

## 6.1 Introduction

Daily climate data from downscaling of the 8 GCMs presented in Table 4.4. were used to drive the APSIM model for each RHFA. As in the combined factor sensitivity analyses, the $CO_2$ levels were set to 500 ppm and the same cultivar (Janz) was selected.

A conservative approach was followed in this study with an important confidence criterion being the consensus between the yield outcomes of the 8 models in the sign (positive or negative) of *direction* of change. Thus with 8 downscaled GCM models used, 5 or more in agreement with regard to direction of change are required to provide a signal of likely future yield changes with any confidence. The language of confidence used in this study is shown in Table 6.1. The median yield value is presented for quantitative purposes, together with outcomes at the 1st and 3rd quartiles, with the *caveat* that the user considers primarily the strength of signal supporting the associated yield projection.

Table 6.1. Strength of change signal and confidence terminology.

| Number of models that agree on sign of change | Strength of change signal as confidence indicator |
|---|---|
| 4 out of 8 | No clear change signal |
| 5 out of 8 | Weak |
| 6 out of 8 | Moderate |
| 7 out of 8 | Strong |
| 8 out of 8 | Very strong |

In analysing the results the following points should be considered:

1. There is a *pattern* of change expected with climate change impacts which is the rationale behind conducting a zonally-based modelling exercise on modelled, *downscaled* future projection data. This pattern is not expected to be apparent

using the “generic” baseline climate perturbation approach where constant perturbations are applied to observed data in each zone. The term “sensitivity analysis” is used to distinguish this approach from the APSIM modelled yield projections based on GCM-derived, plausible future climatologies.

2. Closely related to this point is the key impact factor of changes to rainfall *distribution* within the growing season. With the generally shallow soils in the Western Cape, well-distributed rainfall is essential for successful wheat production. Perturbing observed baseline rainfall data by constant values is unlikely to project any realistic future rain distribution scenario. Likewise any change in the frequency of extreme events of both precipitation and temperature cannot be accounted for with the baseline perturbation approach.
3. Nonetheless the sensitivity analysis approach facilitates investigation of the zonal yield responses to climate changes. As discussed in the literature review of this study, much of the existing literature has based future yield impact projections on such perturbations of baseline data. The utility and validity of this approach in terms of a yield projection methodology is under investigation here (where a suite of downscaled GCM-based data *are* available).

## 6.2 Projected median climate anomalies per RHFA based on downscaled GCM daily data

To set the future climatic context for modelling runs, the projected median climate anomalies for the modelled wheat zones are presented. The median of the 8 GCM downscaling climate outcomes (Figure 6.1) presents a general trend for increased rainfall to the east and south-east of the province whilst the majority of the western RHFAs seem likely to become drier or remain close to current levels into the future study period (2046 – 2065). Both maximum and minimum temperatures are expected to increase, with the greatest increases (in the wheat producing RHFAs) expected in zones in the north-west and the east of the province (Figure 6.2).

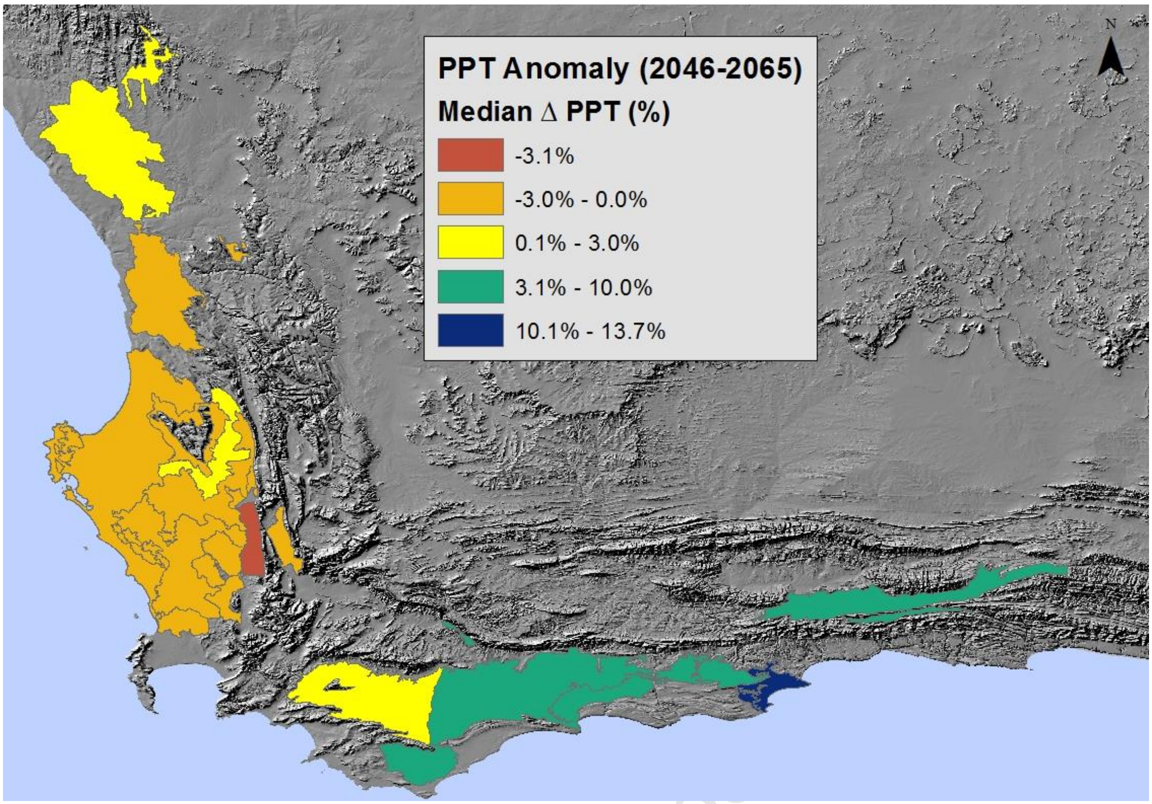


Figure 6.1. Downscaled GCM projected (median) precipitation anomaly outcomes for the period 2046 – 2065 (control period 1979 – 1999).

Table 6.2. Projected precipitation anomalies for each downscaled GCM, per RHFA, for the period 2046 – 2065 (control period 1979 – 1999). Positive anomalies are in red, negative in blue. (These anomalies are presented spatially in Appendix II).

| RHFA | Observed (mm) | Average precipitation anomalies (Δmm) for April - October (2046 - 2065) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | cgcm3_1 | cnrm_cm3 | csiro3_5 | echam5 | echo_g | gfdl2_1 | ipsl_cm4 | mri_cgcm2_3 |
| Agter-Paarl | 664.9 | 42.6 | -38.1 | 51.3 | 55.1 | -63.6 | 51.9 | -3.4 | -14.1 |
| Bo-Langkloof | 303.9 | 13.8 | -5.5 | 5.0 | -20.9 | 39.2 | 30.3 | 29.7 | 11.9 |
| Bredasdorp/Strandveldvlakte | 321.4 | 13.5 | 14.2 | 31.8 | 3.6 | 21.1 | 20.7 | 31.9 | -19.1 |
| Gemengde Boerderygebied | 664.9 | 42.6 | -38.1 | 51.3 | 55.1 | -63.6 | 51.9 | -3.4 | -14.1 |
| Gourits-Rooiruens | 275 | 20.2 | 20.5 | 52.8 | -9.7 | 54.4 | 21.0 | 14.7 | 0.5 |
| Gouritzriviervallei | 246.5 | 6.7 | 11.7 | 34.9 | -18.2 | 29.7 | 20.5 | 30.8 | 10.1 |
| Graafwater/Sandveld | 232.8 | 9.3 | -16.7 | 23.5 | 6.1 | -24.1 | 5.2 | -1.9 | -0.5 |
| Hardeveld | 140.6 | 9.6 | 2.0 | 12.0 | 9.2 | -11.5 | 0.6 | -1.1 | 3.3 |
| Hermon/Gouda | 597 | -3.1 | -58.2 | 33.0 | 31.5 | -46.5 | 29.4 | -27.6 | -11.9 |
| Hoe Reenval Saaigebied | 394.7 | 9.5 | -29.8 | 22.0 | 37.5 | -32.9 | 19.2 | -2.0 | -20.0 |
| Kamanassie | 303.9 | 13.8 | -5.5 | 5.0 | -20.9 | 39.2 | 30.3 | 29.7 | 11.9 |
| Kleinberg/Suurrug | 246.5 | 11.3 | 19.1 | 30.1 | -14.7 | 47.7 | 10.1 | 27.5 | 22.0 |
| Koringberg/Rooi Karoo Saaigebied | 265.7 | 15.2 | -11.8 | 29.8 | 13.3 | -15.9 | -1.5 | 2.6 | 4.5 |
| Malgas/Heidelbergvlakte | 264.9 | 15.0 | 1.6 | 40.2 | -11.3 | 25.9 | 11.2 | 16.1 | 12.6 |
| Middel Swartland Saaigebied | 394.7 | 9.5 | -29.8 | 22.0 | 37.5 | -32.9 | 19.2 | -2.0 | -20.0 |
| Ruens East | 287.2 | 31.8 | 20.9 | 62.8 | 14.1 | 19.8 | 18.4 | 9.4 | 2.9 |
| Ruens West | 348.9 | 20.5 | -5.4 | 39.7 | -7.7 | 14.3 | 15.5 | -1.1 | 3.5 |
| Sandveld Saaigebied | 271.7 | 6.4 | -13.1 | 22.2 | 17.6 | -25.0 | 1.3 | -3.0 | -2.8 |
| Stockwell | 201.1 | 20.8 | 15.6 | 36.3 | -0.3 | 10.6 | 10.3 | 6.1 | 1.3 |
| Tulbagh/Wolseley | 384.4 | 7.1 | -17.0 | 46.2 | 31.0 | -34.8 | -2.2 | -4.4 | -11.6 |
| Urionskraal | 132.3 | 5.4 | 1.2 | 9.7 | 5.9 | -7.8 | 0.7 | -4.4 | -0.1 |

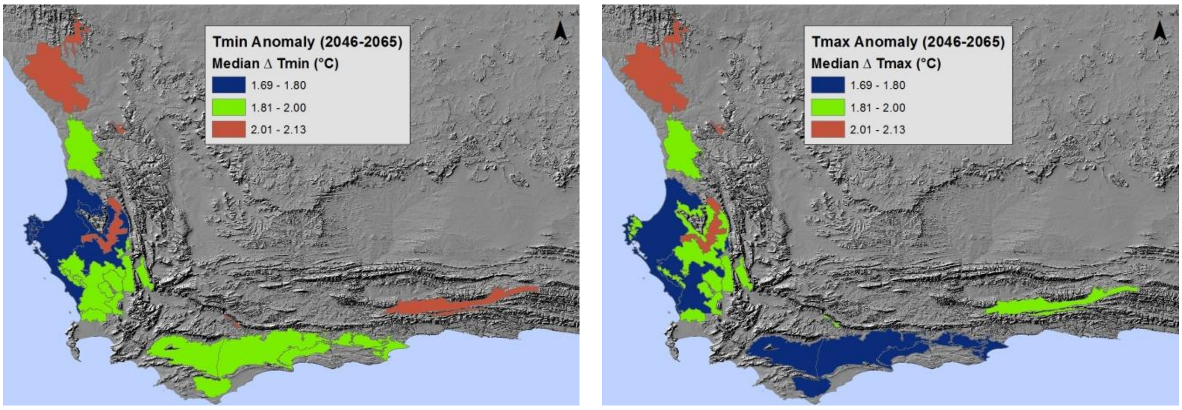


Figure 6.2. Downscaled GCM projected (median) temperature anomaly outcomes for Tmin and Tmax for the period 2046 – 2065 (control period 1979 – 1999). Maps and tables of the temperature anomalies for each of the 8 downscaled GCMs are presented in Appendix II.

## 6.3 Modelled zonal crop responses driven by downscaled daily GCM ensemble

Table 6.3 and Figure 6.3 present the modelled yield anomalies between the control period (1970 – 1999) and the future period (2046 - 2065) forced by each of 8 downscaled GCMs for each RHFA. The $CO_2$ levels were set to 500 ppm. Detailed ensemble outcomes are presented for the 10 primary wheat zones to demonstrate the spread of anomalies.

Table 6.2 and Figure 6.1 and 6.2 provide an indication of the projected characteristics of each downscaling, useful in the assessment of the following results (also see Appendix II and III). For example the "wetter models" (e.g. csiro3_5) may be expected to result in higher yields but this was not always the case due to interactions such as waterlogging. The "hottest" downscaled projections were for the ipsl_cm4 downscaled GCM which showed corresponding high yield reductions in a number of the Swartland, in accordance with their previously identified sensitivity to warming.

Table 6.3. Results of the combined RHFA yield outcomes for APSIM model runs driven by the ensemble of 8 downscaled GCMs' daily data (control period 1979–1999; future period 2046-2065). $CO_2$ levels were set to 500 ppm.

|  |  | Yield anomalies (kg/ha/annum) |  |  |  |  |  |  |  | Δ Sign |  | Statistics (kg/ha/annum) |  |  |  |  |  | Δ Yield (Median) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **RHFA** | Baseline (kg/ha/annum) | cgcm3_1 | cnrm_cm3 | csiro3_5 | echam5 | echo_g | gfdl2_1 | ipsl_cm4 | mri_cgcm2_3 | Pos | Neg | Median | Mean | Max | Min | Range | SD | % |
| Agter-Paarl | 2861 | 102 | 502 | -391 | 276 | 673 | 39 | -558 | 34 | 6 | 2 | 71 | 85 | 673 | -558 | 1232 | 388 | 2.5 |
| Bo-Langkloof | 1918 | 608 | 439 | 203 | -1096 | 36 | 1094 | -75 | 153 | 6 | 2 | 178 | 170 | 1094 | -1096 | 2190 | 592 | 9.3 |
| Bredasdorp/Strandveldvlakte | 2709 | 401 | 504 | 767 | 541 | 326 | 837 | 290 | -53 | 7 | 1 | 453 | 452 | 837 | -53 | 891 | 264 | 16.7 |
| Gemengde Boerderygebied | 3681 | -82 | 429 | -236 | 108 | 543 | 26 | -803 | -63 | 4 | 4 | -19 | -10 | 543 | -803 | 1345 | 388 | -0.5 |
| Gourits-Rooiruens | 1990 | 127 | 300 | 346 | 238 | -3 | 607 | 2 | 138 | 7 | 1 | 188 | 219 | 607 | -3 | 609 | 189 | 9.5 |
| Gouritzriviervallei | 1897 | 210 | 365 | 188 | -24 | 205 | 451 | 100 | 260 | 7 | 1 | 207 | 219 | 451 | -24 | 475 | 137 | 10.9 |
| Graafwater/Sandveld | 1104 | 111 | 116 | 296 | 362 | -263 | 59 | -1 | 50 | 6 | 2 | 85 | 91 | 362 | -263 | 626 | 190 | 7.7 |
| Hardeveld | 429 | 58 | 107 | 69 | 177 | -71 | 63 | -99 | -16 | 5 | 3 | 60 | 36 | 177 | -99 | 275 | 86 | 14.1 |
| Hermon/Gouda | 3145 | -173 | 49 | -377 | 154 | 701 | -8 | -609 | -147 | 3 | 5 | -78 | -51 | 701 | -609 | 1310 | 364 | -2.5 |
| Hoe Reenval Saaigebied | 3443 | -322 | -151 | -41 | 135 | 258 | 186 | -310 | -200 | 3 | 5 | -96 | -56 | 258 | -322 | 579 | 212 | -2.8 |
| Kamanassie | 1395 | 216 | 355 | 320 | -237 | -180 | 303 | 119 | -183 | 5 | 3 | 167 | 89 | 355 | -237 | 591 | 234 | 12.0 |
| Kleinberg/Suurrug | 1781 | 139 | 399 | 248 | 11 | 259 | 403 | 377 | 556 | 8 | 0 | 318 | 299 | 556 | 11 | 546 | 161 | 17.8 |
| Koringberg/Rooi Karoo Saaigebied | 1841 | 383 | 11 | 859 | 518 | -222 | -31 | 204 | 62 | 6 | 2 | 133 | 223 | 859 | -222 | 1081 | 326 | 7.2 |
| Malgas/Heidelbergvlakte | 1741 | 127 | 268 | 400 | 56 | 86 | 281 | 99 | 266 | 8 | 0 | 196 | 198 | 400 | 56 | 344 | 114 | 11.3 |
| Middel Swartland Saaigebied | 3442 | -262 | -120 | 390 | 122 | 271 | 128 | -157 | -66 | 4 | 4 | 28 | 38 | 390 | -262 | 651 | 211 | 0.8 |
| Ruens East | 1911 | 504 | 446 | 457 | 447 | 29 | 341 | -136 | 184 | 7 | 1 | 393 | 284 | 504 | -136 | 640 | 220 | 20.6 |
| Ruens West | 3051 | 423 | 336 | 663 | 450 | -270 | 748 | -139 | 149 | 6 | 2 | 379 | 295 | 748 | -270 | 1018 | 338 | 12.4 |
| Sandveld Saaigebied | 1676 | 295 | 156 | 168 | -116 | 351 | -90 | 64 | -258 | 5 | 3 | 110 | 71 | 351 | -258 | 609 | 198 | 6.5 |
| Stockwell | 1126 | 384 | 306 | 384 | 114 | 91 | 304 | 286 | 148 | 8 | 0 | 295 | 252 | 384 | 91 | 293 | 110 | 26.2 |
| Tulbagh/Wolseley | 2896 | 17 | -9 | 192 | 563 | 650 | -484 | 168 | -359 | 5 | 3 | 92 | 92 | 650 | -484 | 1134 | 371 | 3.2 |
| Urionskraal | 641 | 31 | 196 | 8 | 286 | 15 | 33 | -84 | -30 | 6 | 2 | 23 | 57 | 286 | -84 | 370 | 114 | 3.6 |

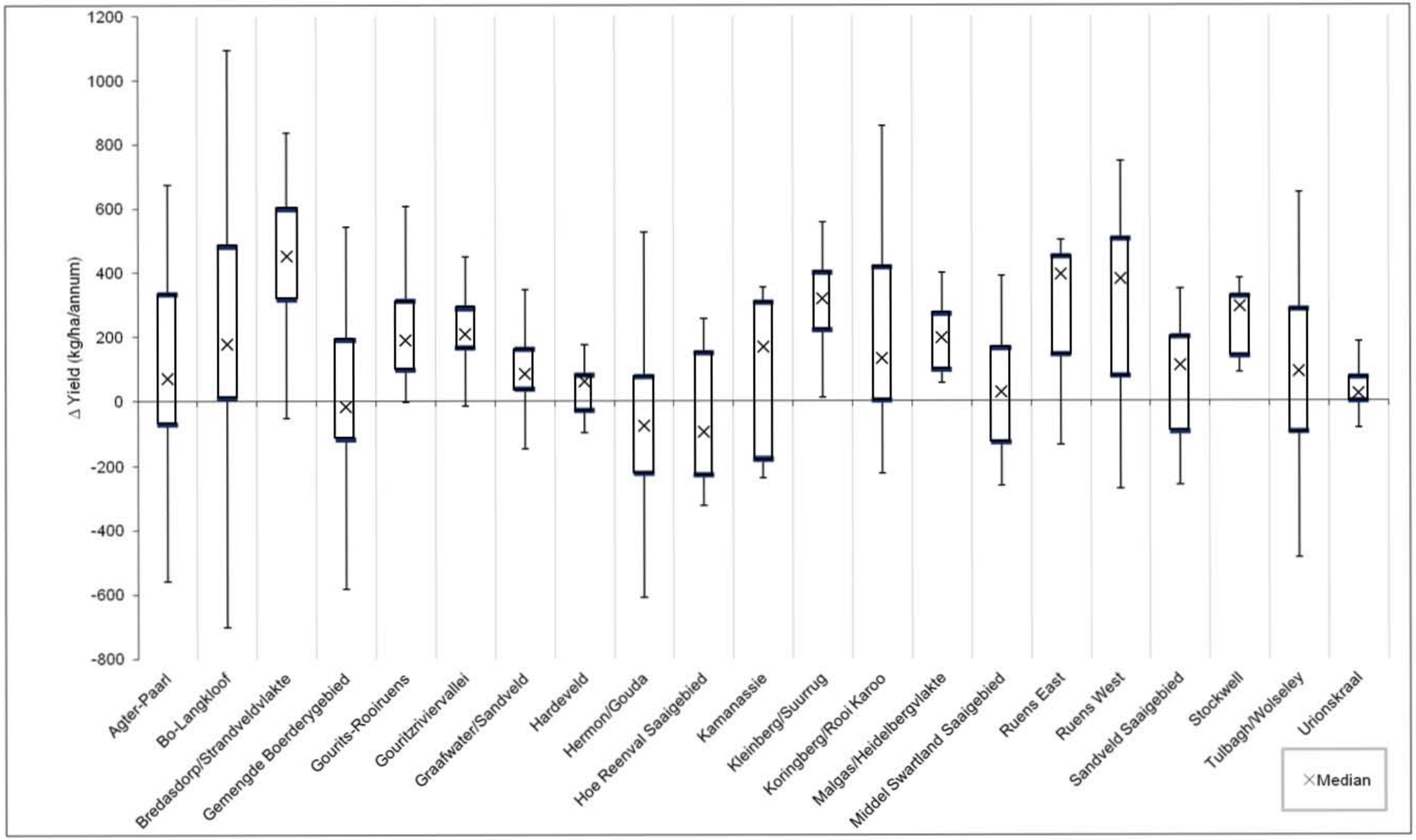


Figure 6.3. Bar and whisker plot showing statistics of the combined RHFA yield outcomes for APSIM model runs driven by the ensemble of 8 downscaled GCMs' daily data (control period 1979–1999; future period 2046-2065). $CO_2$ levels were set to 500 ppm. The bars represent 1st and 3rd quartiles respectively, the cross represents the median value and the "whiskers" indicate the 10th and 90th percentile values.

Agter-Paarl (RHFA 28)

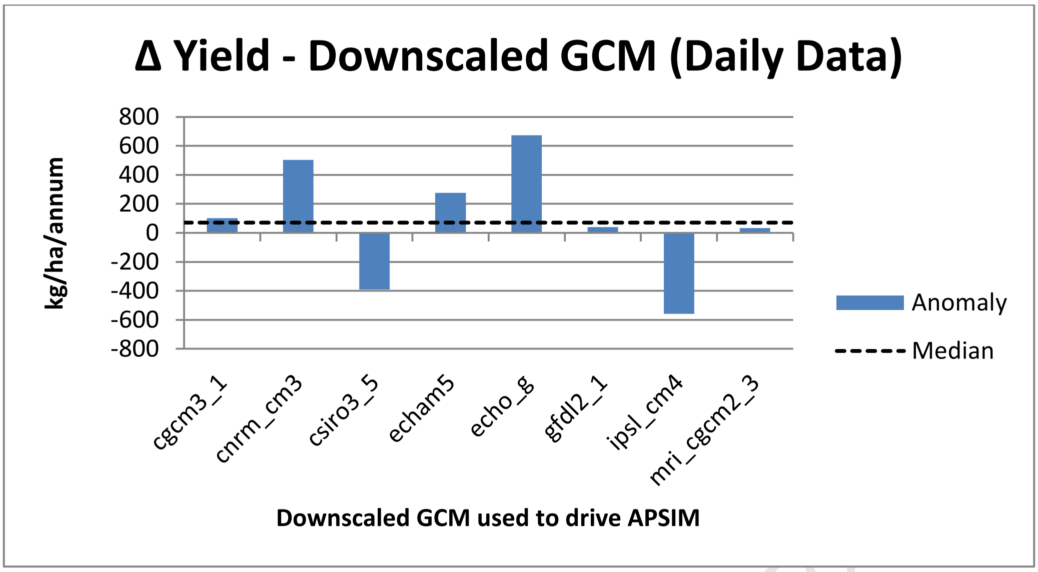


Figure 6.4. Modelled wheat yield anomalies for the Agter-Paarl RHFA driven by the downscaled daily GCM ensemble for the period 2046 to 2065 (control period 1979 – 1999).

Six of the eight modelled future scenarios indicated increased yields for the period 2046 to 2065 in this zone (Figure 6.4). Accordingly the zone is expected with moderate confidence to produce slightly improved yields under climate change. Interestingly a number of the Swartland zones performed relatively better under the lower rainfall regimes projected by the cnrm_cm3 and echo_g rainfall, corresponding to earlier sensitivity results where yields were reduced by increasing rainfall. Similarly the warmer ipsl_cm4 model (see Appendix III) showed a substantial decrease in yield in a zone which previously showed sensitivity to increased temperatures.

Hoë Reënval Saaigebied (RHFA 17)

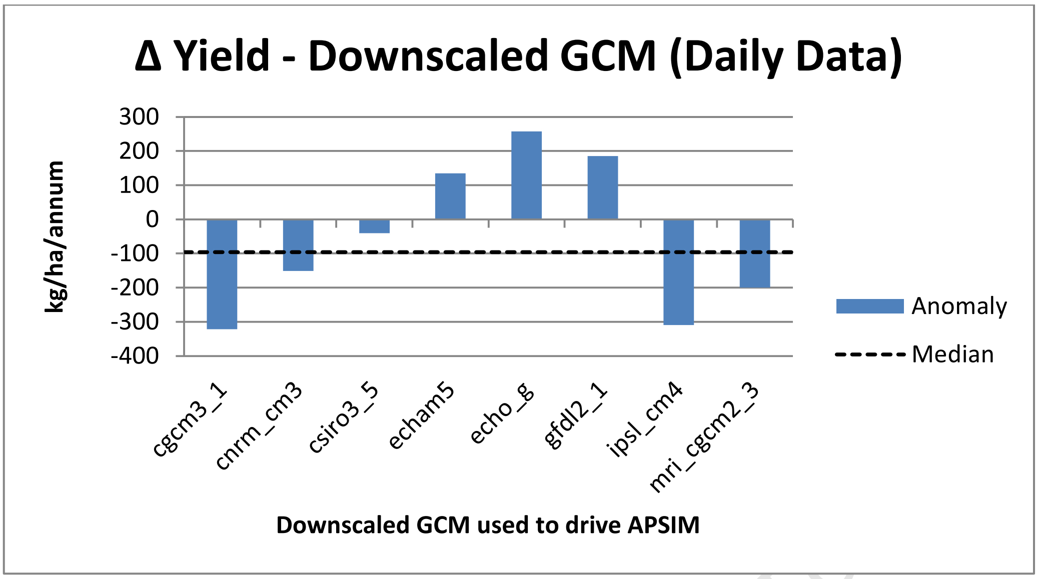


Figure 6.5. Modelled wheat yield anomalies for the Hoë Reënval Saaigebied RHFA driven by the downscaled daily GCM ensemble for the period 2046 to 2065 (control period 1979 – 1999).

Five of the eight modelled future scenarios indicate decreased yields for the period 2046 to 2065 in this zone (Figure 6.5). The modelled results are thus weakly indicative of a slight decline in future yields. The range or envelope of modelled results is noticeably narrow here, considering the relatively high average yields in the zone.

The echo_g scenario projects the most favourable future, although it is generally one of the "drier" models.

Hermon/Gouda (RHFA 29)

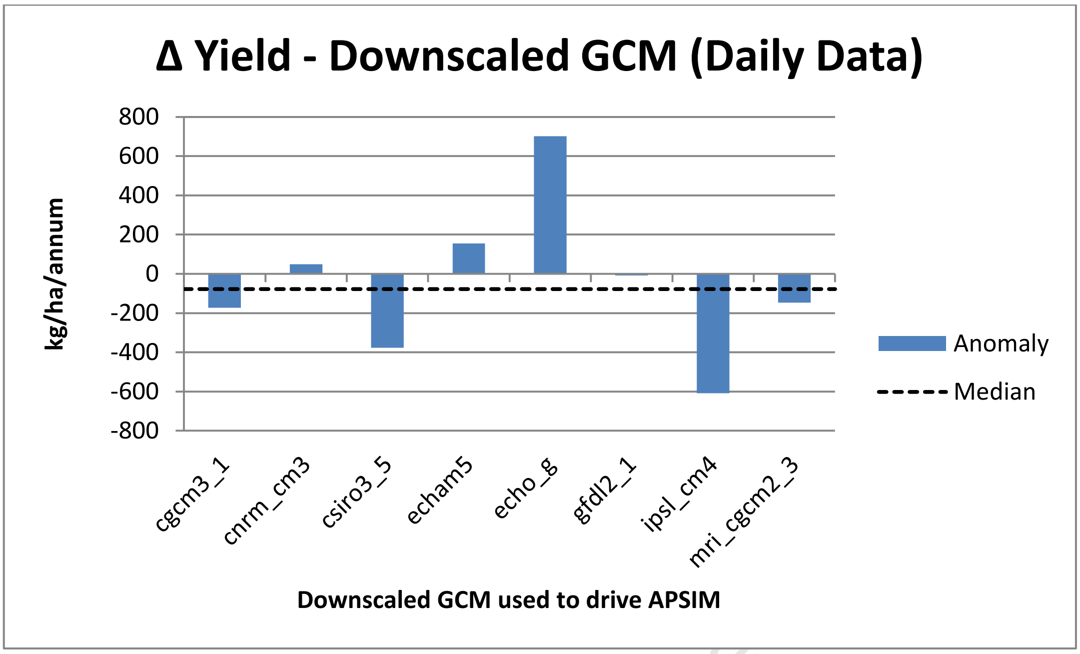


Figure 6.6. Modelled wheat yield anomalies for the Hermon/Gouda RHFA driven by the downscaled daily GCM ensemble for the period 2046 to 2065 (control period 1979 – 1999).

As shown in Figure 6.6, five of the eight modelled future scenarios indicate decreased yields for the period 2046 to 2065 in this zone (gfdl2_1 is, in fact negative, but at -8 kg/ha/annum too small to appear at the scale of this graph). The modelled results are thus weakly indicative of slightly reduced future yields.

A relatively high positive yield result was obtained for the echo_g scenario, which is in fact the second-driest model – a common response in the Swartland zones, where baseline precipitation regimes appear to be near optimal with any excesses resulting in waterlogging. The highest projected RHFA temperatures together with overall drier rainfall regimes resulted in the highest yield reduction being projected under the ipsl_cm4 scenario.

Middel Swartland Saaigebied (RHFA 16)

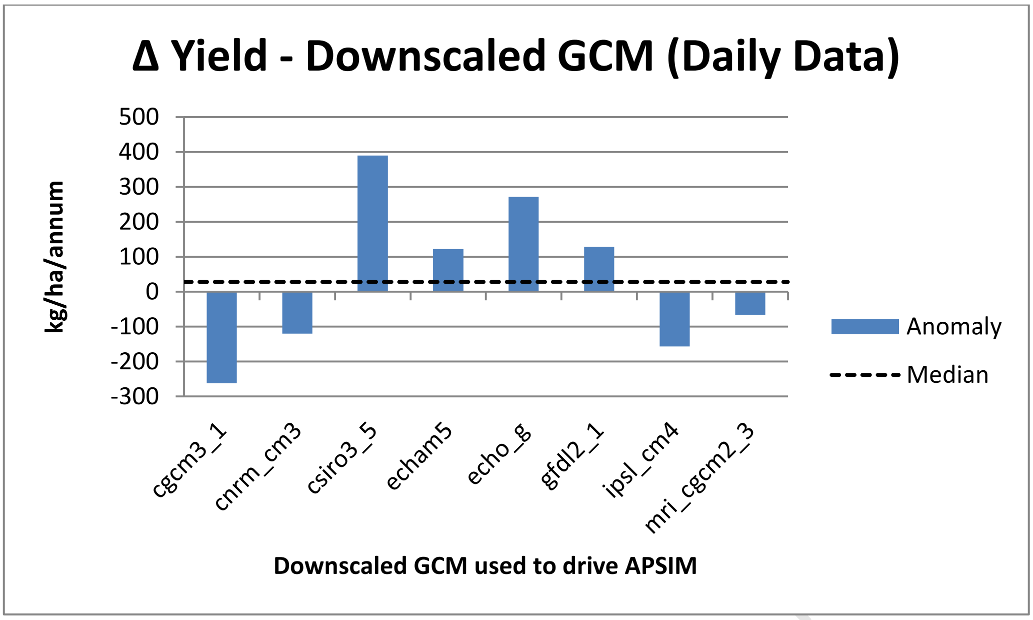


Figure 6.7. Modelled wheat yield anomalies for the Middel Swartland Saaigebied RHFA driven by the downscaled daily GCM ensemble for the period 2046 to 2065 (control period 1979 – 1999).

There is no signal for future change in the Middel Swartland (Figure 6.7), since the models were equally split in terms of the *direction* of change and the spread of yield anomalies was relatively small in most cases, given the historical high yield potential of the RHFA. In this Swartland zone, the slight seasonal increase and rainfall regime (see Appendix III) and relatively small temperature increases projected by csiro3_5 modelled resulted in the greatest yield increase.

Gemengde Boerderygebied (RHFA 18)

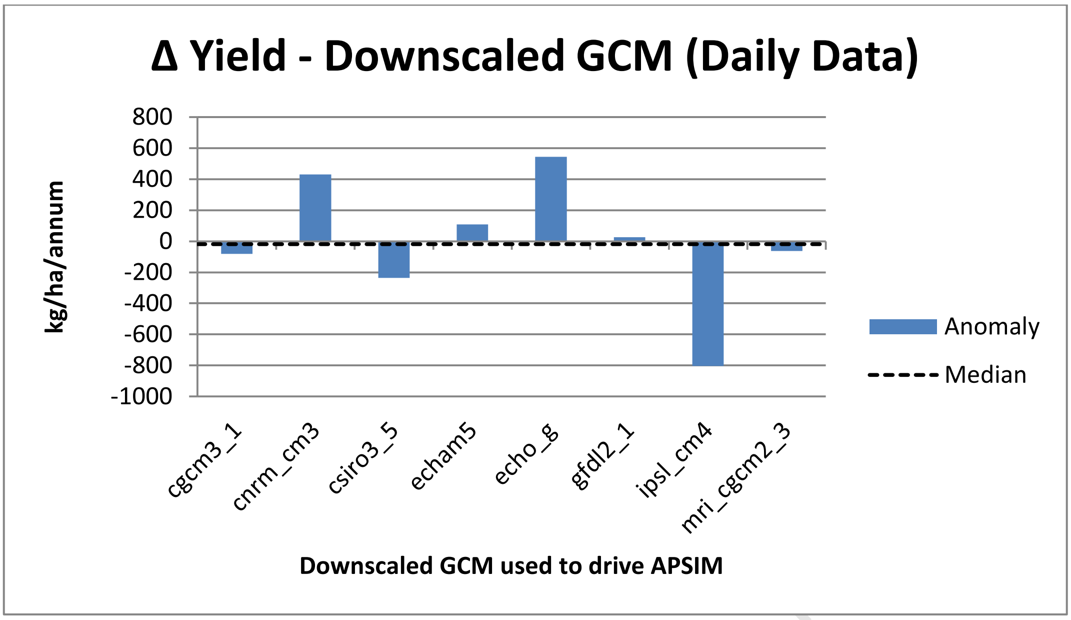


Figure 6.8. Modelled wheat yield anomalies for the Gemengde Boerderygebied RHFA driven by the downscaled daily GCM ensemble for the period 2046 to 2065 (control period 1979 – 1999).

As in the neighbouring Middel Swartland the models were equally split in terms of the direction of change (Figure 6.8). As a result no confident statement should be made on the direction of change in this RHFA. The median anomaly is low, at 20kg/ha/annum. The spread of most of the anomaly values in the envelope is noticeably small in most cases (an obvious exception is ipsl_cm4), given the relatively high baseline yield potential of this zone. This supports the conclusion that future yields are likely to be close to current production.

Koringberg/Rooikaroo Saaigebied (RHFA 15)

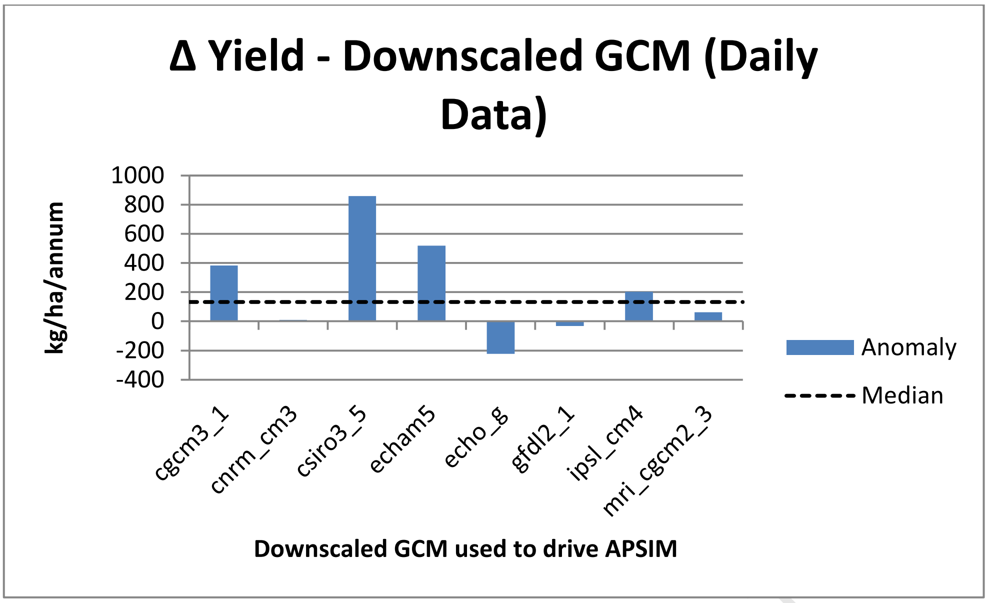


Figure 6.9. Modelled wheat yield anomalies for the Koringberg/Rooikaroo RHFA driven by the downscaled daily GCM ensemble for the period 2046 to 2065 (control period 1979 – 1999).

When the crop model is driven by plausible future climatologies the Koringberg/Rooikaroo RHFA appears moderately likely to benefit from future climate change with 6 out of the 8 models indicating positive anomalies (Figure 6.9). This may be a result of more favourable future synoptic conditions with fewer incidences of rain-shadow effects to which the region is currently subjected.

As may be expected in a zone where high risk is related to low rainfall and rainfall variability, the highest projected yield increase was simulated by the "wettest" model, csiro3_5, and the "driest" model resulted in the lowest yield (echo_g).

Rûens West (RHFA 63)

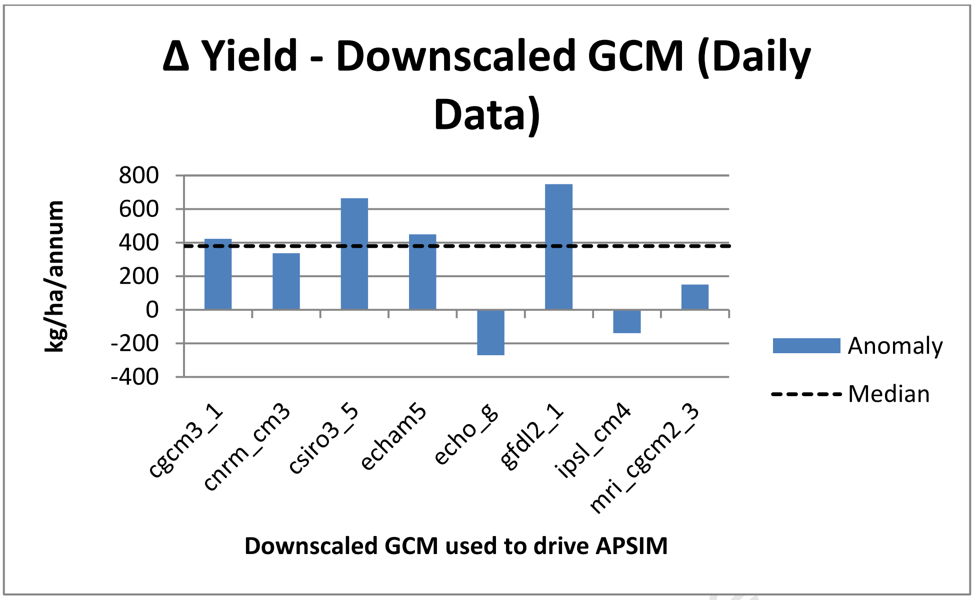


Figure 6.10. Modelled wheat yield anomalies for the Rûens West RHFA driven by the downscaled daily GCM ensemble for the period 2046 to 2065 (control period 1979 – 1999).

With six of the eight models indicating a positive change in yield, the strength of signal can be considered moderate for substantially improved future yields in this region (Figure 6.10). This is currently one of the top wheat production areas of the province – particularly the portion of this RHFA known as the Goue Rûens where soils and climate are conducive to reliably good yields. The generally shallow soils appear to respond favourably to most of the modelled future precipitation distribution regimes. The best yield response was under a relatively wet projection (gfdl2_1) with associated mild temperature increases.

Rûens East (RHFA 63)

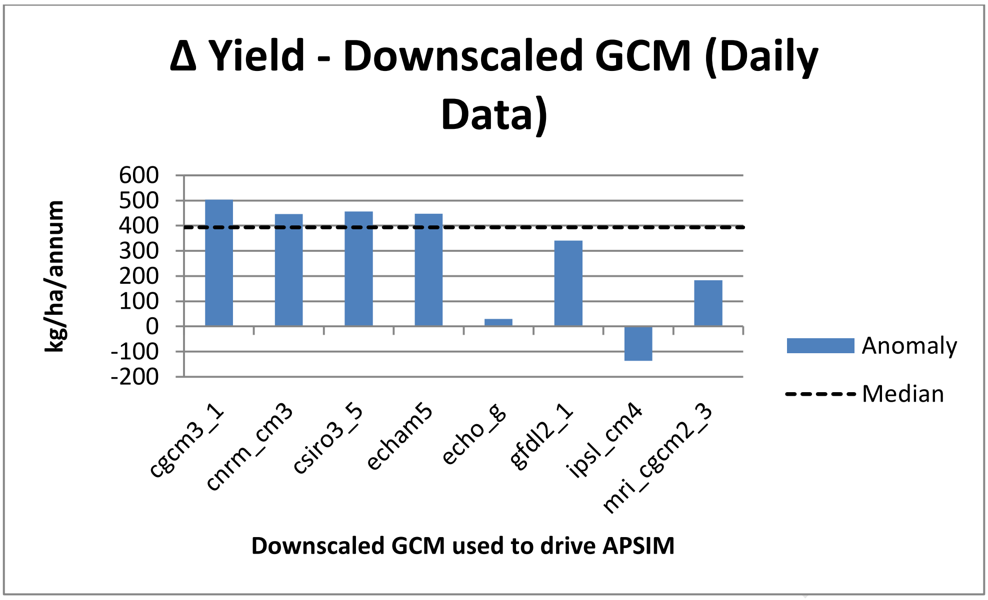


Figure 6.11. Modelled wheat yield anomalies for the Rûens East RHFA driven by the downscaled daily GCM ensemble for the period 2046 to 2065 (control period 1979 – 1999).

Under projected future conditions (Figure 6.11), seven of the eight models indicate a positive change in yield, thus the signal can be considered strong for improved future yields in Rûens East. The area currently has the potential to produce good yields in wetter years, but is subject to periodic dry spells which have a strong impact on production given the generally shallow soils. Future rainfall distribution and the stress moderating impacts of $CO_2$ under moisture limited conditions appear to benefit wheat production in this zone under modelled future scenarios. The negative response was under the “hottest” model, ipsl_cm4.

Bredasdorp-Strandveldvlakte (RHFA 64)

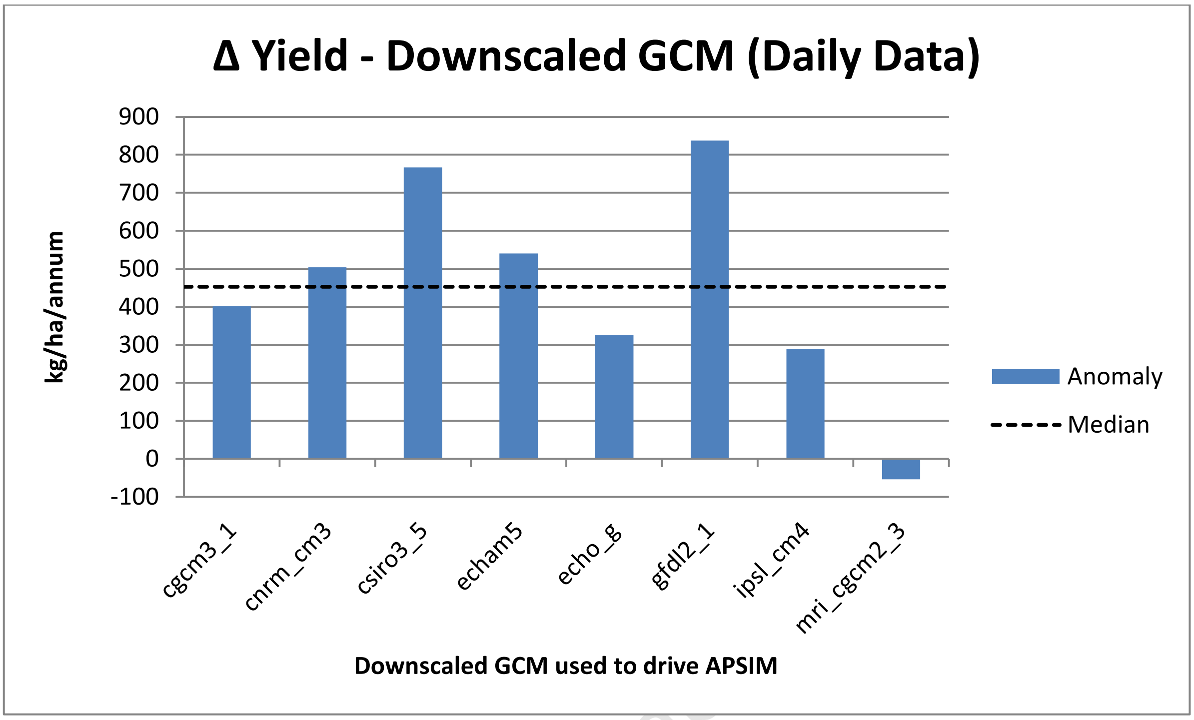


Figure 6.12. Modelled wheat yield anomalies for the Bredasdorp-Strandveld RHFA driven by the downscaled daily GCM ensemble for period 2046 to 2065 (control period 1979 – 1999).

Although this region showed a high level of sensitivity to moisture deficit and increased temperatures in the previous chapter, the favourable future rainfall regimes projected by the majority of downscaled GCMs for this zone resulted in seven of the eight future scenario models indicating a positive change in yield (Figure 6.12). The likelihood can be considered strong for improved future yields.

The mri_cgcm2_3 downscaled GCM was interestingly the only projection showing a decrease in future seasonal rainfall for this RHFA, resulting in the only modelled yield decrease here.

Malgas-Heidelberg Plain (RHFA 69)

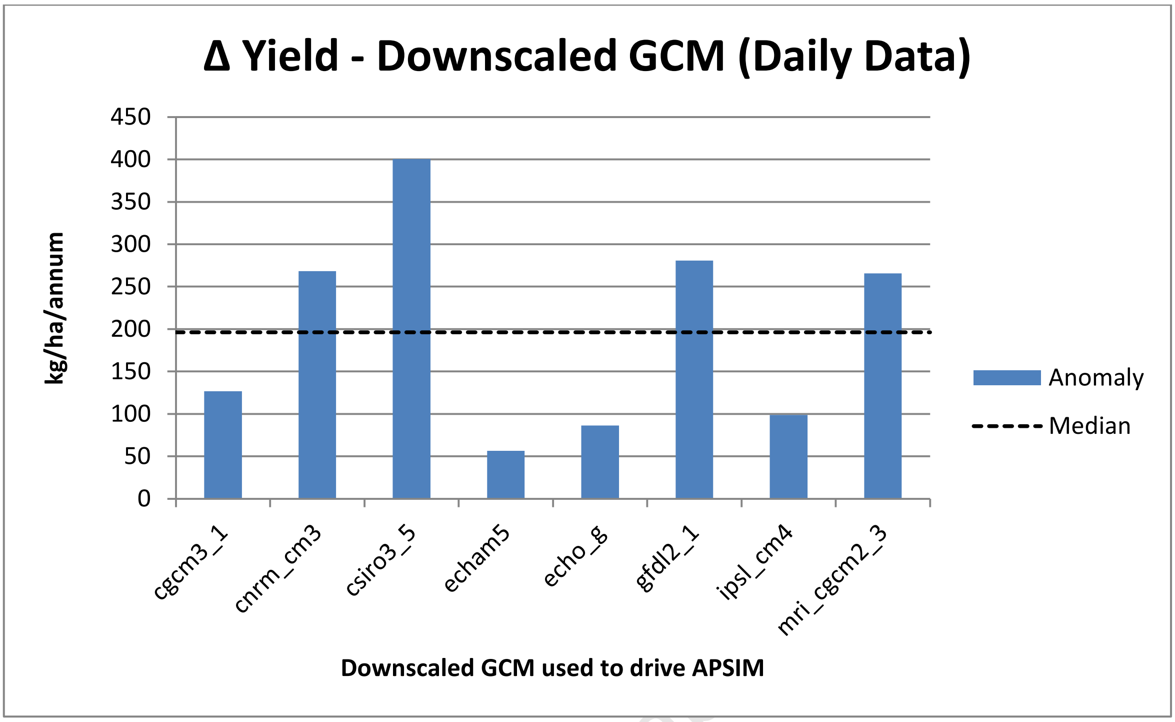


Figure 6.13. Modelled wheat yield anomalies for the Malgas-Heidelbergvlakte RHFA driven by the downscaled daily GCM ensemble for the period 2046 to 2065 (control period 1979 – 1999).

The Malgas-Heidelbergvlakte RHFA exhibits one of the strongest signals for future yield increases, with all 8 models agreeing on the direction of change (Figure 6.13). The spread between the anomalies is also relatively low. Echam5 had the lowest projected rainfall in the ensemble for this zone, resulting in the lowest relative yield increase.

### 6.4 Modelled yield outcome statistics

In assessing these results in terms of the stated confidence one should have in modelled yield changes (Table 6.1 in the introduction to this chapter), the number of outcomes in the model envelope in agreement on the sign of change (Figure 6.14) should be emphasised more than the magnitude of the yield anomalies. The modelled agreement in sign of change is greater in the southern RHFAs and is generally weakest in parts of the Swartland region. In the Middel Swartland and Gemengde Boerderygebied, an equal split in sign-of-change of outcomes occurs. The results should thus be identified as such (or "masked") during further analysis or mapping.

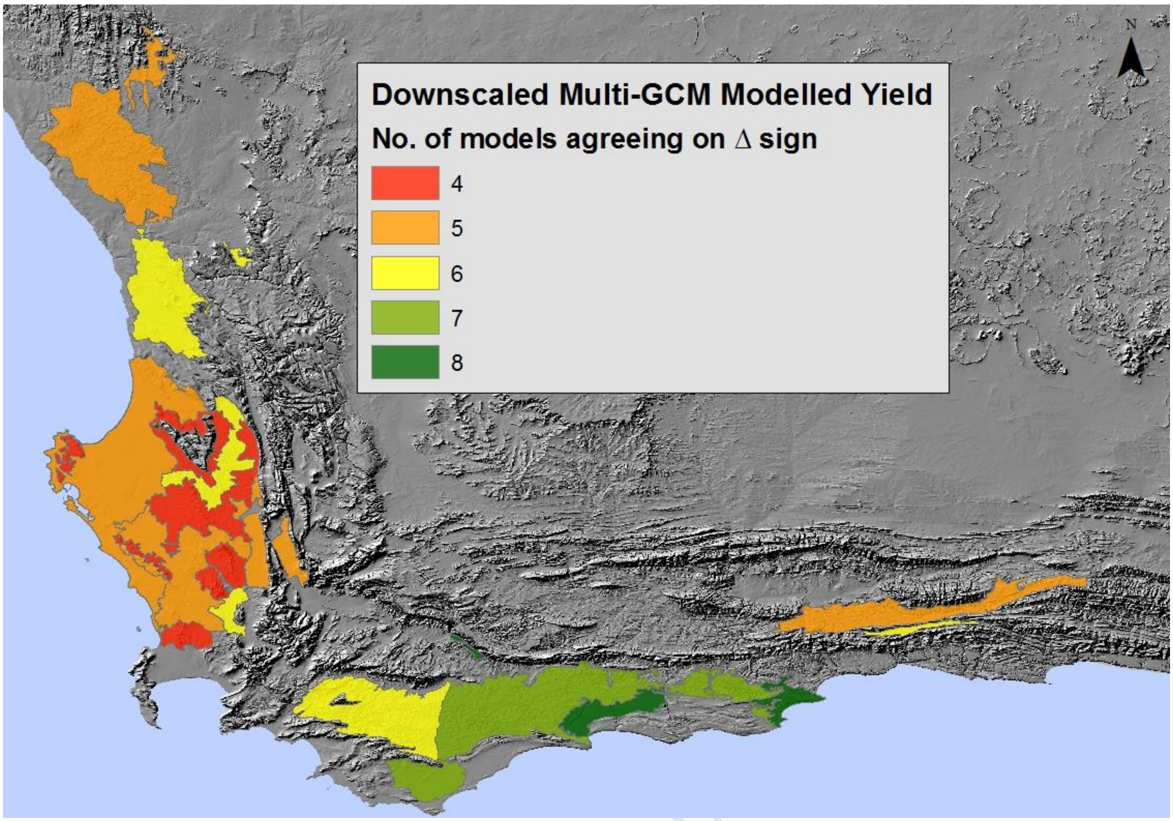


Figure 6.14. Number of models (from a total of 8) in agreement on sign of changes in modelled yields driven by the downscaled GCMs.

Selecting the median value within the envelope of downscaled GCM outputs results in a conservative impact approach where signal from the models at the extremes (both positive and negative) are in effect excluded from the (median) results discussed per zone. The analysis of the first and third quartiles (25th and 75th percentile) gives further insight into the spread of modelled outcomes (see Table 6.4 and the maps in Figure 6.15).

Table 6.4. Modelled yield outcomes (driven by downscaled, daily GCM data) at the first (Q1), second (Q2) and third (Q3) quartiles, for the future period 2046 – 2065 (control period 1979 – 1999). Areas where the sign of future yield change is inconclusive are shown in red.

| | Baseline | Sign | | Δ Yield (%) | | | Δ Yield (%) |
|---|---|---|---|---|---|---|---|
| RHFA | (kg/ha/annum) | Pos | Neg | Q1 | Q2 | Q3 | Range |
| Agter-Paarl | 2861 | 6 | 2 | -2.5 | 2.5 | 11.6 | 14.1 |
| Bo-Langkloof | 1918 | 6 | 2 | 0.4 | 9.3 | 25.1 | 24.7 |
| Bredasdorp/Strandveldvlakte | 2709 | 7 | 1 | 11.7 | 16.7 | 22.0 | 10.4 |
| Gemengde Boerderygebied | 3681 | 4 | 4 | -3.3 | -0.5 | 5.1 | 8.4 |
| Gourits-Rooiruens | 1990 | 7 | 1 | 4.8 | 9.5 | 15.7 | 10.9 |
| Gouritzriviervallei | 1897 | 7 | 1 | 8.8 | 10.9 | 15.1 | 6.4 |
| Graafwater/Sandveld | 1104 | 6 | 2 | 3.4 | 7.7 | 14.6 | 11.2 |
| Hardeveld | 429 | 5 | 3 | -6.9 | 14.1 | 18.3 | 25.2 |
| Hermon/Gouda | 3145 | 3 | 5 | -7.1 | -2.5 | 2.4 | 9.5 |
| Hoe Reenval Saaigebied | 3443 | 3 | 5 | -6.6 | -2.8 | 4.3 | 10.9 |
| Kamanassie | 1395 | 5 | 3 | -13.0 | 12.0 | 22.0 | 35.0 |
| Kleinberg/Suurrug | 1781 | 8 | 0 | 12.4 | 17.8 | 22.5 | 10.1 |
| Koringberg/Rooi Karoo Saaigebied | 1841 | 6 | 2 | 0.0 | 7.2 | 22.6 | 22.6 |
| Malgas/Heidelbergvlakte | 1741 | 8 | 0 | 5.5 | 11.3 | 15.6 | 10.1 |
| Middel Swartland Saaigebied | 3442 | 4 | 4 | -3.8 | 0.8 | 4.8 | 8.5 |
| Ruens East | 1911 | 7 | 1 | 7.6 | 20.6 | 23.5 | 15.9 |
| Ruens West | 3051 | 6 | 2 | 2.5 | 12.4 | 16.5 | 14.0 |
| Sandveld Saaigebied | 1676 | 5 | 3 | -5.7 | 6.5 | 11.9 | 17.6 |
| Stockwell | 1126 | 8 | 0 | 12.4 | 26.2 | 28.9 | 16.5 |
| Tulbagh/Wolseley | 2896 | 5 | 3 | -3.3 | 3.2 | 9.8 | 13.2 |
| Urionskraal | 641 | 6 | 2 | -0.2 | 3.6 | 11.5 | 11.7 |

Even at the first quartile, projected yields for the southern RHFAs appear positive. In this scenario, most of the western zones are generally negatively impacted, as is Kamanassie in the east, which shows the biggest potential loss in terms of yield percentage (Figure 6.15).

At the third quartile, modelled yield results appear positive for the entire province, with a trend for the southern and south-eastern zones likely to show the greatest improvement, together with the Koringberg/Rooikaroo (Figure 6.15).

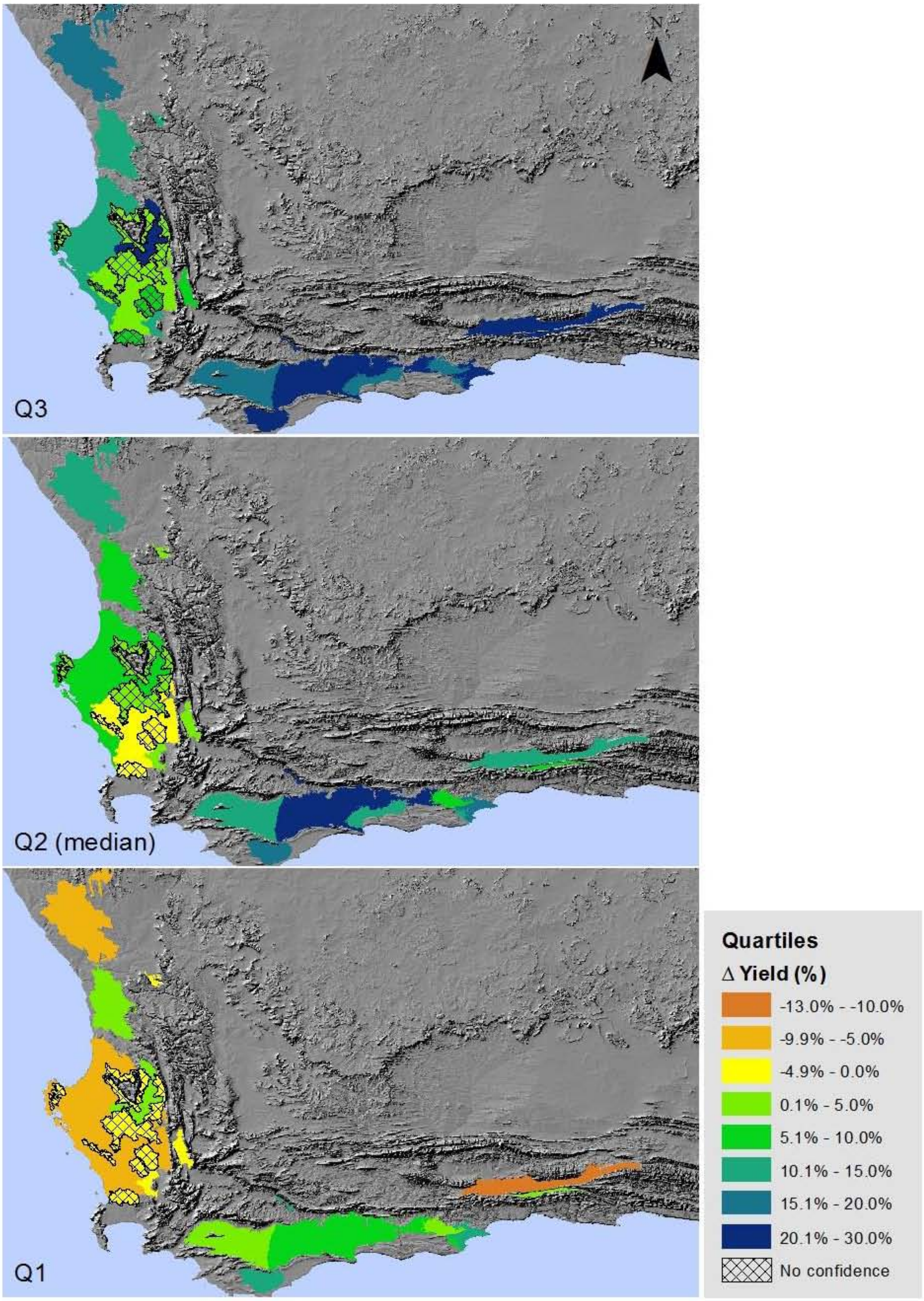


Figure 6.15. Modelled yield anomalies (driven by downscaled, daily GCM data) at the first (Q1), second (Q2) and third (Q3) quartiles, for the period 2046 – 2065 (control 1979 – 1999). Areas where the sign of future yield change is inconclusive are masked by the hatching.

In terms of presenting the "spread" of the modelling envelope, the standard deviation (SD) between modelled outcomes (the ensemble yield anomalies presented in Table 6.3) is shown in Figure 6.16. The spread of results expressed in terms of Δkg/ha/annum is highest in the south-west of the region, but this is where the highest yields are obtained. When normalised by the baseline yield (Figure 6.17), the standard deviation over the majority of zones is within 20% of zonal baseline yield - exceptions being the Hardeveld in the north-west and the Bo-Langkloof which proved to be an outlier with by far the highest deviation from the mean. On analysis of the outputs for this zone (Table 6.3) it can be seen that in this low yielding zone, both the echam5 and gfdl2_1 downscaled GCMs resulted in 1000 kg yield anomalies – the former negative and the latter positive. There was however moderate agreement amongst the remaining 6 downscaled GCM-forced outcomes in sign of change (5 of the remaining 6 were positive).

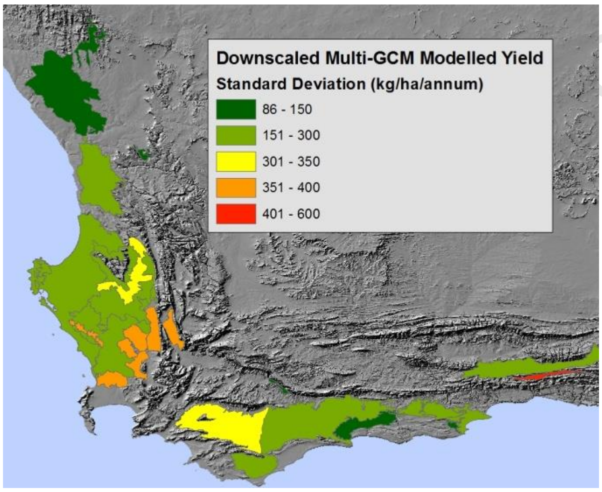


Figure 6.16. Standard deviation between downscaled multi-GCM driven yield anomalies.

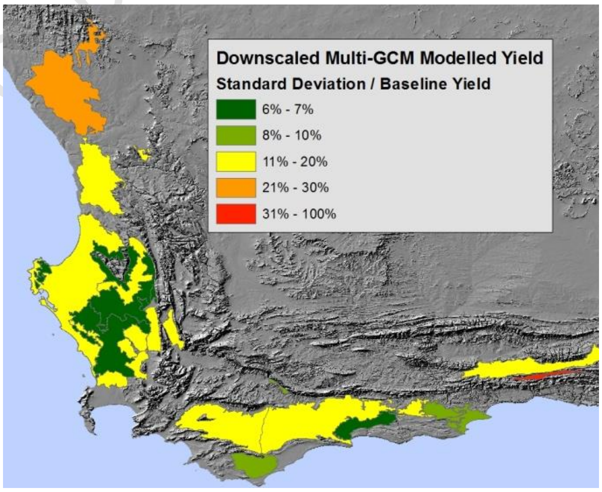


Figure 6.17. Coefficient of variation between downscaled GCM driven yield anomalies, indicating SD as a percentage of baseline zonal yield.

## 6.5 Temporal impacts on wheat growing season length and the potential influence of cultivar choice

The statistic often used for wheat in relation to season length is the number of days to anthesis or flowering. The temporal influences of climate change were thus assessed by modelling the number of days taken to reach the anthesis stage in each RHFA for each downscaled GCM at a daily time step. The model's planting rule requires the onset of rainfall events of 10mm (in less than 2 days) or more to commence planting of winter wheat in autumn. If this rainfall condition is not met by the end of May then planting is forced[20]. $CO_2$ levels were set to 500 ppm.

For 3 different season-length cultivars modelled for the period (2046 – 2065), the growth period from planting to anthesis was reduced by the number of days shown in Figure 6.18 compared to the control. Table 6.5 summarises the data outcomes of this analysis.

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[20] In reality, the commencement of planting is often determined by an individual farmer's farm system schedule, which in the more reliable rainfall areas, is based more on machinery capacity than rainfall. Farmers will thus often sow at a predetermined date each year.

Table 6.5. Modelled yield anomalies and days to anthesis for winter wheat under future (2046 – 2065), downscaled GCM modelled conditions for cultivars of 3 different season-lengths (control period 1979 – 1999).

| **RHFA** | Cultivar (Season length) | Baseline yield (kg/ha/annum) | Days to anthesis | | Statistics (kg/ha/annum) | | | | Δ Yield (%) |
|---|---|---|---|---|---|---|---|---|---|
| | | | Baseline Days | Future Days | Median | Max | Min | Range | |
| Agter-Paarl | Medium | 2861 | 113 | 96 | 71 | 673 | -558 | 1232 | 2.5 |
| Agter-Paarl | Short | 2680 | 102 | 87 | 75 | 511 | -618 | 1129 | 2.8 |
| Agter-Paarl | Long | 2832 | 127 | 108 | 201 | 730 | -402 | 1132 | 7.1 |
| Bo-Langkloof | Medium | 1918 | 139 | 115 | 178 | 1094 | -1096 | 2190 | 9.3 |
| Bo-Langkloof | Short | 1907 | 128 | 105 | 232 | 806 | -980 | 1786 | 12.1 |
| Bo-Langkloof | Long | 1961 | 152 | 128 | 213 | 1333 | -893 | 2226 | 10.9 |
| Bredasdorp/Strandveldvlakte | Medium | 2709 | 123 | 103 | 453 | 837 | -53 | 891 | 16.7 |
| Bredasdorp/Strandveldvlakte | Short | 2574 | 113 | 95 | 279 | 749 | -103 | 852 | 10.8 |
| Bredasdorp/Strandveldvlakte | Long | 2614 | 135 | 115 | 439 | 876 | -247 | 1123 | 16.8 |
| Gemengde Boerderygebied | Medium | 3681 | 113 | 96 | -19 | 543 | -803 | 1345 | -0.5 |
| Gemengde Boerderygebied | Short | 3373 | 102 | 87 | -13 | 150 | -734 | 884 | -0.4 |
| Gemengde Boerderygebied | Long | 3813 | 127 | 108 | 241 | 844 | -352 | 1196 | 6.3 |
| Gouritzriviervallei | Medium | 1897 | 118 | 101 | 207 | 451 | -24 | 475 | 10.9 |
| Gouritzriviervallei | Short | 1797 | 108 | 92 | 124 | 349 | -44 | 394 | 6.9 |
| Gouritzriviervallei | Long | 1932 | 132 | 113 | 300 | 648 | -218 | 866 | 15.5 |
| Gourits-Rooiruens | Medium | 1990 | 115 | 98 | 188 | 607 | -3 | 609 | 9.5 |
| Gourits-Rooiruens | Short | 1924 | 105 | 89 | 195 | 543 | -101 | 644 | 10.1 |
| Gourits-Rooiruens | Long | 1951 | 129 | 111 | 150 | 694 | 47 | 647 | 7.7 |
| Graafwater/Sandveld | Medium | 1104 | 112 | 92 | 85 | 362 | -263 | 626 | 7.7 |
| Graafwater/Sandveld | Short | 1151 | 104 | 85 | 47 | 356 | -226 | 581 | 4.1 |
| Graafwater/Sandveld | Long | 1063 | 123 | 102 | 106 | 329 | -272 | 601 | 10.0 |
| Hardeveld | Medium | 389 | 109 | 84 | 55 | 155 | -76 | 231 | 14.0 |
| Hardeveld | Short | 429 | 100 | 78 | 60 | 177 | -99 | 275 | 14.1 |
| Hardeveld | Long | 372 | 119 | 92 | 46 | 148 | -73 | 221 | 12.4 |
| Hermon/Gouda | Medium | 3145 | 113 | 97 | -78 | 701 | -609 | 1310 | -2.5 |
| Hermon/Gouda | Short | 2813 | 103 | 88 | -266 | 249 | -764 | 1013 | -9.5 |
| Hermon/Gouda | Long | 3323 | 127 | 109 | 45 | 1056 | -189 | 1246 | 1.4 |
| Hoe Reenval Saaigebied | Medium | 3443 | 111 | 97 | -96 | 258 | -322 | 579 | -2.8 |
| Hoe Reenval Saaigebied | Short | 2933 | 100 | 88 | -101 | 69 | -387 | 456 | -3.5 |
| Hoe Reenval Saaigebied | Long | 3688 | 124 | 109 | 99 | 625 | -300 | 925 | 2.7 |
| Kamanassie | Medium | 1395 | 137 | 113 | 167 | 355 | -236 | 591 | 12.0 |
| Kamanassie | Short | 1354 | 127 | 103 | 113 | 384 | -291 | 674 | 8.4 |
| Kamanassie | Long | 1518 | 150 | 126 | 153 | 431 | -285 | 715 | 10.1 |
| Kleinberg/Suurrug | Medium | 1781 | 114 | 98 | 318 | 556 | 11 | 546 | 17.8 |
| Kleinberg/Suurrug | Short | 1721 | 104 | 88 | 203 | 600 | -14 | 614 | 11.8 |
| Kleinberg/Suurrug | Long | 1830 | 128 | 110 | 387 | 528 | -233 | 761 | 21.1 |
| Malgas/Heidelbergvlakte | Medium | 1741 | 119 | 100 | 196 | 400 | 56 | 344 | 11.3 |
| Malgas/Heidelbergvlakte | Short | 1672 | 108 | 91 | 187 | 414 | -9 | 423 | 11.2 |
| Malgas/Heidelbergvlakte | Long | 1738 | 133 | 113 | 195 | 495 | -73 | 569 | 11.2 |
| Middel Swartland Saaigebied | Medium | 3442 | 114 | 97 | 28 | 390 | -262 | 651 | 0.8 |
| Middel Swartland Saaigebied | Short | 2966 | 103 | 89 | -461 | -211 | -644 | 433 | -15.5 |
| Middel Swartland Saaigebied | Long | 3610 | 128 | 110 | 2 | 750 | -461 | 1211 | 0.0 |
| Koringberg/Rooi Karoo Saaigebied | Medium | 1841 | 115 | 97 | 133 | 859 | -222 | 1082 | 7.2 |
| Koringberg/Rooi Karoo Saaigebied | Short | 1779 | 106 | 88 | 62 | 743 | -123 | 866 | 3.5 |
| Koringberg/Rooi Karoo Saaigebied | Long | 1891 | 127 | 107 | 164 | 877 | -129 | 1007 | 8.7 |
| Ruens East | Medium | 1911 | 120 | 101 | 393 | 504 | -136 | 640 | 20.6 |
| Ruens East | Short | 1875 | 109 | 92 | 303 | 447 | -253 | 700 | 16.2 |
| Ruens East | Long | 1854 | 134 | 114 | 422 | 639 | 68 | 571 | 22.8 |
| Ruens West | Medium | 3051 | 122 | 103 | 379 | 748 | -270 | 1018 | 12.4 |
| Ruens West | Short | 2914 | 111 | 94 | 282 | 627 | -347 | 974 | 9.7 |
| Ruens West | Long | 2950 | 136 | 116 | 261 | 862 | 106 | 756 | 8.8 |
| Sandveld Saaigebied | Medium | 1676 | 110 | 99 | 110 | 351 | -258 | 609 | 6.5 |
| Sandveld Saaigebied | Short | 1629 | 104 | 91 | 57 | 333 | -39 | 372 | 3.5 |
| Sandveld Saaigebied | Long | 1568 | 126 | 111 | 88 | 357 | -204 | 561 | 5.6 |
| Stockwell | Medium | 1126 | 122 | 100 | 295 | 384 | 91 | 293 | 26.2 |
| Stockwell | Short | 1134 | 112 | 92 | 279 | 425 | 14 | 410 | 24.6 |
| Stockwell | Long | 1051 | 134 | 111 | 254 | 363 | 54 | 309 | 24.1 |
| Tulbagh/Wolseley | Medium | 2896 | 122 | 102 | 92 | 650 | -484 | 1134 | 3.2 |
| Tulbagh/Wolseley | Short | 2936 | 112 | 92 | -27 | 683 | -571 | 1254 | -0.9 |
| Tulbagh/Wolseley | Long | 2844 | 135 | 114 | 293 | 666 | -212 | 878 | 10.3 |
| Urionskraal | Medium | 641 | 106 | 81 | 23 | 286 | -84 | 370 | 3.6 |
| Urionskraal | Short | 714 | 98 | 77 | 30 | 232 | -48 | 280 | 4.2 |
| Urionskraal | Long | 589 | 115 | 89 | 24 | 250 | -51 | 301 | 4.0 |

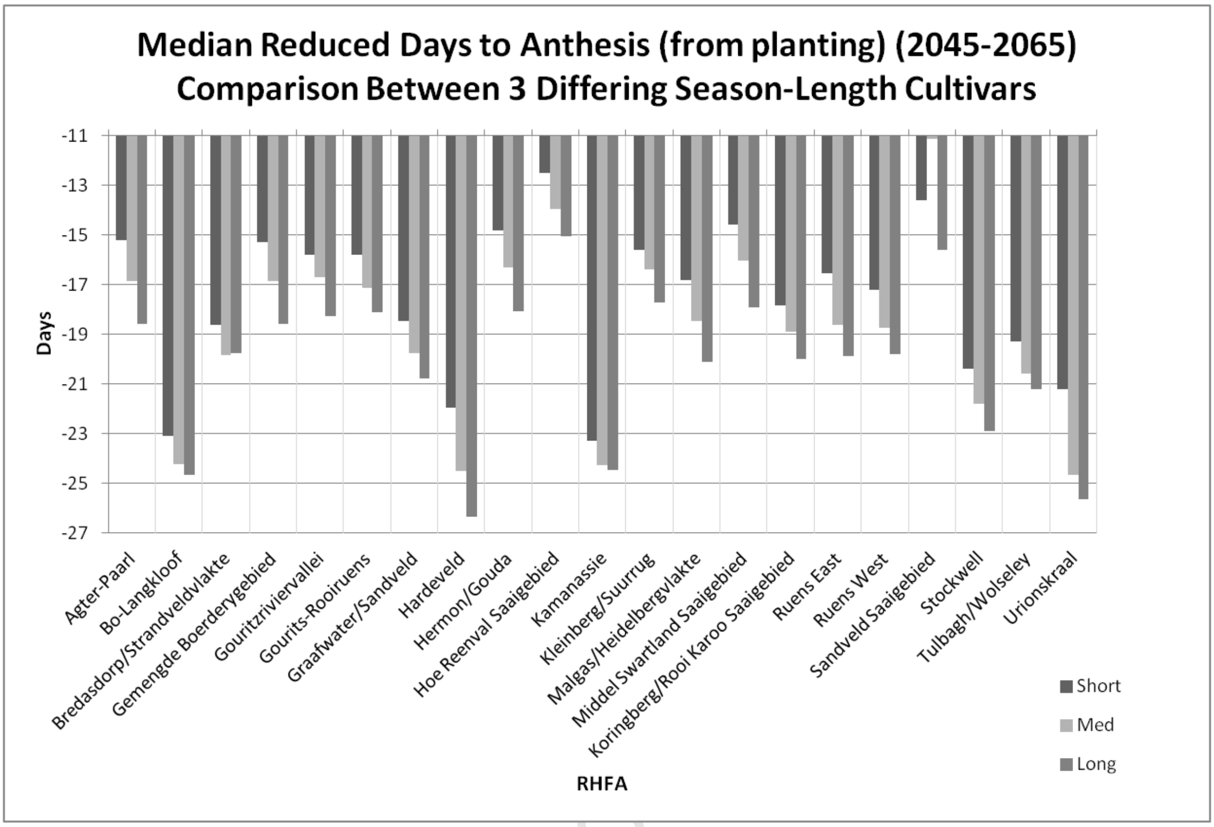

Figure 6.18. Reduction in number of days from planting to anthesis in wheat under future (2046 – 2065), downscaled GCM modelled conditions for cultivars of 3 differing season-length (control period 1979 – 1999).

The results are broadly consistent (in terms of the simulated accelerated phenology) with those found in similar conditions in Western Australia (Potgieter et al., 2013; Sadras and Monzon, 2006) as well as field experiments reported on by Sadras and Monzon (2006). Cultivars into the mid 21$^{st}$ century will most likely be developed with a better capacity to utlilise the elevated rates of $CO_2$ assimilation in a warmer climate (Jaggard et al., 2010) and the concept “early” or “late” maturing cultivars will necessarily be re-defined to match the future accelerated growing conditions. The results illustrate the impact that climate change will have on length of growing season, with the (current) low-production zones such as Bo-Langkloof, Hardeveld, Kamanassie, Stockwell and Urionskraal showing the greatest impacts. Models such as APSIM are strongly temperature driven and assume a linear effect of temperature on development for temperature between base and optimum, due to more rapid accumulation of growing degree days. For above-optimum temperature, APSIM assumes a declining rate of accumulation of thermal time. Further interactions of physiological process are discussed in Section 5.2.

In order to address the potential significance of cultivar choice under future temporal changes (greatly accelerated growing period), the yield impacts on currently available cultivars of different season-lengths is presented in Table 6.6 and Figure 6.19, which summarise the yield anomaly response of the different RHFAs to 3 different season-length cultivars, for the period 2046 to 2065.

Table 6.6. Modelled median future (2046-2065) yield response anomalies under future, downscaled GCM conditions for 3 different season-length cultivars. The Δ Yield (%) column expresses the yield response range expressed as a percentage of baseline (1979 – 1999).

| | (Baseline) | Med | Early | Late | Δ Yield Range | Δ Yield |
|---|---|---|---|---|---|---|
| RHFA | (kg/ha/annum) | (kg/ha/annum) | | | (kg/ha/annum) | (%) |
| Urionskraal | 641 | 23 | 30 | 24 | 7 | 1.0 |
| Malgas/Heidelbergvlakte | 1741 | 196 | 187 | 195 | 9 | 0.5 |
| Hardeveld | 389 | 55 | 60 | 46 | 14 | 3.7 |
| Stockwell | 1126 | 295 | 279 | 254 | 41 | 3.7 |
| Gourits-Rooiruens | 1990 | 188 | 195 | 150 | 44 | 2.2 |
| Sandveld Saaigebied | 1676 | 110 | 57 | 88 | 53 | 3.1 |
| Bo-Langkloof | 1918 | 178 | 232 | 213 | 54 | 2.8 |
| Kamanassie | 1395 | 167 | 113 | 153 | 54 | 3.9 |
| Graafwater/Sandveld | 1104 | 85 | 47 | 106 | 59 | 5.4 |
| Koringberg/Rooi Karoo Saaigebied | 1841 | 133 | 62 | 164 | 102 | 5.5 |
| Ruens West | 3051 | 379 | 282 | 261 | 119 | 3.9 |
| Ruens East | 1911 | 393 | 303 | 422 | 119 | 6.2 |
| Agter-Paarl | 2861 | 71 | 75 | 201 | 130 | 4.5 |
| Bredasdorp/Strandveldvlakte | 2709 | 453 | 279 | 439 | 174 | 6.4 |
| Gouritzriviervallei | 1897 | 207 | 124 | 300 | 175 | 9.3 |
| Kleinberg/Suurrug | 1781 | 318 | 203 | 387 | 184 | 10.3 |
| Hoe Reenval Saaigebied | 3443 | -96 | -101 | 99 | 200 | 5.8 |
| Gemengde Boerderygebied | 3681 | -19 | -13 | 241 | 260 | 7.1 |
| Hermon/Gouda | 3145 | -78 | -266 | 45 | 311 | 9.9 |
| Tulbagh/Wolseley | 2896 | 92 | -27 | 293 | 320 | 11.1 |
| Middel Swartland Saaigebied | 3442 | 28 | -461 | 2 | 489 | 14.2 |

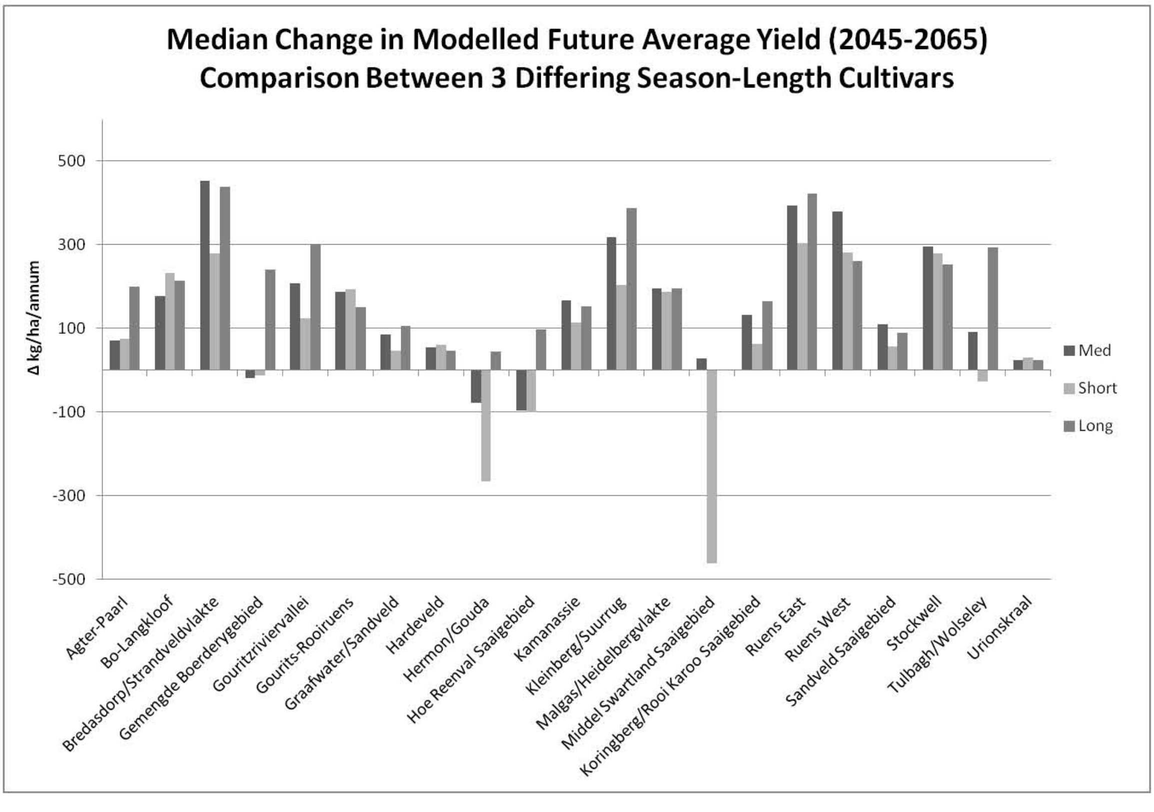

Figure 6.19. Modelled range of median future (2046 - 2065) yield response anomalies under future, downscaled GCM conditions for 3 different season-length cultivars (control period 1979 – 1999).

Based on current cultivar characteristics, in most cases the modelled range of responses to change in cultivar within each zone were relatively small, with the exceptions being Hermon/Gouda and its neighbouring Middel Swartland Saaigebied which show particularly strong *negative* responses to the use of an early maturing, short season cultivar. Tulbagh/Wolseley and the Gemengde Boerderygebied (all falling in the broader Swartland region) exhibited the highest sensitivities to cultivar choice under future conditions in terms of the modelled range of outcomes. A number of areas showed an improved yield response where a later-maturing variety was modelled. Zones such as Tulbagh/Wolseley, Kleinberg/Suurrug, Hoëreenval Saaigebied, Gemengde Boerderygebied and Agter-Paarl appear to perform better under a longer season (later-maturing) cultivar.

Although the scope of the study did not include adaptation issues, the development of cultivars and the issue of cultivar choice can reasonably be expected to play an important role in determining the yield outcomes under future warmer seasons which demonstrably lead to accelerated phenological development of wheat due to the more rapid accumulation of heat units, compounded by the fertilization effects on assimilation due to elevated $CO_2$ levels.

## 6.6 Investigating RHFA responses under lower nitrogen conditions

### 6.6.1 Introduction

This study has thus far focused primarily on simulated yield scenarios with soil inorganic nitrogen set at a high level – with no consideration of economic constraints. The intent was to assess impacts of climate change, rather than N fertiliser response. Furthermore it is recognised that the optimum N fertiliser would differ from year to year depending primarily on in-crop rainfall (Luo et al., 2005). It was identified however, that N fertilisation efficiency may change under future climate and $CO_2$ scenarios (Amthor, 2001).

Current nitrogen fertilisation in the Western Cape is highly dependent on farmer's specific management strategy, and may be varied year-to-year, depending on preceding rotation crop (or fallow), pre-season rainfall, and may even be adjusted to some extent within the season, by means of a top dressing N application. Whilst Western Cape N inputs are well below those used, for example, in high-production areas of Europe, local experts consulted did not consider the Western Cape to be necessarily a low-input wheat production area in terms of the primary wheat RHFAs. Application rates were above 100 kg/ha in many areas[21,22] (Agenbag, 2013; Strauss, 2013) where farmers fertilise to achieve perceived optimal yield potential, based on their economic outlook. Nitrogen fertilisation is largely guided by long-term rainfall averages to optimally achieve this long-term crop potential[23]. It is thus likely that particularly in the lower-production, secondary wheat zones, (described in Section 1.5) where wheat is usually produced as a fodder-flow support crop, that such low N inputs may be encountered.

### 6.6.2 Nitrogen response analysis methodology

In order to investigate the potential effects of future climate change on different RHFAs under limiting nitrogen levels, a nitrogen sensitivity analysis was undertaken using APSIM, driven by the same ensemble of downscaled GCMs described in Chapter 6, and using the same methodology – except that a range of N application rates was applied to each set of simulations per GCM, per RHFA. In an assessment of a wide range of APSIM calibration trials at various sites, mainly in Australia, Wang et al.,(2008) considered APSIM to have performed reasonably well including simulation of N response. Each of the 10 primary wheat production zones was modelled at baseline and future scenarios at 3 different N input levels; 120 kg/ha, 85kg/ha and 50kg/ha at planting. The secondary zones analyses included these 3 application rates, plus a lower rate of 20kg/ha. This range of N fertilisation rates was guided by the advice of Labuschagne (2013) and a local fertilisation guideline document (MVSA, 1999) to cover the range of N fertilisation likely to be encountered in the province.

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### 6.6.3 Results of the nitrogen analysis

The full yield results of the N-sensitivity model runs for the 10 primary RHFAs and for the 11 secondary wheat RHFAs are provided in graphs in Appendix VI. Table 6.7 and Table 6.8 summarise the resulting median yield anomalies for the period 2046 – 2065 for the primary and secondary RHFA groupings respectively. Figure 6.20 indicates the baseline responses (modelled on observed climate 1979 – 1999). This graph and the tables facilitate comparison between RHFAs' responses at different N levels as a percentage of the baseline simulated yield (1979 – 1999) at the corresponding N-level.

Contrary to initial expectations, for both the primary and secondary zonal analyses, the mean relative anomaly in percentage yield increased with decreasing N application. This increase in relative yield response at the lowest N level was evident at all 3 quartiles of the model ensemble results (see Table 6.7. and Table 6.8)

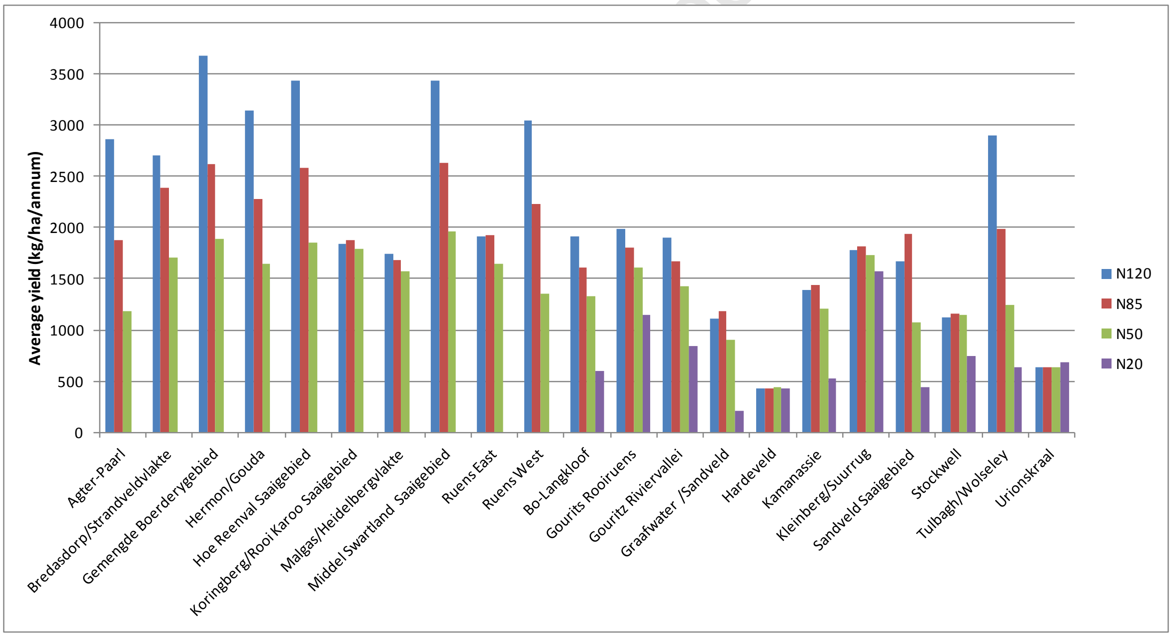

Figure 6.20. Baseline modelled yield at 3 levels of nitrogen application for the primary wheat RHFAs (50; 85; and 120 kg/ha/annum) and 3 levels of N application for the secondary RHFAs (20; 50; 85 and 120 kg/ha/annum).

The two groups of simulations (primary versus secondary wheat areas) did however differ in the *spatial* variability of future responses to decreasing N. The standard deviation of the yield anomalies indicates highest dispersion from the mean across zones under the lowest N level (20 kg/ha/annum) for the secondary wheat zones which may point to increased instability and yield risk across the secondary wheat zones under lower N inputs under future climate change.

Table 6.7. Yield anomaly for primary wheat RHFAs (2046 – 2065) at three different N fertilisation levels at the median, 1st quartile and 3rd quartile compared to each RHFA baseline yield (1979 – 1999), modelled at the corresponding N level. Negative anomalies are in red.

| | 1st quartile of ensemble yield results (Δ%) of baseline at N application level: | | | Median of ensemble yield results (Δ%) of baseline at N application level: | | | 3rd quartile of ensemble yield results (Δ%) of baseline at N application level: | | |
|---|---|---|---|---|---|---|---|---|---|
| **RHFA** | (N 120kg/ha) | (N 85kg/ha) | (N 50kg/ha) | (N 120kg/ha) | (N 85kg/ha) | (N 50kg/ha) | (N 120kg/ha) | (N 85kg/ha) | (N 50kg/ha) |
| Agter-Paarl | -3 | 6 | 12 | 2 | 10 | 16 | 12 | 16 | 30 |
| Bredasdorp/Strandveldvlakte | 12 | 9 | 13 | 17 | 15 | 15 | 22 | 24 | 19 |
| Gemengde Boerderygebied | -3 | 4 | 8 | -1 | 7 | 14 | 5 | 12 | 30 |
| Hermon/Gouda | -7 | 2 | 5 | -2 | 9 | 24 | 2 | 16 | 32 |
| Hoe Reenval Saaigebied | -7 | -1 | 11 | -3 | 8 | 18 | 4 | 18 | 25 |
| Koringberg/Rooi Karoo Saaigebied | 0 | 3 | 2 | 7 | 9 | 11 | 23 | 20 | 27 |
| Malgas/Heidelbergvlakte | 5 | 5 | 2 | 11 | 13 | 6 | 16 | 17 | 15 |
| Middel Swartland Saaigebied | -4 | 0 | 10 | 1 | 9 | 17 | 5 | 20 | 30 |
| Ruens East | 8 | 6 | 0 | 21 | 21 | 19 | 24 | 25 | 25 |
| Ruens West | 3 | 7 | 6 | 12 | 11 | 14 | 17 | 18 | 21 |
| Average | 0 | 4 | 7 | 7 | 11 | 15 | 13 | 18 | 25 |
| Median | -1 | 4 | 7 | 5 | 10 | 16 | 14 | 18 | 26 |
| Standard deviation | 6 | 3 | 4 | 8 | 4 | 5 | 8 | 4 | 5 |

Table 6.8. Yield anomaly for secondary wheat RHFAs (2046 – 2065) at four different N fertilisation levels at the median, 1st quartile and 3rd quartile compared to each RHFA baseline yield (1979 – 1999), modelled at the corresponding N level. Negative anomalies are in red.

| | 1st quartile of ensemble yield results (Δ%) of baseline at N application level: | | | | Median of ensemble yield results (Δ%) of baseline at N application level: | | | | 3rd quartile of ensemble yield results (Δ%) of baseline at N application level: | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **RHFA** | (N 120kg/ha) | (N 85kg/ha) | (N 50kg/ha) | (N 20kg/ha) | (N 120kg/ha) | (N 85kg/ha) | (N 50kg/ha) | (N 20kg/ha) | (N 120kg/ha) | (N 85kg/ha) | (N 50kg/ha) | (N 20kg/ha) |
| Bo-Langkloof | 0 | -13 | 3 | 23 | 9 | 12 | 15 | 40 | 25 | 21 | 22 | 47 |
| Gourits Rooiruens | 5 | 0 | 4 | 10 | 9 | 15 | 10 | 13 | 16 | 17 | 15 | 19 |
| Gouritz Riviervallei | 9 | 6 | 9 | 9 | 11 | 10 | 11 | 12 | 15 | 16 | 15 | 20 |
| Graafwater /Sandveld | 3 | 3 | 0 | -26 | 8 | 6 | 6 | -8 | 15 | 12 | 13 | 43 |
| Hardeveld | -7 | -7 | -7 | -5 | 14 | 14 | 14 | 16 | 18 | 18 | 18 | 22 |
| Kamanassie | -13 | -12 | 0 | 17 | 12 | 13 | 14 | 37 | 22 | 26 | 23 | 48 |
| Kleinberg/Suurrug | 12 | 13 | 13 | 10 | 18 | 18 | 17 | 16 | 22 | 22 | 23 | 20 |
| Sandveld Saaigebied | -6 | -2 | 0 | 4 | 7 | 4 | 7 | 25 | 12 | 9 | 19 | 37 |
| Stockwell | 12 | 17 | 14 | 12 | 26 | 25 | 24 | 21 | 29 | 29 | 31 | 41 |
| Tulbagh/Wolseley | -3 | -1 | 4 | 14 | 3 | 9 | 13 | 31 | 10 | 11 | 19 | 46 |
| Urionskraal | 0 | -1 | 0 | 1 | 4 | 6 | 6 | 5 | 11 | 12 | 12 | 11 |
| Average | 1 | 0 | 4 | 6 | 11 | 12 | 13 | 19 | 18 | 18 | 19 | 32 |
| Median | 0 | -1 | 3 | 10 | 9 | 12 | 13 | 16 | 16 | 17 | 19 | 37 |
| Standard deviation | 8 | 9 | 6 | 12 | 6 | 6 | 5 | 13 | 6 | 6 | 5 | 13 |

It is possible that choosing the median – or indeed the 1st or 3rd quartile of ensemble results may obscure some of the detail and processes at work (Hardy, 2013, personal communication). Whilst beyond the main scope of this study, a preliminary investigation was undertaken into some of the RHFA responses to different downscaled GCMs in the ensemble. Some further discussion and graphs of all the ensemble N responses per RHFA are available in Appendix VI. (Future downscaled GCM rainfall projections for comparative purposes are in Appendix III).

In order to assess changes in *temporal* variability, an analysis of changes in the coefficient of variation (CV%) of annual yield results was undertaken on the annual yield outputs for each downscaled GCMs future (2045 – 2065) and control (1979 – 1999). Nitrogen applications did not however, have a general impact on the *direction* of change in future variability (see Figure 6.21). The result is presented in Section 6.7 in the context of likely increases in production risk. (The only RHFAs where median future interannual variation were shown to be generally increasing, are the marginal wheat zones of Bo-Langkloof, Kamanassie, Stockwell and Urionskraal, with the higher N treatments increasing CV% slightly in the Koringberg/Rooikaroo, shown in Figure 6.21, page 165).

### 6.6.4 Discussion on responses to different nitrogen application levels under modelled future climate

Even at lower N application levels, the modelled responses to changed climate and increased $CO_2$ levels were mostly positive over the 21 RHFAs relative to each RHFA's baseline, modelled at the corresponding N level. A similar response was encountered in large parts of the UK (Cho et al., 2012) and was noted by Asseng et al. (2008) although the authors noted that the phenomenon was not in evidence on lighter and sandy soils. Interestingly the only RHFA to show a substantial reduction in relative yield (at the 1st and 2nd quartiles) at the lowest N-level, was the very sandy Graafwater RHFA, noted in the RDP archive documentation (Department of Agriculture Western Cape, 1990) to have a low-nutrient status and to be subject to rapid leaching of N (Section 1.5.2).

The way in which APSIM simulates the turnover and mineralisation of nitrogen in the soil using the SOILN module, is described by Probert et al.,(1998) and is presented in graphic detail on the APSIM Website (www.apsim.info/Wiki/SoilN.ashx). Nitrogen limitation first reduces leaf area development and then affects radiation use efficiency as it becomes more severe. Critical nitrogen concentrations, which vary with phenological stage, determine the nitrogen allocation within the plant. Nitrogen uptake is a function of root length and distribution, $NO_3$ and $NH_4$ concentration in the soil and soil water content. (Asseng et al., 2004). The latter factor seems to be a critical issue in the Western Cape with its shallow soils. Nitrogen (or water) limitations result in reduced leaf expansion, accelerated leaf senescence or tiller death (Reyenga et al., 1999a). The authors show nitrogen availability to benefit from increased temperature and increased soil moisture (up to a certain level) which may partially explain the future (relatively) improved response to lower N levels simulated in RHFAs under simulated warmer, and in places wetter, conditions. However, in the shallow soils and predominantly moisture-limited wheat conditions of the Western Cape, it is likely that the plants are unable to fully utilise the nitrogen at high N levels where rainfall distribution and resulting soil moisture is unfavourable (Hardy, 2013, personal communication) - a modelled response also noted by Asseng et al.,(2004). Thus in the (drier) secondary wheat zones – even at baseline conditions, there is relatively little difference in response to higher N levels, except for Tulbagh/Wolseley (see Figure 6.20) which has the highest rainfall of the secondary zones.

In a number of RHFAs, the lower rainfall projections within the downscaled GCM ensemble envelope during June, July and August resulted in correspondingly lower responses to increased N under that projection (see examples in Appendix VI). This was not evident in all cases, however. The modelled shortening of the growing season and accelerated phenology under increased temperature and $CO_2$, appeared to induce the so-called “haying-off” effect – the observed negative grain yield response of wheat to nitrogen fertiliser under certain conditions (van Herwaarden et al., 1998). Particularly in the primary wheat zones under future $CO_2$ levels, the effect is likely to arise from the rapid early vegetative growth (in response to the high N), leading to large crop canopies with high evapotranspiration demand thereby depleting soil moisture and resulting in lower yields (van Ittersum et al., 2003a). This may explain the relatively lower response to higher N where (relatively high) rainfall falls away rapidly after July/August (Hermon/Gouda, Gemengde Boerderygebied and Hoe Reenval Saaigebied), compared to Rûens East, Bredasdorp/Strandveldvlakte and Malgas/Heidelbergvlakte where the terminal drought influence is not as prevalent due to the increased portion of spring and early-summer rainfall (see Appendix III). In the secondary zones, Tulbagh/Wolsely, Kamanassie and Bo-Langkloof show signs of this “haying-off” effect.

Whilst further research may reveal some of the complex relationships and nitrogen interactions at work, such a study should be supported by field trial verification i.e. FACE conditions on shallow, low water holding capacity soils. Weigel and Manderscheid (2012) found some evidence for increased nitrogen use efficiency under experimentally simulated future (warmer and higher $CO_2$ ) low-N conditions in wheat, and report on evidence for this phenomenon by Chinese researchers on rice as well.

However, within the simulation context of this study, the question asked was if climate change would result in relatively lower yield responses on wheat grown under nitrogen-limited conditions. According to the modelled responses at each quartile of the ensemble, the situation is unlikely to arise as a general rule, with overall relative increases in yield modelled at lower N applications under future conditions. Asseng et al. (2008) found similar responses in the Mediterranean climate of Western Australia.

The variation in some zonal N responses forced by different GCM downscaling indicates a strong sensitivity to the particular GCM downscaling particularly in certain RHFAs. Given that temperatures are fairly uniformly modelled, this seems likely to be a consequence of these rainfall distributions in the context of very shallow soils and moisture-limited growth conditions in the Western Cape. Once again, some site specificity appears to play a critical role in the evaluation of changing management-determined impacts under climate change. Detailed parameterisation for APSIM soil chemical properties (i.e. laboratory analysis specifically aimed at APSIM soil parameterisation) is not available for local conditions, and will be required if this phenomenon is to be pursued further with improved confidence. Whilst some researchers consider APSIM to have performed well in simulating N-response in a wide range of experiments (e.g. Asseng et al., 1998; Ludwig and Asseng, 2010; Reyenga et al., 1999a) including under FACE conditions, work remains to be done to increase confidence in simulating the complexity of responses to wheat to N fertilisation under the concerted impacts of future climate change and $CO_2$ levels and to develop the finer nuances in the ability of APSIM to correctly calculate N demand and distribution at a plant physiological level (Foulkes et al., 2009). Considered together with the reported zonal response variation and inherent physiological complexities, N-fertilisation response must be added to the list of potential uncertainties to be considered when interpreting future yield impact simulations. Nonetheless the simulations suggest that tactical application of nitrogen (e.g. split applications and topdressing according to in-season rainfall forecast) to avoid unsustainable early vigourous canopy growth may present an adaptation option to optimise the economic use of nitrogen fertiliser under future conditions. (It is also possible that future cultivar development and selection may address this local issue).

## 6.7 Assessment of future wheat production variability and risk per RHFA based on annual downscaled GCM-forced model outcomes

A projection of future wheat production purely in terms of long-term yield averages neglects an important component of agricultural planning. A farmer or economist interested in future farming conditions is likely to also be interested in the level of risk related to yield variability, in terms of the number of years of crop failures that may be anticipated. Simulated results have shown that increased temperature and $CO_2$ concentration can lead to a decrease in interannual variability of wheat yield (Wang et al., 2011) which was also evident in a South African-scale crop modelling study (Estes, 2011, personal communication) using DSSAT. Figure 6.21 shows the modelled median change in coefficient of variation percentage (CV%) between annual yields per downscaled GCM for the future period (2046 -2065) and their control period (1979 – 1999). Different nitrogen levels generally did not play a role in changing the sign (+ or -) of interannual variability, with only Koringberg/Rooikaroo showing slightly increased variability under the higher N treatments, compared to a reduction under the low N treatment. The already marginal areas of Stockwell, Urionskraal, Bo-Langkloof and Kamanassie seem likely to suffer increasing variability in interannual yield in the future.

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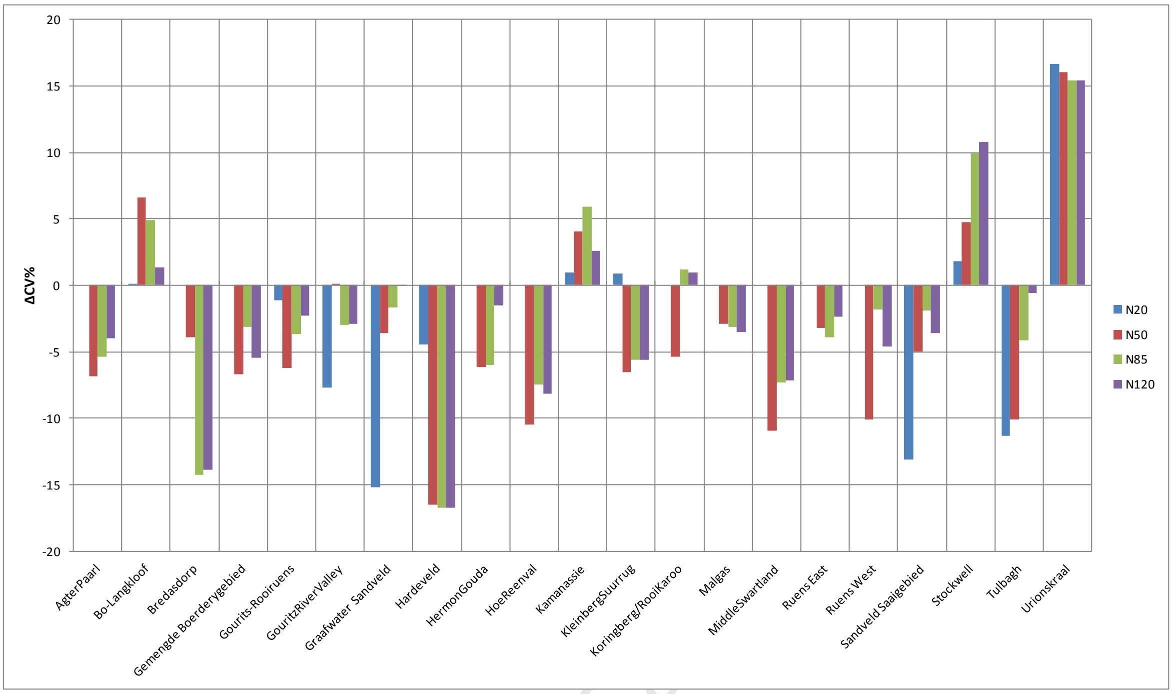

Figure 6.21. Graph comparing median (of downscaled GCM ensemble) changes in CV% between interannual yields [(CV% future 2046 – 2065) – CV% control (1979 – 1999)] per RHFA under different N application levels. Note – there was no 20kg/ha application in the primary wheat zones.

Whilst 1 ton/ha wheat grain yield would be considered a very successful crop in the Hardeveld, in the Swartland this would be considered a crop failure. For comparative purposes an index was therefore derived using 50% of the long-term average baseline as being indicative of potential crop failure "threshold" for the zone. For a 20 year period of control (1980-1999) and future (2046-2065) modelled annual yields (at 120kg/ha N levels), these values could be calculated and compared. This is not an economically rigorous index, but serves to compare current and future yield variability in terms of years in which production outputs drop below a "crop failure" threshold for the particular zone.

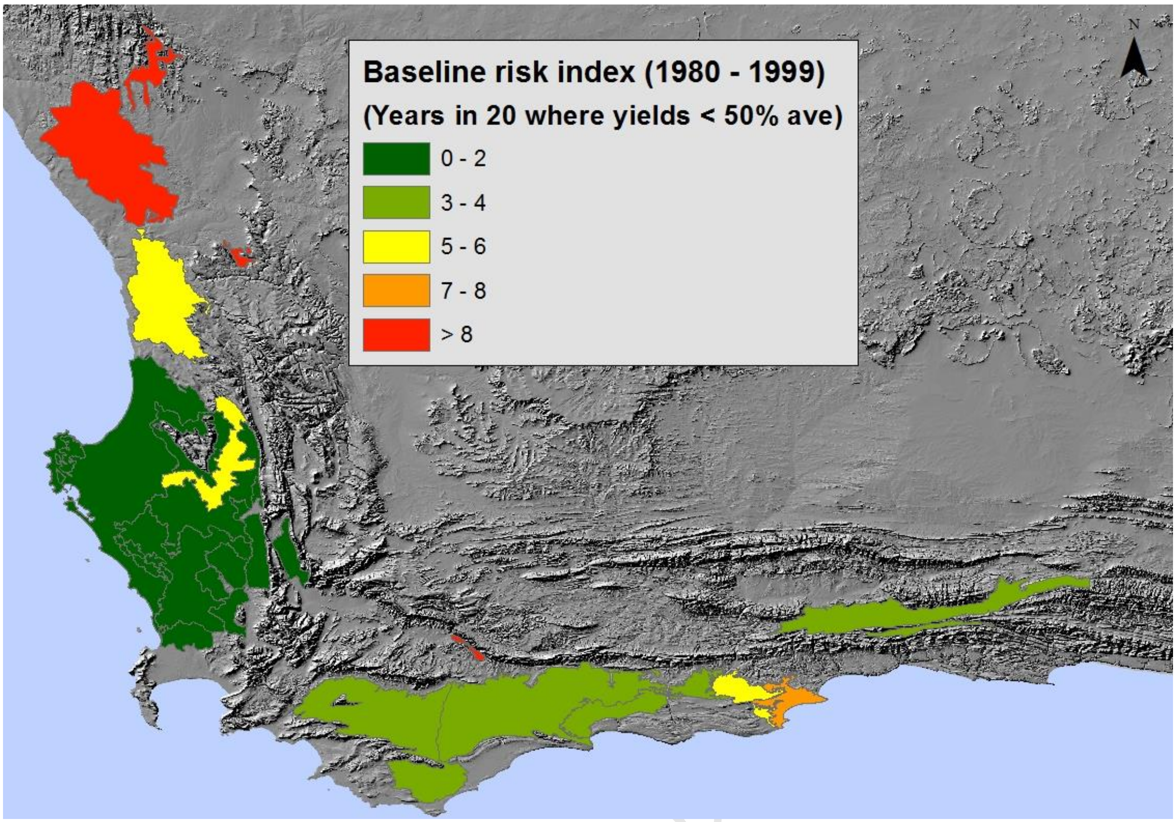

Figure 6.22. Baseline risk index (number of years out of 20 in which yield falls below 50% of the long-term average) for a 20 year control period between 1980 and 1999.

Figure 6.22 maps the baseline risk index for the control period 1980 – 1999 per RHFA. Table 6.9 summarises the number of years where crop failures are projected to occur under future conditions corresponding to the 1st, 2nd and 3rd quartile of modelled yield anomalies (shown in Figure 6.15, page 150). Because there is an even number of downscaled GCMs in the modelled envelope, the average between the 2 “median” ranked values (4th and 5th in the rank) is used to calculate the projected crop failure index for the 2nd quartile for each zone (leading to the “half year” values in some cases).

Table 6.9. Comparison between the 20-year baseline (1980-1999) and future (2046-2065) projected crop failure indicators for the downscaled GCMs corresponding with the 1st, 2nd and 3rd quartile of modelled yield outcomes. The expected *change* in no. of years is given for the median (Q2) value. The list is ranked from lowest to highest based on the baseline risk. The "half year" values are a result of averaging the 2 centrally ranked values to derive the 2nd quartile.

| | Baseline | Q1 | Q2 | Q3 | Q2 |
|---|---|---|---|---|---|
| RHFA | Years | | Years | | Δ Years |
| Agter-Paarl | 0 | 0 | 0 | 0 | 0 |
| Gemengde Boerderygebied | 0 | 0 | 0.5 | 0 | 0.5 |
| Hermon/Gouda | 0 | 0 | 0 | 0 | 0 |
| Hoe Reenval Saaigebied | 0 | 0 | 0 | 0 | 0 |
| Middel Swartland Saaigebied | 0 | 0 | 0 | 0 | 0 |
| Sandveld Saaigebied | 0 | 0 | 0 | 1 | 0 |
| Tulbagh/Wolseley | 0 | 1 | 0 | 0 | 0 |
| Bredasdorp/Strandveldvlakte | 3 | 0 | 0.5 | 0 | -2.5 |
| Malgas/Heidelbergvlakte | 3 | 3 | 4.5 | 6 | 1.5 |
| Ruens East | 3 | 2 | 1.5 | 0 | -1.5 |
| Ruens West | 3 | 1 | 2 | 0 | -1 |
| Bo-Langkloof | 4 | 2 | 4.5 | 3 | 0.5 |
| Kamanassie | 4 | 5 | 4.5 | 2 | 0.5 |
| Gourits-Rooiruens | 5 | 3 | 5 | 3 | 0 |
| Gouritzriviervallei | 6 | 5 | 4.5 | 6 | -1.5 |
| Graafwater/Sandveld | 6 | 6 | 6 | 6 | 0 |
| Koringberg/Rooi Karoo Saaigebied | 6 | 7 | 7 | 2 | 1 |
| Kleinberg/Suurrug | 7 | 3 | 5 | 9 | -2 |
| Hardeveld | 9 | 9 | 7.5 | 10 | -1.5 |
| Stockwell | 9 | 10 | 8.5 | 10 | -0.5 |
| Urionskraal | 9 | 12 | 9 | 9 | 0 |

The results were not indicative of large scale future *changes* in risk with regard to yield variability and crop failure, even when the models were examined which corresponded with the lower quartile of yield outcomes (Q1), with the exception of Urionskraal. Those areas experiencing current high variability and risk are likely to remain in that predicament into the mid-century study period (Figure 6.23).

There was no correlation evident between the risk indicators at the various (envelope of yield anomalies) quartiles. In both Kleinberg/Suurrug and Malgas/Heidelbergvlakte the risk index corresponding to the 3rd quartile yield outcome showed a greater increase than that of the 1st quartile. In both cases the climate model at the 3rd quartile was the downscaled GFDL_CM2.1 GCM. It appears that when forced by this downscaled GCM in these zones, APSIM models a higher inter-annual wheat yield variation than when forced by those producing lower (long-term average) yields.

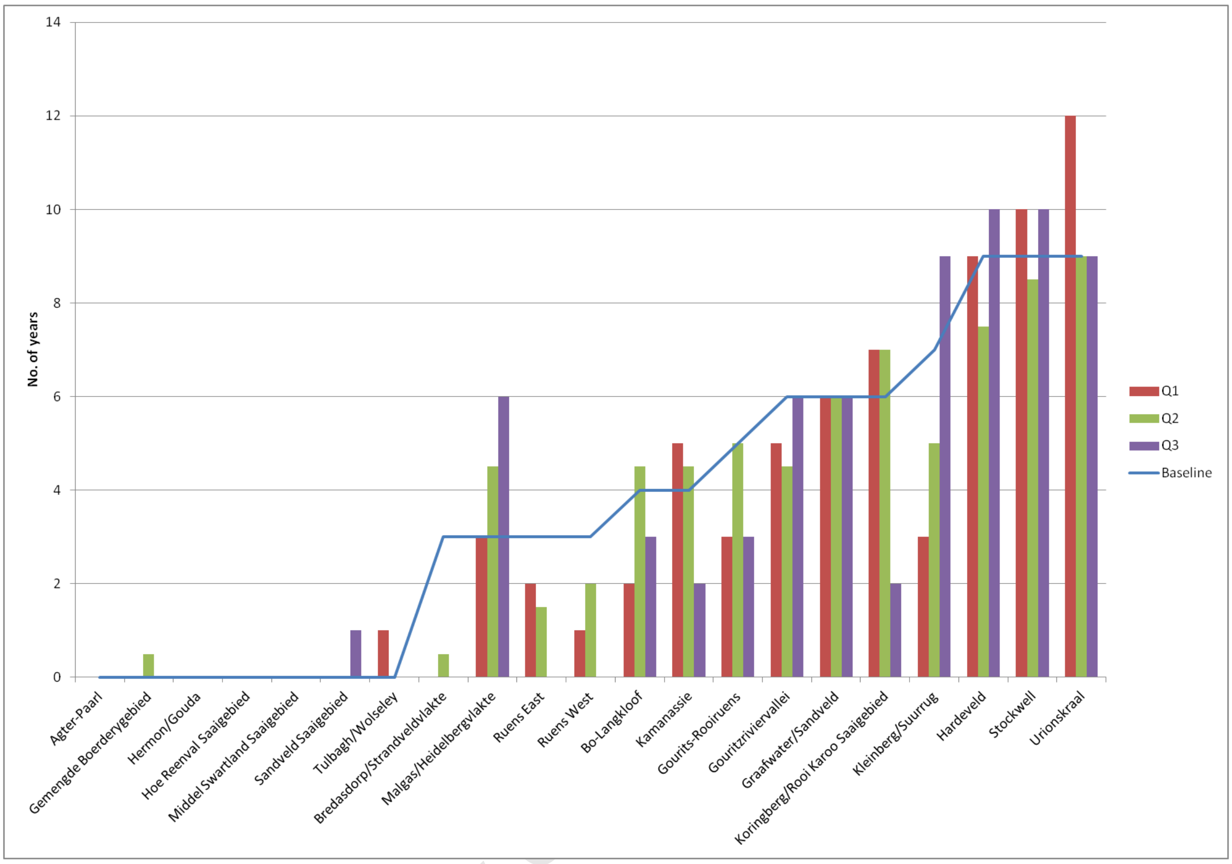

Figure 6.23. Comparison between no. of years in which crop failures can be expected at the baseline (1980-1999) and future (2046-2065) for the downscaled GCMs corresponding with the 1st, 2nd and 3rd quartile of modelled yield outcomes.   The list is ranked from lowest to highest according to the baseline.

Considering the median (Q2) yield outcome only, seven of the 21 zones demonstrated slightly reduced future risk of crop failure, five zones showed slightly increased risks likely in the future, whilst the remaining 9 showed no change.  Of those likely to see an increase in risk are the Koringberg/Rooikaroo – already a region susceptible to high yield variability and Malgas/Heidelbergvlakte – as well as the more marginal wheat zones of Bo-Langkloof and Kamanassie, which both currently produce wheat under high risk conditions.  Bredasdorp/Strandveldvlakte is likely to experience the greatest improvement in production reliability at the median (2nd quartile) of yield outcomes (Figure 6.24).

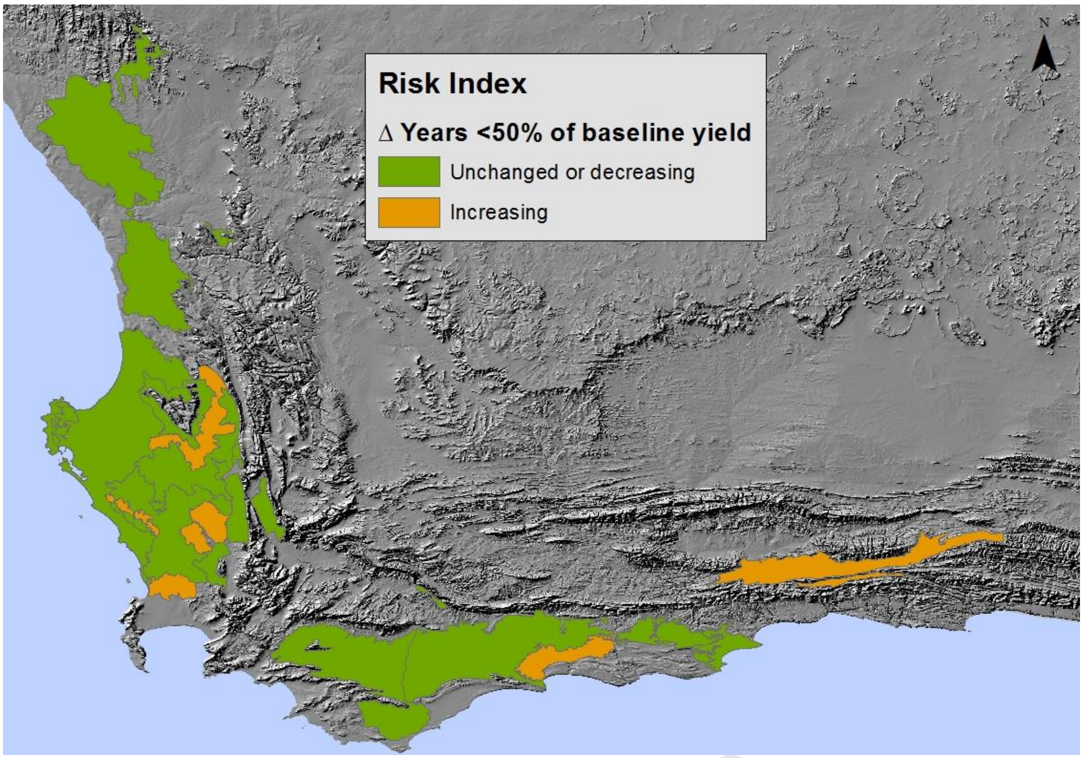

Figure 6.24. Zones where wheat production risk is expected to either decrease or remain at current levels; or increase, between a 20 year baseline (1980-1999) and the 20 year future study period (2046–2065) at the 2nd quartile of yield outcomes per RHFA.

Based on the direction of change in CV%, and the "risk index" discussed above, there is no signal evident in the future projections for a widespread increase in risk by mid 21st century. Those RHFAs where increasing interannual wheat production risk is likely are summarised in Table 6.10. This is consistent with the findings of van Ittersum et al. (2003a) for Western Australia under projected future conditions.

Table 6.10. RHFAs simulated to experience increased wheat production risk by mid 21st century.

| Risk index method | Increasing CV% |
|---|---|
| Koringberg/Rooikaroo | Bo-Langkloof |
| Malgasheidelbergvlakte | Kamanassie |
| Bo-Langkloof | Stockwell |
| Kamanassie | Urionskraal |
|  | Koringberg/Rooikaroo (under higher N) |

# Chapter Seven: Discussion - zonal wheat production impacts under modelled conditions

## 7.1 Introduction

Model results from the analyses in the preceding three chapters address one of the introductory assertions made in Chapter One of this study, that due to the heterogeneity of the province, “blanket” statement regarding the future of local wheat yields under climate change may be misleading if incorrectly interpreted, and that a downscaled, zonal approach would be required to assess the local responses.

Table 7.1. Summary of modelled yield impacts across all RHFAs. (The minimum value in each column is in blue, the maximum value is green). Q = the quartile of outcomes within the yield envelope of APSIM runs based on downscaling of each 8 GCMs for each RHFA.

| Modelled impact scenario | Δ Yield* (kg/ha/annum) | | | | | | |
|---|---|---|---|---|---|---|---|
| | Average | 90th percentile | 10th percentile | Median | Max | Min | Range |
| **Perturbed Baseline** | | | | | | | |
| +1 °C | -118 | 1 | -245 | -136 | 112 | -282 | 394 |
| +2 °C | -284 | -20 | -561 | -328 | 145 | -625 | 770 |
| -10% Rainfall | -171 | 47 | -347 | -177 | 103 | -773 | 876 |
| +10% Rainfall | 114 | 288 | -90 | 172 | 329 | -121 | 450 |
| +2 °C & 500ppm & -10% Rain | -125 | 169 | -292 | -141 | 190 | -766 | 956 |
| +2 °C & 500ppm & +10% Rain | 156 | 332 | 11 | 147 | 351 | -61 | 412 |
| +2 °C & 500ppm | 41 | 148 | -51 | 40 | 182 | -112 | 294 |
| **Downscaled GCM (Q2)** | | | | | | | |
| CO2 500ppm, med cultivar | 152 | 379 | -19 | 133 | 453 | -96 | 549 |
| CO2 500ppm, short cultivar | 79 | 279 | -101 | 75 | 303 | -461 | 764 |
| CO2 500ppm, long cultivar | 194 | 387 | 45 | 195 | 439 | 2 | 437 |
| CO2 400ppm, med cultivar | -66 | 116 | -427 | -5 | 200 | -534 | 733 |
| **Downscaled GCM (Q1)** | | | | | | | |
| CO2 500ppm, med cultivar | 6 | 166 | -181 | 0 | 317 | -227 | 544 |
| **Downscaled GCM (Q3)** | | | | | | | |
| CO2 500ppm, med cultivar | 288 | 481 | 79 | 286 | 597 | 73 | 524 |

* Baseline average yield across all RHFAs is 2100kg/annum (1979 - 1999)

Table 7.1 (above) summarises the range of modelled scenarios outcomes (both in terms of sensitivity analyses and future projections) from the preceding three chapters. Given that the averaged yield across all RHFAs is in the order of 2.1 tons/ha, the ranges in modelled yield anomalies per zone were from a low of 14% (294 kg/ha/annum) of that average yield, to a high of 45% (956 kg/ha/annum).

The impact scenario producing the greatest likely increase, or "best case" yield across all RHFAs, was the third quartile (Q3) of downscaled-GCM future yield outcomes (average increase of 288 kg/ha/annum). The sensitivity analysis for a 2°C increase in temperature *without* concomitant increase in $CO_2$ produced the "worst case" outcome (average decrease of 284 kg/ha/annum). In both cases the associated range of zonal outcomes was greater than 500 kg/ha/annum.

This chapter presents a review of the two modelling approaches, followed by a zonal synthesis and discussion of the modelled yield impacts per RHFA, demonstrating the variability of responses at different locations. Some likely implications and adaptations for wheat production into the mid-century future are discussed per RHFA.

## 7.2 The perturbed climate baseline approach and the downscaled GCM daily data approaches used in this study – a review

There is some temptation to compare the modelled outputs of the two modelling approaches in terms of representing future wheat production scenarios. Comparison should be avoided, since they represent different approaches towards different ends, as previously discussed.

Any application of process-based crop models such as APSIM or DSSAT in climate impact studies require the availability of *daily* climate data sets. Where reliable, downscaled future data are available at a daily time-step, this would be the preferred methodology to adopt for future impact assessment. The value of the perturbed baseline approach resides nonetheless in its contribution to the understanding of the impact of individual changes (and concerted changes) as defined and controlled by the user to assess particular sensitivities. In the absence of suitable *daily* downscaled GCM data, the baseline perturbations should at least be guided by the best available downscaled GCM mean anomalies available (on a grid or a zonal basis) in an attempt to simulate spatial variation in expected impacts.

The attractiveness of the baseline perturbation approach lies in the following:

- Its accessibility; all that is needed in terms of crop model input is a properly formatted “clean” *baseline* climate data set and the ability to modify input parameter values by defined “perturbations”.
- It has the advantage of isolating the impacts of individual parameters (or defined combinations thereof) for analytical purposes.
- The skill of downscaling precipitation patterns is currently not high – it may be argued that perturbation of current patterns may provide a useful proxy until GCM and downscaling skill improves in this area.
- It allows some informed evaluation of sensitivities and potential impacts where GCM downscaling-based modelling results lack confidence.

The use of downscaled multi-GCM daily data has the following issues:

- Reliable downscaled daily data according to peer reviewed methodologies are not universally available.
- GCM outputs can be in arcane formats – including 360 day-year outputs - which require considerable manipulation and reformatting before they can be used in impact models.
- The spread and apparent contradiction of multiple outputs can be confusing without an understanding of processes and uncertainties. Due consideration

must be given to explanation of model ensembles, the “envelope” of associated model results and the propagation of uncertainty through the modelling process.

- Lack of trust. Users may intuitively prefer the control of a more “tangible” or understandable data manipulation than trusting in the mechanisms of third party research.
- The downscaled approach has the advantage of accounting for the heterogeneity in climate changes – especially relevant in a topographically complex region such as the Western Cape. This in turn, implies an inherent risk in the method, in that the downscaling model may not accurately transpose large scale climate changes to local responses.

Having assessed both methodologies, there is clearly utility in the perturbed baseline approach as an accessible means to assess zonal sensitivities in response to changed inputs. This helps in developing an understanding of zonal responses and can point to unexpected, non-linear or non-intuitive model responses such as a reduced yield under wetter conditions or increased yields under warming which both presented in certain RHFAs. In certain cases where downscaled GCM-based outcomes do not provide a confident change signal (as in a number of the Swartland RHFAs) the perturbation approach can help to assess the likely direction of response. It is also a very useful approach in the data-scarce crop-modelling environment in South Africa to help ensure that (crop model) soil and management parameterisations result in sensible modelled yield outcomes.

The downscaled-GCM ensemble approach although intensive, resulted in an “informed” future climate parameterisation per zone, which incorporated the pattern of expected change to impact model outputs. The “spread” of yield impact anomalies in the downscaled GCM envelope was surprisingly narrow in most cases, relative to long-term yield, as indicated by the standard deviations in yield (shown in Figure 6.16). Presentation of 1st and 3rd quartiles helps to exclude the impact of potential outliers whilst preserving the signal of the model spread.

The maps in Figure 7.1 allow evaluation of the outcome scenarios of both methods simply in terms of expected increases (blue) or decreases (red) in yield, with areas remaining within 2% of current baseline yields in yellow. The stippled areas indicate where the 8 downscaled GCM ensemble model outcomes were even in terms of positive or negative sign of change.

Whilst much of the existing literature has based future wheat yield projections on perturbation of observed data, the perturbation methodology at best gives us an interesting and helpful indication of wheat sensitivity under estimated future conditions and at worst, a potentially misleading and skewed impression of future impacts, since the pattern of expected climate change impacts, at both temporal and spatial scales, is ignored.

For example in Figure 7.1- in the (a) and (d) scenarios (the two “worst case” outcomes of each modelling approach), the 2 main wheat regions, the Swartland and the Rûens (as demarcated in Figure 1.4), show contrasting yield responses. With an understanding of the underlying methodology, the result is readily explained; the pattern of change in the downscaled GCM ensemble applied in (d) is not accounted for in (a). The response in (a) is driven by a very different set of climate data with a considerably lower rainfall regime.

Whilst the results of the “perturbation of baseline” approach were informative and very useful, it is evident that the method should preferably only be presented in the context of a sensitivity analysis. In terms of future yield projections, the responsible application of downscaled GCM forcing provides a preferable method, in that the expected spatial and temporal variations in the in climate change impacts can be addressed.

Having access to the outputs of both methodologies contributed considerably to the assessment and understanding of processes and responses operating at the RHFA scale.

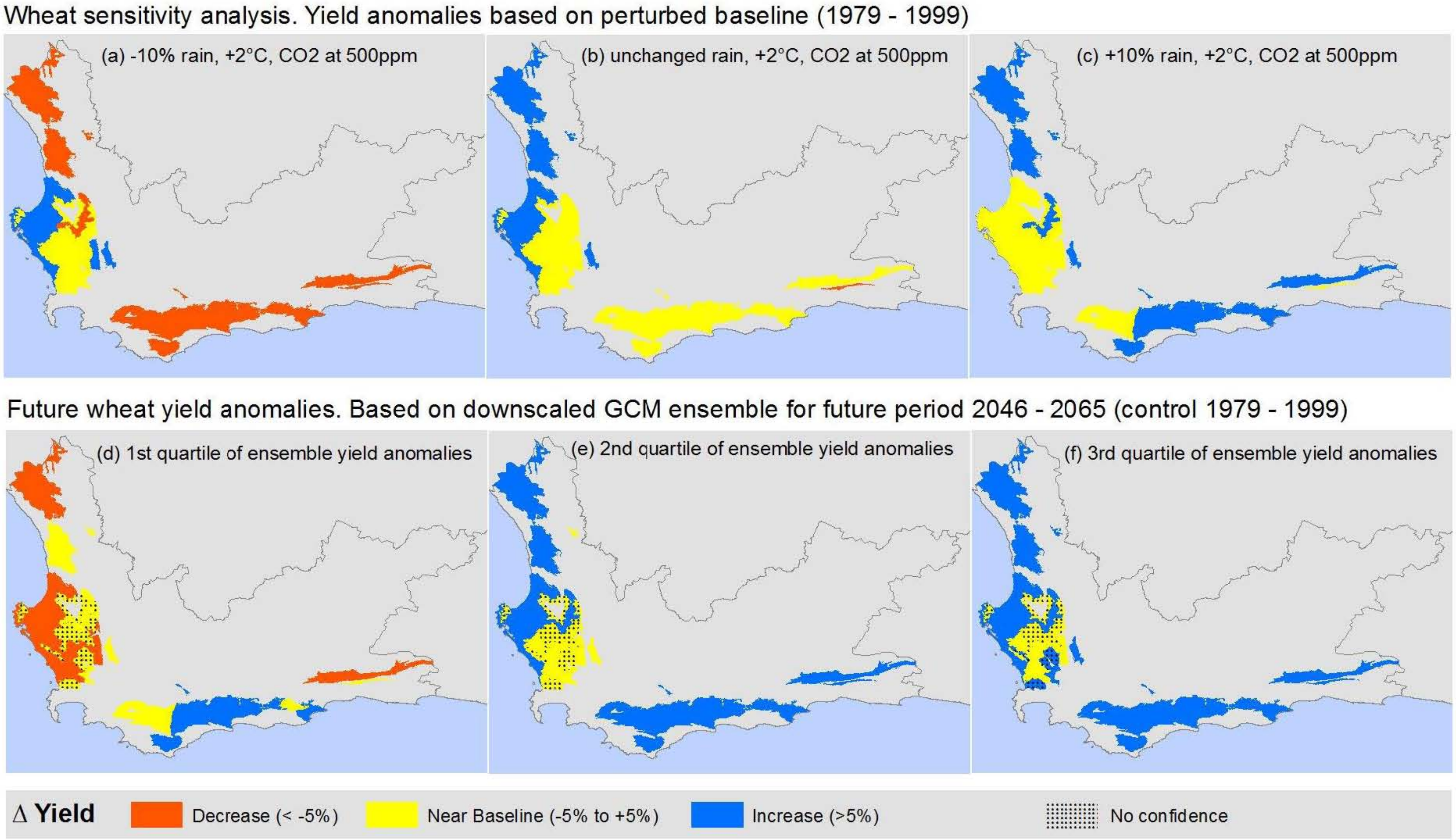

Figure 7.1. Simplified and combined presentation of crop model yield anomalies driven by perturbation of baseline climate (a, b and c) as a wheat sensitivity analysis, and by downscaled GCMs. (d, e, and f) to investigate future yield scenarios. $CO_2$ levels are set to 500 ppm throughout.

## 7.3 Impact pathways and suggested adaptation responses resulting from this study

Although detailed adaptation recommendations were not part of the initial scope of this study, the likely impact pathways regarding information generated in this study need to be placed in context. Climate change adaptation responses occur at a range of spatial and temporal scales, implemented by a range of agents from individual farmers to governments, each with diverse objectives (Challinor, 2009). Three mechanisms of climate response are identified by Adger et al. (2005), in that they either:

1. alter exposure to climate change
2. reduce sensitivity to climate change, or
3. increase the resilience of the system

In the context of this study, likely impact pathways will mainly address the second point. Recent sentiment in scientific literature cautions against the use of long-term climate change impact studies to inform decisions in policy-making (Challinor, 2009), although the application of process-based crop models may help understanding regarding the likely impact of complex climate patterns and nutrient limitations (Moore et al., 2012). Challinor (2009) further recommends that increasing capacity to deal with current climate variability presents a way to adapt to longer term changes – and indeed in the context of Western Cape agriculture, with consideration of multiple uncertainties in future projections - would seem to be a sensible approach. Likewise, Asseng and Pannell (2013) and Potgieter (2013) consider the most important adaptation response for studies of this nature to be focused research and development which facilitate future adaptation to climate change by farmers. The adoption of a sub-regional (in this study, RHFA) approach also allows for the characterisation of such impacts and adaptations at a local scale, which would be beyond the scope of regional or country-level assessments (Thornton et al., 2009).

In the Western Cape context, wheat is grown as a commercial, predominantly dryland crop on farms usually exceeding 1000 ha (Hoffmann, 2010). There is no significant local reliance on wheat as a subsistence crop by smallholder farmers (BFAP et al., 2005). Food security implications must therefore be viewed at a macro level, where national and indeed regional demand is increasingly exceeding local production by a large margin (see Figure 1.2) and these macro-scale impacts involving policy and trade strategies are beyond the scope of this study. The modelled zonal responses to climate change projections are considered in the provincial, subregional context, to guide possible adaptation interventions at the scale of the RHFA. Table 7.3 and Table 7.4 summarise the likely primary impacts and comment on some likely adaptation responses in the light of RHFA sensitivities or vulnerabilities to future (mid 21st century) climate change.

The fundamental avenues of response, given the uncertainty limitations of such long-term studies to guide any “hard” policy making, take the form of prioritisation of research and institutional capacity to address identified (modelled) sensitivities or vulnerabilities. They thereby attempt to initially reduce the sensitivity to (shorter-term) change or variability. It firstly requires that the likely “clients” or users of such information be identified in order to frame impact pathway responses. Projection-based simulation approaches based on process models are particularly suited to research pathways – particularly in terms of identifying and analysing underlying processes (Challinor et al., 2013).

In the Western Cape context these users are likely to be the following:

- agricultural research organisations involved in local research, such as the Western Cape Department of Agriculture, the Agricultural research Council and the CSIR,
- agri-business – particularly those involved in cultivar development and fertilisation recommendations,
- nature conservation – considering the high conservation priorities in the province, and

- farmers and farmer study-groups, particularly with regard to farm systems-level adaptation in an environment with limited options.

Some of the specific focus areas where these findings are likely to be useful in guiding institutional research adaptations are:

- to support continued research towards improving the understanding and quantification of climate change – in particular - regional downscaling and the handling of uncertainty
- modelling to provide locally refined requirements in the development or import of new germplasm (by government and agribusiness) more suited to local response to $CO_2$, accelerated phenology, drought resistance and heat tolerance
- to develop crop modelling scenarios which correspond to seasonal climate or weather-forecast time-scales to guide (in-season) farmer management of variability
- to restore the culture of modelling to mainstream agricultural research in the province, to help address issues such as the complexity of nitrogen fertilisation responses under likely future conditions and to facilitate research on other local responses to and mitigation of climate variability impacts. One of the key required outcomes will be to promote institutional and farm-level support for well-parameterised calibration sites (in the manner of the AgMIP "sentinel" sites (Rosenzweig et al., 2013), particularly with regard to developing baseline, time-series, observed yield data
- to further exploit NDVI/EVI to validate modelled yield response spatially
- within the context of a country with many competing national priorities, to re-emphasise the value at all levels, of creating and maintaining up-to-date, geographically referenced databases of information and knowledge relating to climatic and other natural resources, land use and land potential. These are particularly important in understanding national and local vulnerabilities to climate change (Challinor et al., 2007)

- to help prioritise long-term planning of conservation targets in relation to long-term expectations of agricultural productivity (within the bounds of uncertainty)
- in the light of localised sensitivities or vulnerabilities, to help further refine work such as that of Hoffmann (2010) to optimise whole-farm diversification at the RHFA scale across the whole wheat production area in the province in the context of climate variability and change

Particularly in the more risky wheat production areas, there has been progress towards including a greater livestock component, with the objective of diversification of production risk. In the primary wheat areas however, such initiatives are regarded with caution since any major diversification is thought to limit the farmer's opportunity to take advantage of high wheat prices. Other than adjusting the ratio of the livestock component, there are limited alternative systems currently considered feasible. In order to maximise whole-farm profitability (and reduce risk) under current conditions, expert groups consulted in the Hoffmann study (2010) suggested the following as potential adaptations:

- implement crop rotations according to best practices for a region, maximise the benefits of nitrogen-fixing species (legumes) preceding a wheat crop
- optimise stocking rate of ewes to take advantage of increased stubble and pasture resulting from the above point
- increase dairy and pasture component, producing oats and other fodder crops on poorer soils – particularly for farms near major towns or cities
- promote the development and testing of cultivars suited to risky areas
- increase farm size (economies of scale)
- allocate a portion of the farm (20%) to continuous small-grain mono-cropping to maximise the opportunity to take advantage of the occurrence of high grain prices
- conservation tillage to conserve soil moisture
- other issues pertaining to optimisation of cropping machinery

In Western Australia, where future impacts of climate change are likely to negatively influence wheat production, Asseng and Pannell (2013) found little scientific or economic justification for any immediate adaptation action by farmers, other than interventions aimed at normal responses to weather variability. They considered the most important policy response to be research and development to enable farmers to facilitate adaptation to climate change. In the Western Cape, the response pathway is likely to be similar. Farmers have had to adapt to drastic marketing reforms (Section 1.4) and have to compete on the open market with countries where wheat production is subsidised (BFAP et al., 2005). Promoting further adaptation to weather variability, rather than a distant threat of climate change, seems to be a sensible option. Despite the uncertainties in long-term agro-climatic modelling (see Section 4.5) we do have some plausible indications of spatial and temporal wheat yield responses under changed climate scenarios under elevated $CO_2$ levels which can contribute to long-term research strategies at a local level. The simulations point to potential options in terms of cultivar choice and tactical nitrogen application (or the use of slower release N fertiliser where local conditions permit) to guide further research and adaptation to the expected accelerated wheat phenology in the shallow, low water holding capacity soils of the Western Cape.

Plant breeding (to develop new cultivars) is a slow process, taking up to 12 years (Asseng and Pannell, 2013). Thus long-term research towards new cultivars which are better suited to future conditions should be a productive long-term adaptation option. In a province with few alternatives for wheat farmers, other than wheat/livestock diversification, the search for alternative crops and new germplasm to take advantage of expected future conditions should be intensified.

## 7.4 Likely implications for future wheat production per RHFA

Table 7.2 summarises the modelled yield impacts per RHFA for all the wheat producing RHFAs examined in various scenarios in the preceding chapters to frame the context for discussion on expected local impacts per zone. For comparative purposes here, in all cases the cultivar modelled characterises a medium season cultivar in common use under current conditions, N application is 120 kg/ha and the $CO_2$ levels are all set to 500 ppm.

- For the sensitivity analysis, 3 rainfall scenarios are presented based on perturbation of baseline climate from 1979 to 1999; +10%, unchanged and -10%.
- For the downscaled GCM-driven scenarios, results are given firstly for the 2nd quartile or median (Q2) and subsequently for the 1st (Q1) and 3rd (Q3) quartiles.
- In the downscaled GCM-driven scenarios, RHFA yield anomalies where there was an even number of positive and negative yield outcomes are "greyed out".

The modelled future yield outcomes (from downscaled GCMs) represent plausible scenarios for the period 2046 to 2065. Attempting to assess predictions of future wheat demand and prices is complex, with issues such as genetic modification, competition between food crops and biofuel crops, the rampant Chinese economic growth and global climate change all having influences. It seems unlikely that demand and prices will decrease in the long-term. In discussing the likely subregional outcomes there is no assumption made of significant, relative economic changes in either input costs, the wheat price or indeed the price of other agricultural commodities that may compete with wheat, which could alter the production margins and wheat viability considerably. Previously stated "confidence terminology" regarding the future GCM-derived outcomes is used in the ensuing zonal synthesis. The discussion also refers to modelled cultivar choice outcomes (see Table 6.5 and Table 6.6), modelled responses to variations in N applications (Table 6.7 and Table 6.8) and indicators of future risk anomalies (Table 6.9). The RHFA maps in Appendix I illustrate the spatial context of these zones within the Western Cape.

Table 7.2, Table 7.3 and Table 7.4 summarise the likely (primary or "first-order") impact implications for some of the future yield sensitivities and scenarios per RHFA. Potential wheat cultivation areas, tonnages and farm dependants are estimated from Hoffman (2010), DAF&F (2011) and the RDP manuals (Department of Agriculture Western Cape, 1990). These estimates are coarse, and will be substantially improved after the current agricultural commodity census in the province is complete (commencing 2013). (Given the uncertainty approach in this study of generally discussing sensitivities and sign of change, rather than absolute yield values, the temptation to infer gross production change values for these summaries is avoided here). Further discussion on likely impact pathways per zone is presented after the following 3 tables.

Table 7.2. Summary of modelled wheat yield impacts per RHFA under both perturbed baseline and downscaled GCM-driven conditions. For the downscaled scenarios, the number of positive and negative outcomes is given, based on the 8 GCMs used. Where the sign of change does not have a majority the corresponding value is “greyed out” and should not be used with any confidence.

| | | Model forced by Perturbed Baseline | | | Model forced by Downscaled GCM Ensemble | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | (+2 °C, CO2 at 500ppm) | | | (CO2 at 500ppm) | | | Sign of Change | |
| **RHFA** | Baseline (kg/ha/annum) | Rainfall -10% | Rainfall unchanged (%) | Rainfall +10% | Q1 | Median (Q2) | Q3 | Pos | Neg (no. out of 8) |
| Agter-Paarl | 2861 | 3.9 | 3.6 | 0.4 | -2.5 | 2.5 | 11.6 | *6* | *2* |
| Bo-Langkloof | 1918 | -13.4 | -5.8 | 4.1 | 0.4 | 9.3 | 25.1 | *6* | *2* |
| Bredasdorp/Strandveldvlakte | 2709 | -28.3 | 1.5 | 12.3 | 11.7 | 16.7 | 22.0 | *7* | *1* |
| Gemengde Boerderygebied | 3681 | 4.6 | 4.0 | 0.9 | -3.3 | -0.5 | 5.1 | *4* | *4* |
| Gourits-Rooiruens | 1990 | -12.1 | -1.3 | 7.6 | 4.8 | 9.5 | 15.7 | *7* | *1* |
| Gouritzriviervallei | 1897 | -12.2 | -1.4 | 7.9 | 8.8 | 10.9 | 15.1 | *7* | *1* |
| Graafwater/Sandveld | 1104 | -12.1 | 8.2 | 31.8 | 3.4 | 7.7 | 14.6 | *6* | *2* |
| Hardeveld | 429 | -22.8 | 16.8 | 60.8 | -6.9 | 14.1 | 18.3 | *5* | *3* |
| Hermon/Gouda | 3145 | 6.0 | 4.0 | 1.1 | -7.1 | -2.5 | 2.4 | *3* | *5* |
| Hoe Reenval Saaigebied | 3443 | 1.3 | 0.9 | -1.5 | -6.6 | -2.8 | 4.3 | *3* | *5* |
| Kamanassie | 1395 | -10.1 | -3.7 | 8.4 | -13.0 | 12.0 | 22.0 | *5* | *3* |
| Kleinberg/Suurrug | 1781 | -16.4 | -4.1 | 6.3 | 12.4 | 17.8 | 22.5 | *8* | *0* |
| Koringberg/Rooi Karoo Saaigebied | 1841 | -14.0 | 2.2 | 16.1 | 0.0 | 7.2 | 22.6 | *6* | *2* |
| Malgas/Heidelbergvlakte | 1741 | -16.9 | 0.1 | 15.2 | 5.5 | 11.3 | 15.6 | *8* | *0* |
| Middel Swartland Saaigebied | 3442 | 1.2 | 0.1 | -1.8 | -3.8 | 0.8 | 4.8 | *4* | *4* |
| Ruens East | 1911 | -7.7 | 4.3 | 16.4 | 7.6 | 20.6 | 23.5 | *7* | *1* |
| Ruens West | 3051 | -9.1 | -1.1 | 1.9 | 2.5 | 12.4 | 16.5 | *6* | *2* |
| Sandveld Saaigebied | 1676 | 7.3 | 9.2 | 4.8 | -5.7 | 6.5 | 11.9 | *5* | *3* |
| Stockwell | 1161 | -20.6 | 0.5 | 21.9 | 12.4 | 26.2 | 28.9 | *8* | *0* |
| Tulbagh/Wolseley | 2896 | 6.6 | 6.3 | 5.1 | -3.3 | 3.2 | 9.8 | *5* | *3* |
| Urionskraal | 635 | -19.2 | 14.5 | 53.9 | -0.2 | 3.6 | 11.5 | *6* | *2* |

Table 7.3. Summary of primary wheat RHFA estimated potential wheat production per RHFA and number of farms and labourers; potential yield responses to cultivar choice, N-fertilisation sensitivity range, risk; and future yield responses at 3 quartiles of the yield ensemble colour-coded for positive or negative projections. (The approximate proportion of wheat from Hoffmann (2010) is a consequence the crop rotation system per region).

|  | RHFA statistics |  |  |  |  |  |  | Future period (2046 - 2065) |  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
|  |  |  |  |  |  |  |  | Median (Q2) |  |  |  |  |  |  |  |
| RHFA (Primary wheat zones) | Dryland area (ha) | Approx prop. wheat (%) | Potential wheat (ha/annum) | Baseline yld (kg/ha/annum) | Potential wheat (t/annum) | Approx. no farms* | Approx. labourers | Cultivar range (%) | N response range (%) | Δ Risk Index | Risk Index | Q1 Δ Yield (%) | Q2 Δ Yield (%) | Q3 Δ Yield (%) | Comment on RHFA response, likely impact pathway/research intervention |
| Agter-Paarl | 13327 | 35 | 4665 | 2861 | 13345 | 26 | 416 | 5 | 14 | 0 | 0.0 | -2.5 | **2.5** | 11.6 | Fairly resilient zone, status quo likely to remain. |
| Hoe Reenval Saaigebied | 136805 | 60 | 82083 | 3443 | 282624 | 248 | 3968 | 6 | 15 | 0 | 0.0 | -6.6 | **-2.8** | 4.3 | Major wheat area, showing possibility of decreasing future yields, affecting many livelihoods. Focus on heat & drought resistant cultivars & minimum tillage to conserve soil moisture. |
| Hermon/Gouda | 18697 | 35 | 6544 | 3145 | 20583 | 20 | 320 | 10 | 27 | 0 | 0.0 | -7.1 | **-2.5** | 2.4 | Cultivar choice sensitivity & high N response anomaly range warrants further study |
| Middel Swartland Saaigebied | 172297 | 60 | 103378 | 3442 | 355868 | 310 | 4960 | 14 | 16 | 0 | 0.0 | -3.8 | **0.8** | 4.8 | Model confidence low - possible important role of cultivars indicated. High number of livelihoods potentially affected warrants prioritisation for studies to reduce uncertainty here. Good zone for "sentinel" site. |
| Gemengde Boerderygebied | 50009 | 60 | 30006 | 3681 | 110457 | 140 | 2240 | 7 | 15 | 0.5 | 0.5 | -3.3 | **-0.5** | 5.1 | Model confidence low - showed highest future positive respose to a longer season cultivar. Research focus on reducing uncertainty and cultivar choice. |
| Koringberg/Rooi Karoo Saaigebied | 72082 | 50 | 36041 | 1841 | 66361 | 110 | 1760 | 6 | 4 | 1 | 7.0 | 0.0 | **7.2** | 22.6 | High risk remains. Good focus area for risk mitigation research . |
| Ruens West | 168866 | 20 | 33773 | 3051 | 103033 | 84 | 1344 | 4 | 2 | -1 | 2.0 | 2.5 | **12.4** | 16.5 | Yields likely to increase. Likely to be the biggest contributor to increased W.Cape wheat tonnage. |
| Ruens East | 234841 | 17 | 39923 | 1911 | 76286 | 156 | 2496 | 6 | 2 | -1.5 | 1.5 | 7.6 | **20.6** | 23.5 | Increasing yields likely, indications for reduced risk |
| Bredasdorp/Strandveldvlakte | 26636 | 20 | 5327 | 2709 | 14431 | 18 | 288 | 6 | 2 | -2.5 | 0.5 | 11.7 | **16.7** | 22.0 | Although yields likely to increase, wetter conditions will increase harvest losses due to to waterlogging at harvesting. |
| Malgas/Heidelbergvlakte | 46942 | 24 | 11266 | 1741 | 19616 | 32 | 512 | 1 | 6 | 1.5 | 4.5 | 5.5 | **11.3** | 15.6 | Strong signal for yield increase, but risk may increase. The "vlakte" (plain) also likely to experience increased harvest problems under wetter conditions. |
| Total | 940502 |  | 353005 |  | 1062605 | 1144 | 18304 |  |  |  |  |  |  |  |  |

Table 7.4. Summary of secondary wheat RHFA estimated potential wheat production per RHFA and number of farms and labourers; potential yield responses to cultivar choice, N-fertilisation sensitivity range, risk; and future yield responses at 3 quartiles of the yield ensemble colour-coded for positive or negative projections. (The approximate proportion of wheat from Hoffmann (2010) is a consequence the crop rotation system per region).

| RHFA | RHFA statistics | | | | | | | Future period (2046 - 2065) | | | | | | | Comment on RHFA response, likely impact pathway/research intervention |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | Median (Q2) | | | | | | | |
| (Secondary wheat zones) | Dryland area (ha) | Approx prop. wheat (%) | Potential wheat (ha/annum) | Baseline yld (kg/ha/annum) | Potential wheat (t/annum) | Approx. no farms* | Approx. labourers | Cultivar range (%) | N response range (%) | Δ Risk Index | Risk Index | Q1 | Q2 | Q3 | |
| | | | | | | | | | | | | Δ Yield (%) | | | |
| Bo-Langkloof | 8544 | 20 | 1709 | 1918 | 3278 | 30 | 480 | 3 | 31 | 0.5 | 4.5 | 0.4 | **9.3** | 25.1 | Slightly increase CV% and risk. Range in future N response warrants further investigation. |
| Gourits-Rooiruens | 22972 | 20 | 4594 | 1990 | 9144 | 15 | 240 | 2 | 5 | 0 | 5.0 | 4.8 | **9.5** | 15.7 | Wheat yields may improve, livestock diversification likely to continue. |
| Gouritzriviervallei | 3698 | 20 | 740 | 1897 | 1403 | 45 | 720 | 9 | 2 | -1.5 | 4.5 | 8.8 | **10.9** | 15.1 | Wheat prospects likely to improve. Cultivar choice warrants further study. |
| Graafwater/Sandveld | 76272 | 30 | 22882 | 1104 | 25257 | 144 | 2304 | 5 | 15 | 0 | 6.0 | 3.4 | **7.7** | 14.6 | Remains risky, diversification towards livestock likely to continue. |
| Hardeveld | 37353 | 30 | 11206 | 429 | 4810 | 46 | 736 | 4 | 2 | -1.5 | 7.5 | -6.9 | **14.1** | 18.3 | Risk may decrease but still very high. Low yields persist. Research alternative fodder crops. |
| Kamanassie | 31780 | 30 | 9534 | 1395 | 13301 | 79 | 1264 | 4 | 25 | 0.5 | 4.5 | -13.0 | **12.0** | 22.0 | N response warrants further investigation. |
| Kleinberg/Suurrug | 18852 | 20 | 3770 | 1781 | 6717 | 18 | 288 | 10 | 1 | -2 | 5.0 | 12.4 | **17.8** | 22.5 | Cultivar choice warrants further study towards reducing risk. |
| Sandveld Saaigebied | 108715 | 50 | 54358 | 1676 | 91099 | 287 | 4592 | 3 | 21 | 0 | 0.0 | -5.7 | **6.5** | 11.9 | Large RHFA. Low risk, low yields, status quo likely to continue. High no. of farms & labour. |
| Stockwell | 1426 | 20 | 285 | 1126 | 321 | 8 | 128 | 4 | 5 | -0.5 | 8.5 | 12.4 | **26.2** | 28.9 | Risk remains high. Diversification to livestock likely to continue, with improved prospects for wheat fodder production likely. |
| Tulbagh/Wolseley | 7136 | 35 | 2498 | 2896 | 7233 | 15 | 240 | 11 | 28 | 0 | 0.0 | -3.3 | **3.2** | 9.8 | Relatively high sensitivity to cultivar choice - may present an adaptation option. N fertilisation strategy research. |
| Urionskraal | 3412 | 30 | 1024 | 641 | 656 | 50 | 800 | 1 | 3 | 0 | 9.0 | -0.2 | **3.6** | 11.5 | High risk persists, wheat as fodder flow support only. |
| Totals | 320162 | | 112599 | | 163219 | 737 | 11792 | | | | | | | | |

### 7.4.1 Agter-Paarl

The projected future for this high rainfall zone shows only very slight changes with moderate signal strength for slightly increased yield. Only at the 1st quartile of future outcomes does yield decrease slightly. Similarly, the perturbed baseline scenarios produce little yield variation, with the increased rainfall perturbation resulting in the lowest increase, due to the susceptibility of the zone to saturated soil conditions. Production risk is likely to remain low.

### 7.4.2 Bo-Langkloof

The confidence is moderate for increased yield in this zone. The region is expected to experience increased rainfall into the future, resulting in increased yield at all quartiles. However, only the perturbed baseline scenario with increased rainfall shows a positive result for this zone, indicating a strong sensitivity to drying. The RHFA is likely to remain a risky production area but with a moderately strong signal for improved yields. If conditions do indeed become wetter into the future as expected, the region may see a reversal of the current trend away from wheat production. The wide variation in nitrogen response here may warrant further investigation.

### 7.4.3 Bredasdorp/Strandveldvlakte

With a reduced level of risk and a strong signal for significant yield improvements projected (16.7% at the median outcome), the zone is likely to increase its importance as a wheat production region. It is difficult to assess the future impact on harvest losses due to frequent excessive wetness experienced in the region during harvesting – these may become worse under projected wetter conditions, although increased temperatures may facilitate quicker drying after wet events. This aspect is not captured in the crop model. A further cautionary note is that the perturbed baseline scenarios show the region to be highly sensitive to the impact of reduced rainfall, with losses of 28.3% of yield indicated under (perturbed baseline) drier conditions. Downscaled median GCM-based projections do however indicate increased rainfall in the future study period for this RHFA.

The area is experiencing a strong move towards conservation agriculture through the efforts of the Agulhas Biodiversity Initiative (Carinus, 2008 personal communication). By restricting wheat production to only the most suited fields, fencing these off from game and promoting biodiversity conservation and tourism on the remainder, wheat production in the zone is likely to experience a sustainable future in balance with the extraordinary biodiversity of the region.

### 7.4.4 Gemengde Boerderygebied

This is currently the highest rainfall area after Agter-Paarl. The envelope of downscaled GCMs used to force the APSIM crop model showed no conclusive signal for direction of change in this currently high production RHFA. A strong reliance on the effects of elevated $CO_2$ level to compensate for losses due warmer, drier conditions was evident. The perturbed baseline scenarios however indicate that the zone is likely to be resilient to future climate fluctuations, with all 3 perturbed baseline rainfall scenarios resulting in small but positive yield outcomes even under warmer conditions (see Table 7.2). The zone was one of the few that showed sensitivity to cultivar choice with the use of a longer season cultivar resulting in a modelled yield increase of 7%. Nitrogen application rate strategy appears to be particularly important here, under future conditions (for reasons discussed in Section 6.6.4). A slight signal for a possible increase in production risk is evident, but overall the zone appears likely to continue on similar production levels to those currently experienced. The zone supports a relatively high number of farmers and labourers.

### 7.4.5 Gourits-Rooirûens and Gouritzriviervallei

A strong signal for future yield increases was obtained for both of these zones, and both exhibit a similar response to future yield risk which remains moderately high at around 5 failed crop years in 20. Gouritzriviervallei indicated a higher sensitivity to the choice of cultivar however, showing an increase of 5% yield on selection of a longer season cultivar. The perturbation-based sensitivity analyses showed yield improvement only in the +10% rainfall scenario.

With large tracts of land currently under-utilised in these RHFAs following the demise of the wheat marketing board in 1997 and some ensuing dry years, this outcome should be encouraging to farmers in the area. To help reduce risk exposure, wheat production is likely to continue in combination with small stock systems where crop/pasture rotations play an important economic and biological role. The anticipated increase in the yield of wheat is likely to benefit both winter cash cropping and sustaining stock fodder supplies through the dry summer months.

### 7.4.6 Graafwater/Sandveld

A moderate signal is obtained for slightly improved average wheat yields into the future. However, the risk profile remains high, unchanged from the current index with expectations of 6 failed crops in 20 years. The perturbed scenario outcome with 10% reduced rainfall is the only scenario that resulted in reduced yield expectations for the zone.

The scale of production in the region is small with many of the strip-fields (from the “boom” years of single-channel wheat marketing) lying fallow, or planted to low production dryland pastures or rooibos tea (*Aspalathus linearis*). Given the high input costs in relation to the continued risky nature of wheat production projected here, it is likely that the current *status quo* will continue.

### 7.4.7 Hardeveld

Very high production risk seems likely to persist in the Hardeveld, although the signal for change is weak in terms of confidence. Given the low baseline yield here, the modelled variation or range in yields is large in terms of Δ percentage. Both the 1st quartile and the warmer, drier perturbation scenarios resulted in reduced yield.

Choice of cultivar had very little impact on modelled yield outcomes. Currently wheat is produced in isolated pockets in the region as a relatively drought-hardy source of fodder for livestock. Despite any likelihood of future more drought-hardy cultivars, wheat will remain in its supplementary role in this arid area, supporting livestock systems in the future by making use of the short winter rainfall season to help supplement the low grazing potential of its natural vegetation.

### 7.4.8 Hoë Reënval Saaigebied and Hermon/Gouda

These two high-production, neighbouring regions in the Swartland subregion exhibited similar yield responses to future climate change projections. The signal for change was weak and the direction of change was negative at both the 1st and 2nd quartiles. Both regions showed a strong sensitivity to the beneficial effect of elevated $CO_2$, but in neither case did it compensate fully for losses due to heating and drying. Risk of production failure remains low, so continued yields similar to, or slightly lower than those currently experienced, are likely. Development of cultivars suited to hotter, drier conditions is likely to be an important factor in ensuring the continued competitive advantage of this area, which is not likely to benefit from future climate change in terms of any improved rainfall regime. The region may lose its status as the stronger of the wheat producing subregions in the province to the Rûens if the GCM-based yield-impact scenarios are proved correct. Hoe Reenval Saaigebied supports the second highest number of farm labour of the primary wheat zones. (The impacts on “downstream” economies resulting from any decline in the wheat industry are beyond the scope of this study, but could be considerable in this part of the Swartland).

### 7.4.9 Kamanassie

Although this RHFA exhibits a weak signal for the likelihood of improved future yields, the risk of production remains moderate to high (increasing slightly in the future median scenario). The zone shows sensitivity to drying, with reduced yields indicated even under unchanged rainfall regimes under hotter conditions (perturbed baseline analysis) and at the lower quartile of the downscaled GCM outcomes. Given the weak signal here for positive yield increase, increased risk, variability and the inevitable steady increase in input costs it seems unlikely that the speculative wheat cropping currently practiced here will continue into the future at the same scale.

### 7.4.10 Kleinberg/Suurrug and Stockwell

Both of these zones exhibit very strong positive signals for substantial yield improvement in the future (17.8 to 26.2% respectively at the 2nd quartile). GCM-derived yield outcomes are modelled as positive throughout. Although the perturbed baseline scenarios show a strong sensitivity to rainfall decrease, the GCMs suggest that these regions will become wetter. Even at the 1st quartile of modelled outcomes, the expected yield increases exceeded 10% of baseline in both cases.

Whilst risk in both cases is likely to be slightly lower in the future, it remains overall at a high level – particularly in Stockwell. Currently the percentage of percentage of previously cultivated land still planted to wheat is very low in both regions, with vast expanses of fallow and low-input pastures in evidence in former wheat lands. Projected increases of close to 20% in average yields may re-stimulate the wheat economies in both regions. Given the high potential and the associated high risk, these are regions that may particularly benefit from marketing strategies such as hedging or crop insurance. Should the skill of seasonal forecasting improve, as can reasonably be expected over the next half century, this could also help farmers here to make more successful decisions with regard to farming strategies aimed at reducing their risk exposure. Cultivar choice appears to influence yields by more than 10% and warrants further investigation as an adaptation option here.

### 7.4.11 Koringberg/Rooikaroo

A moderate signal was obtained for a slight yield increase here in the future period under both the 2nd and 3rd quartile yield projections, with the 1st quartile indicating zero change in long-term yield. Accordingly, the perturbed baseline scenario where rainfall is unchanged results in very slight yield increases. Risk is however expected to become slightly higher in an area already subject to high variability in yield. The continuation of current trends towards minimum tillage, a greater reliance on leguminous fodder crops, reliance on the livestock component to offset risk and careful economic planning will be important to maintain sustainable production of wheat in this area under future conditions.

### 7.4.12 Malgas/Heidelbergvlakte

The signal strength for improved yields was strong here, with all 8 models in the ensemble projecting positive yield changes. Risk of crop failure is expected to increase slightly, however. Farmers in the area have adapted well to the inherent variability, through the adoption of risk spreading systems, such as leguminous pasture and Canola rotations and livestock diversification – particularly into semi-extensive ostrich production during the last five years. The very strong signal for increased yields should compensate for the slight increase in projected variability, given good planning. Although the result indicates a strong likelihood for sustained or slightly increased wheat production in this sought-after farming area into the future, the potential implications of wetter in-field harvest conditions in this predominantly flat area are not captured in the model. Not only is rainfall projected to increase, but harvest will be shifted earlier due to accelerated plant phenology under warmer conditions. Later planting in this RHFA may provide an adaptation option for this issue.

### 7.4.13 Middel Swartland Saaigebied

Although the resulting median yield value from the model envelope is positive, the models were equally split between positive and negative outcomes in this strong production area, although at the 1st quartile of the envelope, yields decreased. There is no confident signal for any change in this RHFA. Production is expected to continue to be reliable, and in the absence of a change signal may continue at current baseline levels, especially as the perturbation scenarios also show very little sensitivity to future changes under any of the rainfall scenarios (see Table 7.2).

The region did however show the highest sensitivity of all modelled zones to the elevated $CO_2$ levels in terms of compensating for losses due to temperature and water balance (i.e. without the elevation of $CO_2$ to 500 ppm as expected, the region would most likely suffer heavy losses in average yield). Cultivar choice produced the highest range of outcomes in this RHFA and may warrant further investigation. Farmers in the region are increasingly implementing rotation systems and practicing minimum tillage. This is expected to have a long-term beneficial effect on the soil water balance and productivity, and should contribute to the region’s sustainability into the future. Nitrogen application rates produced a wide range of responses here and the region is likely to benefit from research into nitrogen application options suited to faster phenology development under future conditions.

Of all the wheat RHFAs, this primary wheat zone supports the highest number of farmers and labourers and given the particular uncertainty here, would be a good candidate zone for any pilot studies to refine modelling and perhaps develop a “sentinel” site for model comparison analysis (Rosenzweig et al., 2013) for the region.

### 7.4.14 Rûens East

This region shows a strong positive response to expected future conditions at all 3 quartiles of modelled yield outcomes. A median yield increase in the order of 20% is modelled for 2046 - 2065. Even under an unchanged rainfall regime in the perturbed baseline scenarios, the area shows a modelled increase in yield of 4.3% with increased $CO_2$ and temperature. The Rûens East area is generally subject to a moderate level of production risk due to periodic drought, but exposure to the risk of wheat crop failure seems likely to decline here under future conditions.

The large-scale integration of small stock into the farming systems in the Rûens was only made possible relatively recently by major stock-watering schemes during the 1970s and 80s. Natural water sources for livestock on farms are very limited and were thus supplemented by a network of piped water from some of the large dams in the region. The impact of future climate change on these water supply systems should also be considered in future studies. The successful integration of wheat and small stock into local farm systems seems likely to continue with possibly less economic reliance on the livestock component necessary, given the expectation of improved wheat production conditions into the future.

### 7.4.15 Rûens West

As with Rûens East, this RHFA is expected to benefit from future conditions, although the signal strength here is moderate (6 of the 8 models positive). Risk of crop failure is expected to decrease slightly. This RHFA seems likely to continue to be one of the strongest wheat production zones of the province. Given the anticipated future conditions in the Swartland, Rûens West may indeed become the highest producing region in the province. Minimum tillage, crop residue retention and crop/pasture rotations are likely to continue to play a role in wheat/small stock farming systems in the region.

### 7.4.16 Sandveld Saaigebied and Tulbagh/Wolseley

There is a weak signal for similar and slightly increased yield in these (non-neighbouring) RHFAs at both the 2nd and 3rd quartiles, whilst risk in both remains low. Wheat in the Sandveld is likely to remain fairly marginal due to the inherently poor nutrient status of the soil. The Tulbagh/Wolseley region shows much greater sensitivity to $CO_2$ levels and cultivar choice than is evident in the Sandveld Saaigebied.

### 7.4.17 Urionskraal

With the lowest rainfall of all the modelled RHFAs, and the area with the highest modelled risk of crop failure and yield CV%, the situation seems unlikely to change in the future. The area does exhibit a moderate signal for small overall yield increases in the future but these are unlikely to significantly impact the *status quo* of wheat in the region which is mostly produced in support of livestock enterprises, and only in exceptional years as a cash crop. Inputs (both in terms of machinery replacement and fertilizer and chemicals) are likely to remain minimal.

# Chapter Eight: Summary and conclusion

## 8.1 Summary

### 8.1.1 Introduction

The fundamental goal of this study was to address the lack of wheat modelling studies in the Western Cape province that assess both the subregional baseline yields (i.e. crop modelling studies on observed data) and the changes in yield that can be expected in these zones under future climate change. The subregional or zonal approach was required due to the heterogeneity of the Western Cape, regarding geological (soil), topographical and climatological influences. In this diverse region, projected wheat yield impacts under future climate change need to be researched and analysed at a local level. Variations in yield responses to climate change impacts, even between some neighbouring RHFAs differ markedly and there was little available information upon which to base future yield projections. In order to facilitate the zonal analysis, the Relatively Homogeneous Farming Area (RHFA) was selected as an appropriate modelling unit. A crop modelling approach was implemented at a local scale which facilitated the integration and analysis of discrete (model input) datasets all at a scale appropriate to the extent of the RHFA study zones. The APSIM crop model was parameterised for each of 21 RHFAs in which wheat is produced in the province.

Three specific research objectives were identified (Section1.7) in order to understand the following:

1. The sensitivity of wheat in different RHFAs, in terms of a modelled yield response per zone to changes in temperature, rainfall and $CO_2$ concentrations using perturbed baseline climate data to drive APSIM.
2. The likely spatial and temporal impacts on wheat yield and production risk across the Western Cape under future GCM-based climatologies per RHFA, where APSIM was driven by an ensemble of 8 downscaled GCM (daily) data for the period 2046 to 2065 (A2 SRES scenario). Within this objective, the following were assessed:

  - The yield anomaly "envelope" per zone of a range of plausible changes in yield by the future period (2046 – 2065)
  - The modelled future zonal responses to cultivar choice (short, medium and long season) in terms of expected yield and growing period anomalies
  - The modelled yield response to reduced nitrogen applications under future conditions
  - An investigation into future interannual variability and production thresholds with regard to crop risk, comparing current to likely future years of crop failure

3. The likely magnitude and geographic distribution of subregional responses to the beneficial effects of future elevated $CO_2$ concentrations.

There are inherent uncertainties in long-term agro-climatic modelling of this nature. These are a consequence of the uncertainty in climate itself, the uncertainty of socio-economic development pathways influencing greenhouse gas emissions, of model parameterisation values, influencing factors that are not modelled and of structural uncertainties within the crop model itself. These were discussed together with the approach by which the uncertainties were mitigated in the modelling process where possible (Section 4.5).

### 8.1.2 Sensitivity analysis - the perturbed baseline modelling approach

The first objective was achieved through parameterising the APSIM crop model for local conditions per zone (RHFA) and driving the crop model based on perturbations of the baseline climate for the period 1979 to 1999 per zone. The perturbed baseline or wheat sensitivity analysis approach contributed towards understanding complex responses per RHFA to climatic changes. Although future climate changes will see temperature, precipitation and $CO_2$ changing in concert, the ability to isolate single or user-defined combined factor perturbations provided insight into some unexpected and non-linear responses. In 7 of the RHFAs, mostly in the Swartland region, increases of 10% rainfall resulted in slight *reductions* in yield (see Figure 5.4) due to the impacts of waterlogging stress. In most of these RHFAs some form of field modifications to assist drainage are already evident – a sign that current rainfall regimes result in waterlogging which would be further exacerbated by additional rainfall. By contrast, RHFAs currently experiencing very dry conditions (such as Hardeveld, Stockwell and Urionskraal) show a marked improvement to a rainfall increase. The indication is thus that much of the Swartland is currently experiencing an optimum rainfall regime given the limited natural drainage capacity of the medium-shallow depth, higher clay content soils, particularly on flatter topography.

Increases of 1°C temperature had either a yield limiting, or negligibly small positive impact throughout most RHFAs (see Figure 5.2), with the exception of the Sandveld Saaigebied where a 6.7% increase was modelled. This zone was the only one where a further modelled increase in temperature (+2°C) still resulted in an increased yield. The topographic exposure of the Sandveld Saaigebied to the cold Atlantic Ocean winter frontal systems may be a contributing factor to this anomaly, where warming of a few degrees appeared to be beneficial to crop growth. Elsewhere the responses to a 2°C increase in temperature ranged from reductions of between 3.1 and 20.7% in yield, with Bredasdorp/Strandveldvlakte showing the greatest yield reduction under perturbed warming (with no concurrent increase in $CO_2$ levels).

In the remainder of the sensitivity analyses $CO_2$ levels were set to 500 ppm. The combined impacts of increased temperature (+2°C) with 3 different rainfall regimes (a reduction of 10%, no change and an increase of 10%) were modelled.

Under an unchanged rainfall regime ($CO_2$ at 500 ppm, +2°C), the modelled yield responses to increased temperature and $CO_2$ resulted in 6 zones showing reduced yield outcomes and 15 positive. Where yield declines occur, changes were relatively small, with the largest negative response (-5.8%) occurring in the Bo-Langkloof. The largest amongst the positive yield outcomes, were the Hardeveld (+16.8%) and Urionskraal (+14.5%). A comparison between the outcomes of this scenario and the single factor 2°C temperature increase give an indication of the apparent impacts of increased $CO_2$ levels to largely compensate for yield losses due to warming alone, (discussed further in section 8.1.4 below).

A reduction in rainfall of 10% (together with $CO_2$ at 500 ppm, +2°C) resulted in 13 negative and 8 positive outcomes. The positive yield outcomes in all cases could be considered small in magnitude (the Sandveld Saaigebied being the largest, at 7.3%). As could be expected, the RHFAs showing the greatest reductions in yield under this scenario are the currently dry areas of Hardeveld, Urionskraal and Stockwell, with the Bredasdorp/Strandveldvlakte showing the highest yield sensitivity in the reduced rainfall scenario, with a modelled yield reduction of -28.3%.

Although two Swartland waterlogging-prone zones showed very small negative yield responses to the increased rainfall scenario (with $CO_2$ at 500 ppm, +2°C) the remaining 19 all showed a positive yield response. The greatest positive responses were from the currently dry, drought-prone Hardeveld (+60.8%), Urionskraal (+53.9%) and Graafwater/Sandveld (+31.8%).

Whilst the sensitivities of the wheat zones currently in dry, drought-prone areas (such as the Hardeveld and Urionskraal) to modelled drier scenarios are in accordance with expectation, their resilience to and in some cases, positive response to increased temperatures, is noteworthy. Farmers in these regions have historically favoured wheat as a forage crop for its resilience to heat and drought compared to other forage crop options. The strongly negative response of Bredasdorp/Strandveldvlakte to the combined scenario with reduced rainfall (CO2 at 500 ppm, temperature increased by 2°C and -10% rainfall) is also noteworthy, as this is considered a fairly reliable wheat production area which currently has waterlogging problems under wetter conditions and yet does not appear to benefit from slightly drier conditions as do certain Swartland zones. The strong negative impact however may be a consequence of the predominantly shallow soils in this zone, which have a correspondingly low water holding capacity and thus appear to offer little resilience or “buffering capacity” under conditions of reduced moisture and increased evapotranspiration.

Table 8.1. Summary of the two highest and lowest APSIM-modelled RHFA yield responses to perturbations of baseline conditions.

| Perturbation | Best performing 2 RHFAs | Worst performing 2 RHFAs |
|---|---|---|
| +1°C | Sandveld Saaigebied | Kamanassie |
| | Agter-Paarl | Kleinberg/Suurrug |
| +2°C | Sandveld Saaigebied | Bredasdorp/Strandveld |
| | Hardeveld | Bo-Langkloof |
| +10% rainfall | Hardeveld | Sandveld Saaigebied |
| | Urionskraal | Hoë Reënval Saaigebied |
| -10% rainfall | Hermon/Gouda | Hardeveld |
| | Gemengde Boerderygebied | Urionskraal |
| $CO_2$ at 500 ppm & +2°C | Hardeveld | Bo-Langkloof |
| | Urionskraal | Kleinberg-Suurrug |
| CO2 at 500 ppm & +2°C & +10% rain | Hardeveld | Middel Swartland |
| | Urionskraal | Hoë Reënval Saaigebied |
| CO2 at 500 ppm & +2°C & -10% rain | Sandveld Saaigebied | Bredasdorp/Strandveld |
| | Tulbagh/Wolsely | Hardeveld |

Modelled temperature projections and extrapolated temperature trends in the Western Cape afford some confidence to the level of temperature perturbation (+2°C) used here and a conservative perturbation of $CO_2$ levels (500 ppm) was applied. Whilst future rainfall projections are less certain, the final 3 scenarios in Table 8.1 (also mapped in Figure 5.6) provide plausible indication of local wheat sensitivity and potential vulnerability to future changes.

The use of the perturbed baseline approach has been widely reported in yield impacts studies under future climate change. The method provides useful insight into regional sensitivities, the extremes of which are summarised in Table 8.1 Since future rainfall regimes (in terms of temporal distribution and spatial pattern), temperature variation and potential changes in climate *extremes* cannot be addressed, its utility is limited in terms of producing future yield projections.

### 8.1.3 The downscaled GCM modelling approach

In order to address the second objective, the use of statistically downscaled daily data from 8 GCMs was used to drive the crop model for the period 2046 to 2065 for each RHFA. To avoid model biases influencing the results unduly, yield anomalies were determined for each GCM by comparing it to its own control period. The resulting anomalies were then compared with baseline yields.

The agreement between the 8 models in terms of the sign of direction of yield change provided an indication of the likelihood for expected future change direction. The resulting median yields for each RHFA from the downscaled analysis were imported into GIS and mapped and presented together with the 1st and 3rd quartiles of the resulting model yield anomalies (Figure 6.15, page 150) to provide an indication of alternative (“worse” or “better”) plausible scenarios within the envelope of possible yield changes.

In regional terms, the southern wheat zones showed the most consistently modelled signal for increased yields under future conditions whilst the change signals for the current major provincial wheat region, the Swartland, were generally considered unclear or weak (according to the terminology presented in Table 6.1), precluding any confident statement on future trends in yield for that region. A summary of these yield anomalies is available in Table 6.4 (page 149), whilst the two best and worst performing RHFAs under each quartile scenario are presented in Table 8.2.

Table 8.2. Summary of the two highest and lowest APSIM-modelled RHFA yield responses to downscaled GCM climate conditions (2046 – 2065).

| Quartile | Best performing 2 RHFAs | Worst performing 2 RHFAs |
|---|---|---|
| 1st | Stockwell | Kamanassie |
| | Kleinberg/Suurrug | Hermon/Gouda |
| 2nd | Stockwell | Hoë Reënval Saaigebied |
| | Rûens East | Hermon/Gouda |
| 3rd | Stockwell | Hermon/Gouda |
| | Bo-Langkloof | Hoë Reënval Saaigebied |

Although there was considerable variation between zones, the modelled wheat growing period from planting until anthesis in all zones was reduced by an average of 19 days across all zones and all cultivars (by the period 2046–2065), due mainly to the more rapid accumulation of heat units leading in turn to accelerated plant assimilation and growth.

The influence of cultivar choice on yield (based on currently available season-length defined cultivars) was used to investigate and compare the potential yield sensitivity of zones to cultivar choice under current and future conditions. The model ensemble was run in each RHFA for a medium, short and long season cultivar respectively. The outcomes again varied zonally, with Swartland RHFAs generally showing the greatest range in modelled yield anomalies (*i.e*. as a result of choice of cultivar) under modelled future temperature, climate and $CO_2$ regimes.

The initial crop modelling runs were undertaken at a high nitrogen application level, considered to be non-limiting in all but the highest rainfall RHFAs. The objective was to compare RHFAs in a generally non-limiting framework with regard to N fertilisation, in order to isolate impacts due to changes climate parameters only. However in order to investigate the likely response of wheat to climate change under nitrogen-limiting conditions (as future economic conditions may dictate) a sensitivity analysis was undertaken by running the model for each RHFA at a range of nitrogen application rates. Responses varied considerably across RHFAs, but contrary to expectations, the low N applications generally resulted in increased yield under future climate change relative to the zone’s baseline modelled at the same N-level. Whilst the incidence of similar responses is reported in some of the literature studied, it seems to be specific to local conditions of low water holding capacity soils and the terminal drought. Responses also showed considerable variation *within* some ensembles of modelled future yields most likely in response to specific changes in rainfall distribution. The results provided insight into the response of mostly increased yield responses (relative to a baseline modelled at the same N application), particularly under the lowest N applications. The discussion and literature on this response is presented in 6.6.4.

The downscaled GCM-driven crop modelling yield outcomes provided the opportunity to examine the yield data on an annual basis for indications of future changes in production risk. Analysis of modelled change in interannual variation of yields by the mid 21st century showed a general tendency towards reduced variability with increasing variability only likely in four zones already noted to be risky production areas. A "crop-failure" index was derived for comparative purposes, based on a threshold of 50% of average yield for each RHFA. Years in which yields fell below this threshold within the 20 year study period were summed and compared to the data corresponding with each of the 1st, 2nd and 3rd yield quartiles (as presented in Figure 6.15), within the 8 model ensemble, for each of the RHFAs, for both the control and future periods. The baseline index thus modelled, provided scenarios which corresponded closely to observed baseline risk variation in the RHFAs according to the RDP narratives for each RHFA (Department of Agriculture Western Cape, 1990). Future risk patterns were generally found to be similar to those currently experienced. The greatest modelled increase in risk was found for Urionskraal at the 1st quartile of yield outcomes, where 3 additional years (in 20) of failure could be expected, resulting in an expectation of crop failure in a total of 12 out of 20 years in the future period. Bredasdorp/Strandveldvlakte appeared to benefit the most, showing a reduction of 2.5 to 3 years across all 3 quartile outcomes for 2046 to 2065. Figure 6.24 (page 169) illustrates zones where risk is expected to either decrease or remain at current levels, or increase by the future study period (2046 – 2065) at the median of yield outcomes.

### 8.1.4 The impact of rising atmospheric $CO_2$ levels

During the sensitivity analysis described in Chapter 4, summarised in Table 5.1, it was found that a 2°C warming (by perturbing baseline temperatures) resulted in yield losses in 20 of the 21 RHFAs, with a maximum yield reduction of 21% in the Bredasdorp/Strandveldvlakte RHFA. However, concomitantly increasing $CO_2$ elevation from 350 ppm to 500 ppm resulted in only 6 RHFAs experiencing reduced yield, with the maximum loss reduced to 5.8% of baseline (Table 5.3). A further sensitivity analysis based on perturbation of baseline climate data showed that across all RHFAs, yields were increased by raising $CO_2$ levels from 350 ppm to 500 ppm, under a constant 2°C elevation in temperature (Table 5.5). The average increase in yield resulting from the 150 ppm increment in $CO_2$ alone was 15%.

In order to assess the magnitude of the impact of $CO_2$ concentration under downscaled GCM-based climate conditions, the entire suite of GCMs per RHFA were modelled again – this time with $CO_2$ for the future period 2046 – 2065 reduced to 400 ppm. This facilitated comparison with the previously modelled 500 ppm scenarios and provided further insight into the spatial impacts of $CO_2$ levels on subregional wheat yields. Hoë Reenval Saaigebied, Middel Swartland Saaigebied and the Hermon/Gouda region (all within the Swartland region) displayed the highest sensitivity of all zones to this 100 ppm increment (Figure 5.21 on page 129) with a strong level of confidence regarding the agreement on direction of change within the modelled envelope. On average across all RHFAs, the resulting increase in yield from the 100 ppm $CO_2$ increment was 10%.

In order to assess the modelled yield response to further increases in $CO_2$ concentrations, three RHFAs were selected at the 10th, 50th and 90th percentiles of yield response to $CO_2$ elevation. $CO_2$ levels were increased in 50 ppm increments to 700 ppm and the resulting yields were graphed and analysed, showing linear or near linear modelled responses to the $CO_2$ increments.

## 8.2 Conclusion

In the light of predominantly economic issues resulting in the dramatic reduction in wheat plantings over the last 2 decades, research agencies of the beleaguered wheat industry in the Western Cape are understandably concerned with the potential impacts of future climate change on the industry at a local level. Research into climate change impacts on wheat have understandably been overshadowed by weighty economic and socio-political issues of the last 15 years. Provincial authorities and their agents assessing climate change impacts and planning adaptation options have thus had no recent wheat yield studies in the region upon which to base future planning strategies.

Researchers in a number of wheat industries worldwide have used a variety of crop models, parameterised for their local conditions, and using various sources of climatic data to represent likely future scenarios. The APSIM model used in this study, although stringent in its input parameter requirements, provided a plausible means to convert local observed climate data, future scenario climate data, soil parameters, crop-specific information and field management practices into annual wheat yield information for impact analysis. GIS tools helped to both refine data inputs, and to analyse and visually present the spatial or geographic dimension of expected change and satellite imagery (MODIS NDVI/EVI) proved a useful tool in spatial verification of crop model yields.

As the science of climate modelling develops, decision-makers' expectations for accurate climate predictions are growing. Natural climate variability, however, poses inherent limits to climate predictability and the related goal of adaptation guidance (Deser et al., 2012). The question must be asked: how much trust can be placed in these model results? Traditionally, the uncertainties associated with a research study would be presented at the end of the concluding chapter. The uncertainties inherent in modelling (future) climate impacts as in this study however, required that the uncertainties be clearly framed at the outset (see Section 4.5 and the summary of these uncertainties and mitigation measures in Figure 4.8). The modelling results should be assessed within the context of these uncertainties and the measures taken to mitigate these in the modelling process where possible.

In addressing the first objective of this study, the crop modelling sensitivity analysis using perturbed baseline climate data to drive APSIM, showed wheat yield responses to the individual or compounded effects of climate and $CO_2$ changes to be complex, often non-linear and variable between zones. Although some zones showed strong sensitivities to temperature increases, these impacts were in turn generally strongly modified by the concurrent elevation of $CO_2$ levels. Rainfall sensitivities also showed strong spatial variation, with a number of Swartland zones actually responding favourably to the decreased rainfall perturbation, whilst wheat in the shallow soils of the Rûens and the warm northern and extreme eastern regions showed considerable (negative) sensitivity to the warmer and drier regimes. Fortunately, the perturbed level of desiccation was not evident in GCM-based future projections, but nonetheless, warning signs are evident for certain zones, should future precipitation levels decline below expectations.

The second study objective required the use of an ensemble of downscaled GCM data to enable the APSIM crop model to simulate spatial and temporal, regional climatic impacts and responses for the period 2046 to 2065. These responses were expressed through projected changes in crop yield, changes in response to nitrogen application, changes in (interannual) production risk expectation (using a “crop-failure index” and an analysis of change in CV%) and in the range of yield impacts predicated on cultivar choice.

The modelled future yield impact anomalies were certainly not as dire as some of the broad national or provincial-scale expectations quoted in the literature review and in the introductory section suggested. Although the Swartland region appeared to be the worst affected of the major wheat production regions, the confidence level is low there in terms of modelled *direction* of yield change, resulting in no clear signal for direction of change for 2 of the RHFAs within the Swartland. At the 2nd quartile (median) of yield responses, the majority of RHFAs are likely to experience improved yields under this particular array of downscaled future scenarios for the period 2046 - 2065, apart from four RHFAs in the Swartland. Indications are that major southern production areas such as the Rûens East, which has suffered from regular drought and variable production in the past few decades, are likely to experience improved wheat conditions by mid-21st century (even at the 1st quartile of yield impact projections).

In terms of temporal changes across the province, the modelled warmer conditions accelerated modelled wheat phenology by an average of 19 days across all zones from planting to anthesis, again with substantial variation across spatial gradients. The earlier flowering may in places have a beneficial effect on yield of shifting the critical grain-filling growth stage into the cooler, wetter part of the winter season, where rainfall is generally more reliable, whilst in other zones it appears likely to lead to an aggravation of the terminal drought and reduced yields. In the Western Cape the grain-filling period currently falls towards the end of the winter rainy season when evaporative demand increases and rainfall becomes less reliable. In a number of zones, it was evident however, that the accelerated phenology and earlier, larger canopy development under climate change, high $CO_2$ (and high nitrogen applications) enhanced (worsened) the effect of the terminal drought.

In the generally shallow Western Cape soils, under the mostly water-limited wheat production conditions, the influence of water availability in the soil resulting from changes in rainfall distribution appears to be a key factor in nitrogen response under the concerted influence of $CO_2$ and temperature increases. The higher nitrogen levels may impose a *relative* yield penalty in many cases where (under increased $CO_2$ and temperature conditions) the initial flush of growth and canopy development in the early stages, reduces soil water availability later in the grain-filling stage. At lower N rates, this initial growth would not be as vigorous resulting in a more beneficial soil-water balance later in the season. The complexity of nitrogen response under climate change warrants further research to improve confidence, but results suggest that the judicious application of nitrogen at planting, tactical “split” application or the use of slow-release nitrogen fertilisers may present adaptation strategy options under future conditions.

The downscaled suite of GCMs was used to drive APSIM for each zone using a short-, medium- and long-season length cultivar to explore the potential impact of cultivar choice on future yield anomalies. Although the impact of cultivar choice was generally small, the study did identify certain RHFAs where cultivar choice appeared to be more significant than others. As a major production region, the Swartland generally performed better under longer season-length cultivars and correspondingly it showed the strongest negative responses to shorter cultivars in certain RHFAs. The obvious limitation in this approach is that it is restricted to currently available, parameterised cultivars. This was not intended as a rigorous treatise on adaptation strategies but indicates the potential utility of this crop modelling approach towards optimising cultivar characteristics to local conditions into the future.

In terms of addressing the remainder of the second objective, the likely impact of climate change on future production risk was investigated through the derivation and analysis of a "crop-failure" index and a coefficient of variation analysis of modelled *annual* yield results. The modelled baseline results satisfactorily reflected the current (narrative) descriptions in the RDPs per RHFA, and future changes were generally not indicative of any large scale changes to current risk patterns by the future study period (2046 - 2065). Of concern is that a number of zones where production risk is already high, appear likely to experience slightly elevated risk into the future (e.g. Koringberg/Rooikaroo, Bo-Langkloof and Kamanassie). It may be helpful to apply this risk threshold methodology in future impact work to examine the changes in production risk associated with specific climate models. This will contribute towards a fuller understanding of the impacts of different future climate scenarios on not just yield, but the likely economic sustainability of local wheat production. With a background knowledge of local economic factors such as input costs, wheat production margins and farm size, a more focused concept of what constitutes a crop failure threshold (for each RHFA) could readily be incorporated into this methodology in future work. This would add further value to localised crop impact analysis of future climate change, particularly in terms of the assessment of future economic sustainability.

The third and final objective was addressed by examining the modelled impacts achieved by adjusting $CO_2$ levels under both perturbed baseline and expected future climate conditions in a sensitivity analyses based upon an incremental increases of $CO_2$ per zone. This facilitated evaluation of the magnitude of the impact of $CO_2$ elevation on future wheat yield. From modelled results it appears that wheat in many parts of the Western Cape is likely to show resilience to future climate conditions due largely to the expected associated increase in atmospheric $CO_2$. Modelled yield responses to $CO_2$ levels vary widely across RHFAs, but were on average within the experimental ranges reported in both growth chamber and free air experimentation on wheat and other C3 plants. The

RHFAs falling within the Swartland region demonstrated the highest regional sensitivity to $CO_2$ levels, implying that these modelled $CO_2$ impacts are critically important in terms of their positive influence on yields under warmer (and possibly drier) conditions, thereby contributing towards the sustainability of near-current production levels in this region. The modelled impacts of temperature and $CO_2$ acting in concert differed across zones, from the additive response (of the individual impacts). This interaction is thought to be largely a consequence of future accelerated phenology and the previously discussed impacts of high nitrogen application level, shallow Western Cape soils and associated water balance serving to either avoid or aggravate the effects of the terminal drought depending on soil characteristics and rainfall distribution at the zonal scale.

Although the APSIM model has been validated for the range of $CO_2$ concentrations examined here and under a wide range of field conditions, potential deleterious effects on the yield response may yet be experienced where future combinations of high temperatures, degraded soils, altered soil water balance regimes and pest and disease issues have a concerted impact. In a real future, the near-linear response to increasing $CO_2$ concentrations modelled in this study is unlikely to realise due to the associated increase in temperatures and other associated crop stresses. Furthermore, it is reported that at temperature increases greater than 3°C, a threshold is likely to be reached above which further increases due to $CO_2$ elevation are negated (Attri and Rathore, 2003), making it improbable that elevated $CO_2$ levels will continue to ensure the sustainability of Western Cape wheat production into the latter part of this century as temperatures approach or exceed this threshold. Whilst technological advancement in cultivars (including genetic modification) may yet play a significant mitigating role in improving the capacity of wheat to take advantage of higher $CO_2$ levels, some uncertainty regarding the *net* effects of elevated $CO_2$ levels on future wheat production in the Western Cape appears inevitable. Given this uncertainty, $CO_2$ concentration was set to a conservative 500 ppm for the mid-century future period under examination here, to avoid possible over-emphasis of simulated $CO_2$ beneficial impacts, given the near-linear yield response to $CO_2$ modelled in APSIM. Modelled responses were generally in line with the experimental outcomes of the FACE at both the Tubiello et al. (2007) and Ainsworth et al. (2008b) interpretations thereof.

Within the constraints of uncertainties inherent in long-term agro-climatic modelling, the Western Cape exhibited generally positive wheat impact responses to the expected (GCM-based) climate and $CO_2$ forcings, modelled under projected mid-21st century conditions. Variation in responses was evident across RHFAs – and between the two major production regions, the Swartland and the Rûens, with the latter likely to fare relatively better under expected future conditions. These future yield scenarios together with the resulting advances in the understanding of zonal impact responses, especially in terms of the compounding or synergistic impacts of climate change and $CO_2$ factors in the context of the zonal (RHFA) environment, will contribute towards the formulation of regional agricultural research and development to facilitate adaptation strategies into the future. Of further consequence is the need to ensure that the outcomes of studies such as this are presented in an accessible manner to the target agricultural community and research bodies, with responsible acknowledgement of the associated uncertainties.

## 8.3 Recommendations for future research

Mechanistic crop models, carefully parameterised at a scale appropriate to the study zone, have the ability to distil the downscaled GCM outputs into primary, or “first-order” agricultural impact; change in *tons per hectare per annum*. The collation of zonal model parameter data, analysis and modelling methodology, impact sensitivities and likely future outcomes presented in this study should contribute towards addressing the current knowledge gap regarding future wheat performance across production zones in the Western Cape under future climate change.

However, one of the major factors limiting more widespread studies of this nature is the lack of readily available crop modelling-specific soil parameters in South Africa. A large component of crop modelling projects is therefore a parameterisation and testing exercise, which is likely to be needlessly repeated by researchers from different organisations. Similarly, the observed, daily climate databases upon which these crop models must be calibrated are generally unsuitable for daily time-step modelling (for reasons discussed in Chapter One and in Section 4.3.4).

Some specific recommendations for future crop modelling impact work in South Africa are therefore:

- The establishment of a single body (such as the former Computing Centre for Water Research) tasked with integrating and patching climate data from the various sources. This would avoid the massive duplication of effort that must occur amongst various organisations requiring model-usable data, and facilitate the implementation of a common, peer-approved methodology for “cleaning” and patching the data.
- The establishment of a soil survey and laboratory analysis project aimed at defining soil properties specific to modern crop and hydrological modelling requirements.
- The continued support and development of data portals (such as that provided by CSAG, UCT) providing users with the latest downscaled GCM data. Whilst data

formatting issues are an inherent part of mechanistic modelling, the availability of future GCM outputs formatted to calendar-correct years would be beneficial.

- Recent attempts to encourage the formation of a crop modelling forum in South Africa should be supported. In an ideal world, impact modellers would co-operate more, share ideas and equally importantly, their data and input parameters, to enable comparable studies to be made.
- The recently established AgMIP simulation exercise (http://www.agmip.org) should provide a much needed collaborative platform at an international scale, which should be supported by local modellers. As with climate models, the ability to run an "ensemble" of crop models collaboratively should considerably improve confidence in crop model results. The ability of models to simulate the effects of $CO_2$ and temperature increases needs to be further refined (collaboratively) to improve crop model confidence. The establishment of an AgMIP "sentinel site" – ideally in each of the major production regions (Swartland and Rûens) should be promoted (also addressed in Section 7.3) and would contribute significantly to improved crop model confidence in these important local wheat regions.
- In a similar vein, CSAG is a role player in the Coordinated Regional Climate Downscaling Experiment (CORDEX) project, from which a new set of local downscaled data will be produced according to international standards. The CORDEX downscaling activities are based on the latest set of GCM climate scenarios and predictions produced within the 5th Coupled Model Intercomparison Project (CMIP5). It will be useful to model future projected yields based on CMIP5 downscalings for comparative purposes.
- APSIM provides a modelling platform for a wide range of domains and disciplines, few of which have been exploited in South Africa. There is scope to undertake a wide range of farming system research, including adaptation options to both climate variability and change. Optimisation modelling for crop management practices (e.g. fertilisation strategies, timing of planting, irrigation, tillage options and crop rotations) could be particularly valuable in this regard (Crespo, 2010, personal communication). In terms of cultivar optimisation, APSIM allows the customisation of cultivar descriptions to allow local cultivars to be defined in

terms of their phenology. Empirical work to define the major South African cultivars in this way would be valuable.

- Economic aspects of production were not considered in this study. There were however, impact results which could readily facilitate economic modelling of likely climate change impacts applicable to dryland winter wheat production in the Western Cape. Since actual zonal wheat areas (hectares) are given (Table 7.4) and yield impacts are calculated in terms of kg/ha/annum, some potential financial values based on current or expected future wheat prices and production margins could be ascribed to the various impacts of climate change on a zonal basis. The estimation of risk based on modelled inter-annual modelled yield variation may also support economic assessment of future climate impacts. Furthermore, this study examines anomalies in grain yield – not grain quality. Increasing $CO_2$ levels can lead to reduced grain quality, which may have significant economic consequences (Ainsworth and McGrath, 2010), warranting further research based on local conditions.

Further research into the findings presented by Hoffman et al. (2011), and McVicar et al. (2012) is recommended, to determine whether components of crop models should be modified to account for recent evaporative demand trends. It may become necessary to apply slight regional modification to the current evapotranspiration algorithms if current wind "stilling" trends continue. There are also indications that future elevation of ozone concentrations may have some negative effects on yield (resulting from cell damage) under certain conditions, which need to be explored and incorporated into crop models if significant. At present most work is focused on the northern hemisphere, where ozone-related yield reductions are thought to be more severe (Ainsworth and McGrath, 2010; Hollaway et al., 2012).

It would be informative to run the APSIM model forced by downscaled data from alternative sources to compare with the CSAG downscaling-driven outputs. Similarly, as new GCM data become available corresponding with the release of the new IPCC Assessment Reports, it will be important to evaluate the crop model outcomes driven by downscaling of the new GCMs (e.g. from CMIP5 mentioned above). It can be assumed that the resolution and skill of climate modelling and downscaling will improve and that the model envelope should therefore narrow correspondingly as skill improves – particularly with regard to future downscaled rainfall distribution projections. The urging of Wilby et al.,(2004) should be heeded, to constantly re-evaluate insights that have been gained through impact modelling as new and refined downscaling model data become available.

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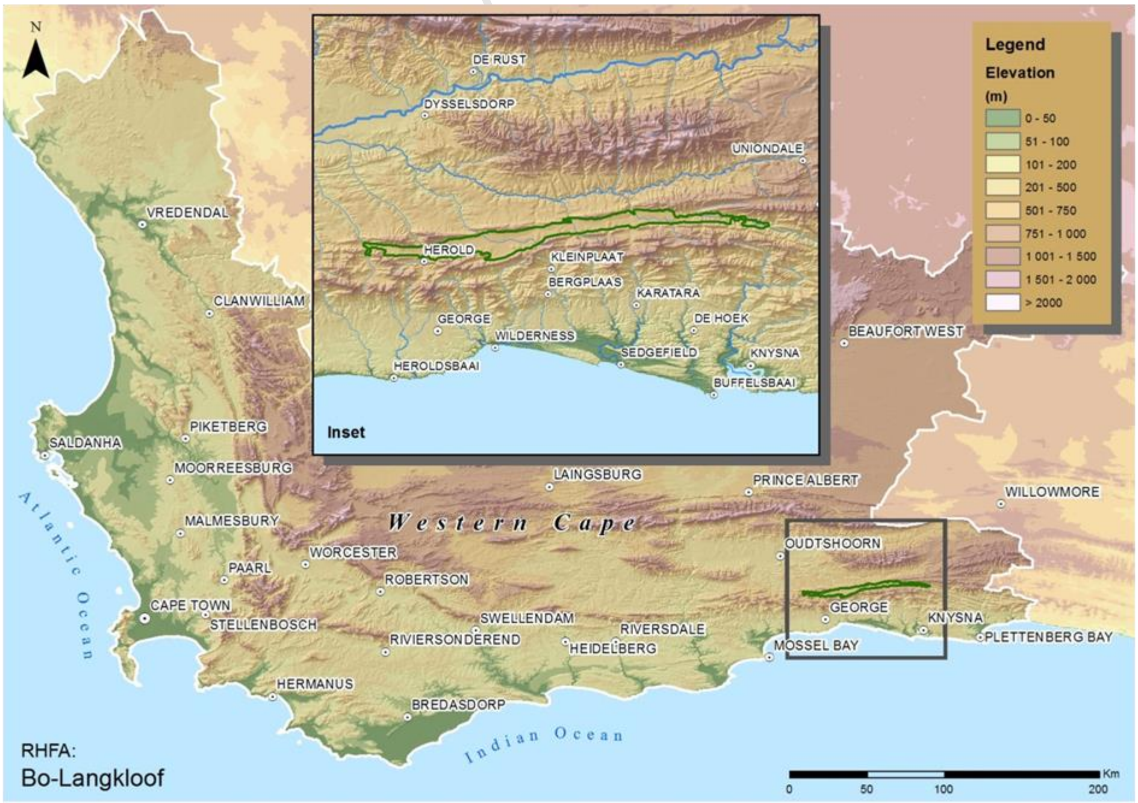
# Appendices

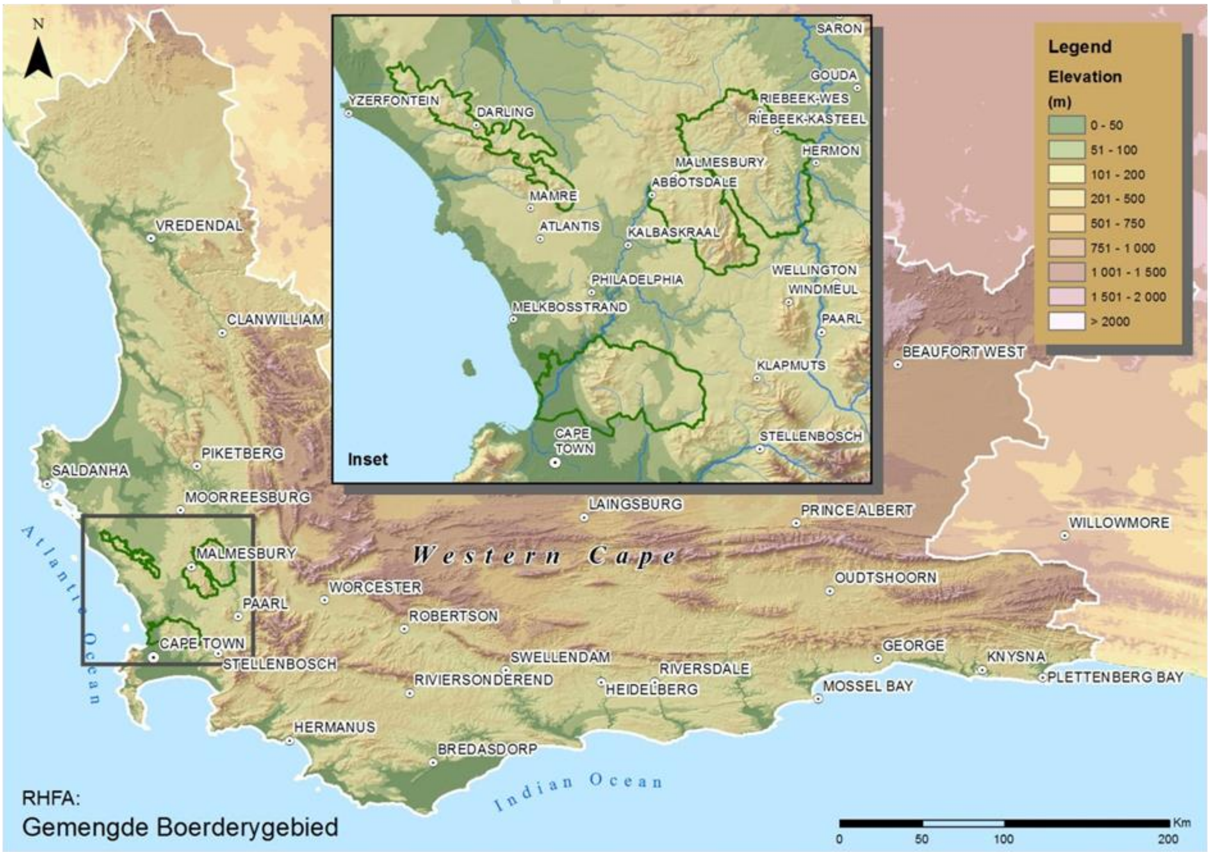
# Appendix I - Maps of RHFA wheat study zones in the Western Cape

Appendix Figure 1. Agter-Paarl (RHFA 28)



Appendix Figure 2. Bo-Langkloof (RHFA 56)

Appendix Figure 3. Bredasdorp/Strandveldvlakte (RHFA 64)



Appendix Figure 4. Gemengde Boerderygebied (RHFA 18)

Appendix Figure 5. Gourits-Rooirûens (RHFA 72)

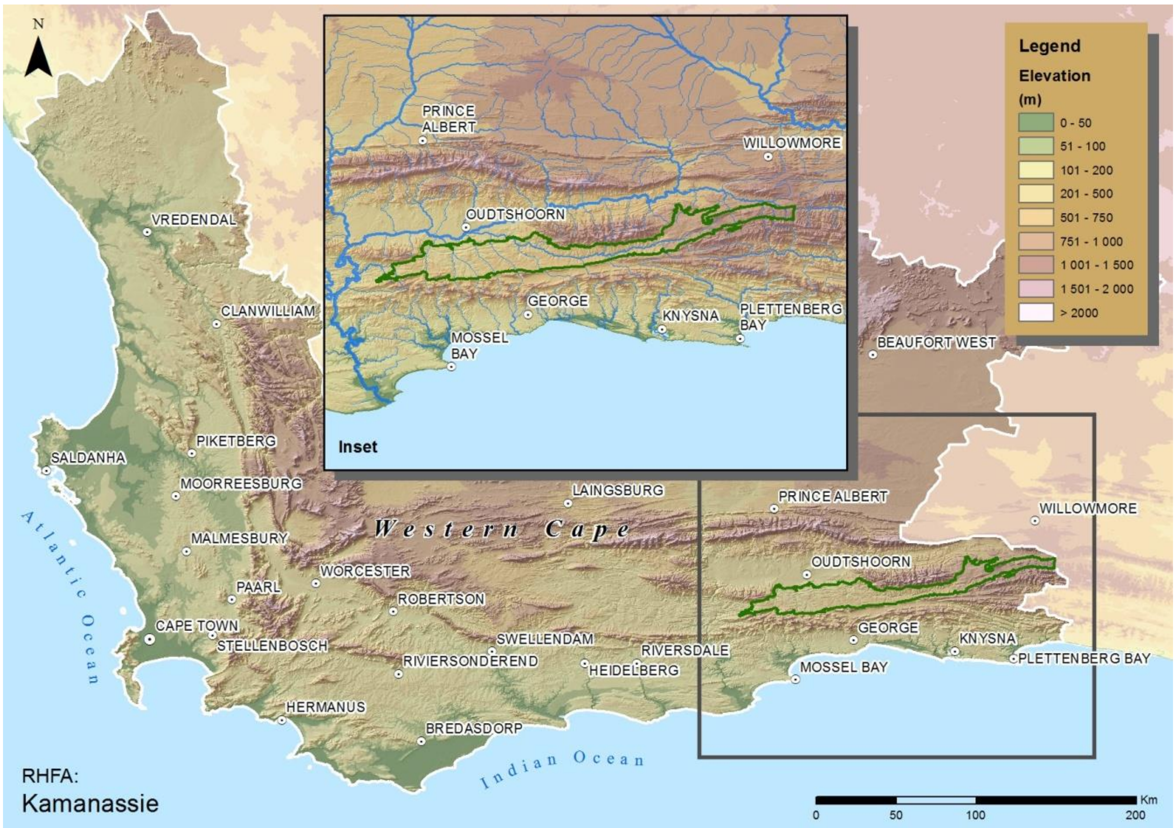
Appendix Figure 6. Gouritzriviervallei (RHFA 73)

Appendix Figure 7. Graafwater/Sandveld (RHFA 4)

Appendix Figure 8. Hardeveld (RHFA 10)

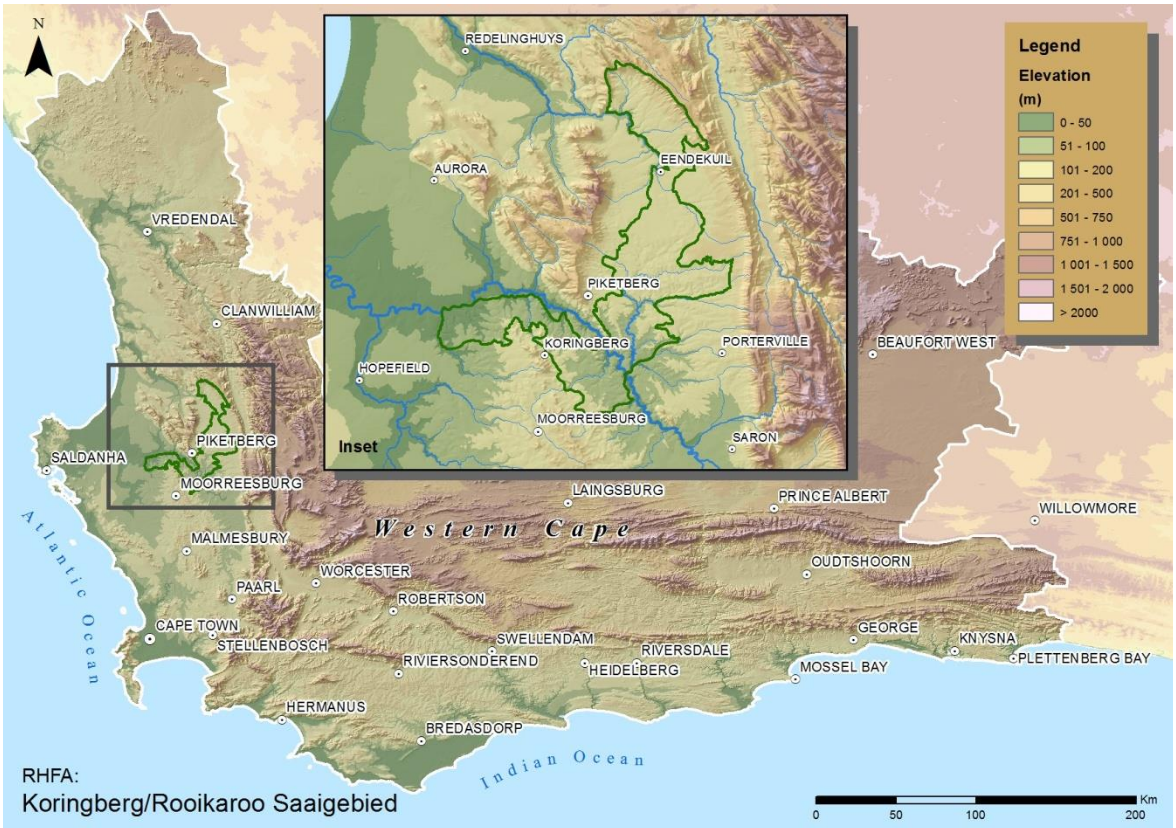
Appendix Figure 9. Hermon/Gouda (RHFA 29)

Appendix Figure 10. Hoë Reënval Saaigebied (RHFA 17)



Appendix Figure 11. Kamanassie (RHFA 57)

Appendix Figure 12. Kleinberg/Suurrug (RHFA 74)



Appendix Figure 13. Koringberg/Rooikaroo Saaigebied (RHFA 15)

Appendix Figure 14. Malgas/Heidelbergvlakte (RHFA 69)

Appendix Figure 15. Middel Swartland Saaigebied (RHFA 16)

Appendix Figure 16. Rûens East (RHFA 63)

Appendix Figure 17. Rûens West (RHFA 63)

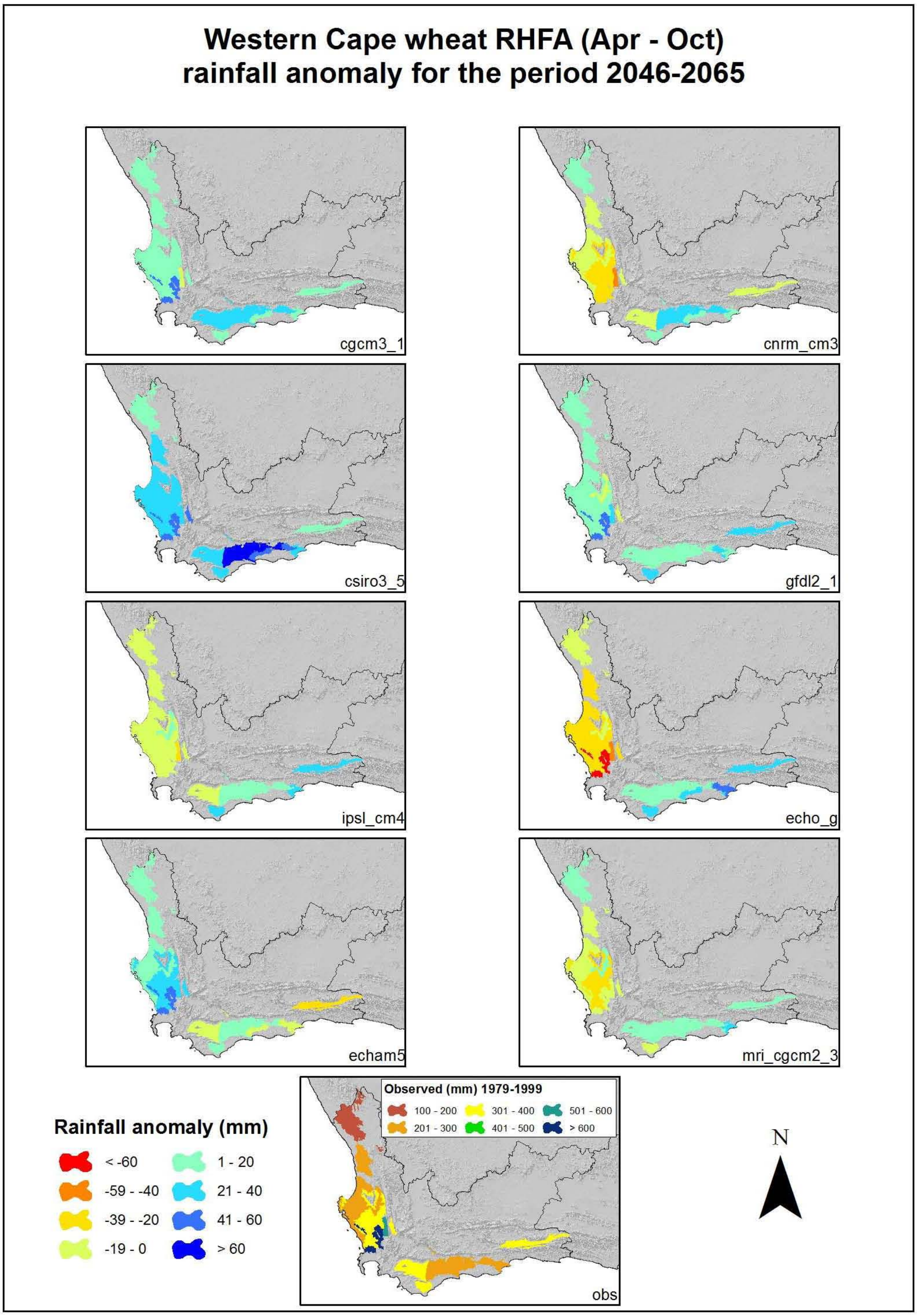
Appendix Figure 18. Sandveld Saaigebied (RHFA 14)

Appendix Figure 19. Stockwell (RHFA 45)

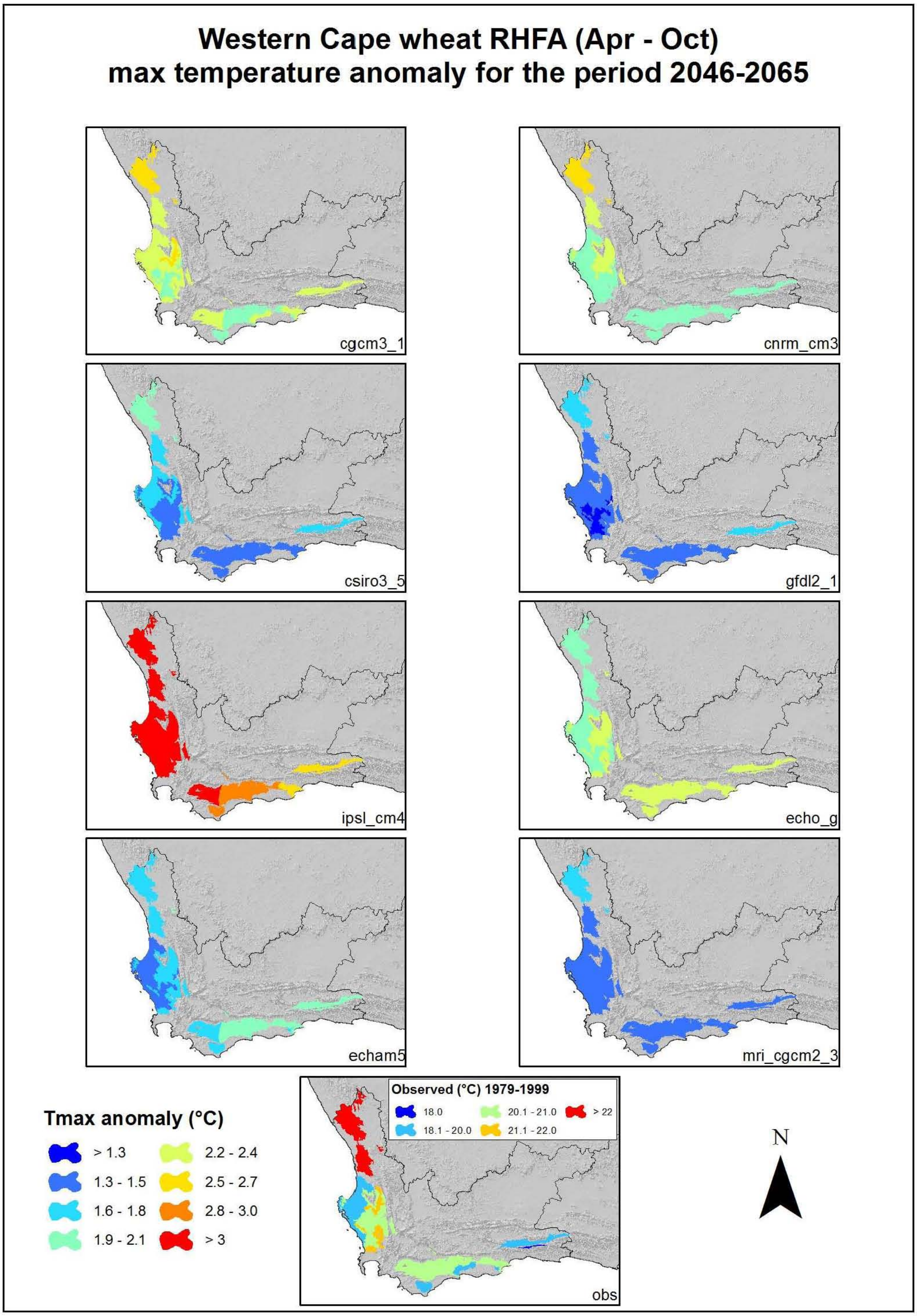
Appendix Figure 20. Tulbagh/Wolseley (RHFA 32)

Appendix Figure 21. Urionskraal (RHFA 9)

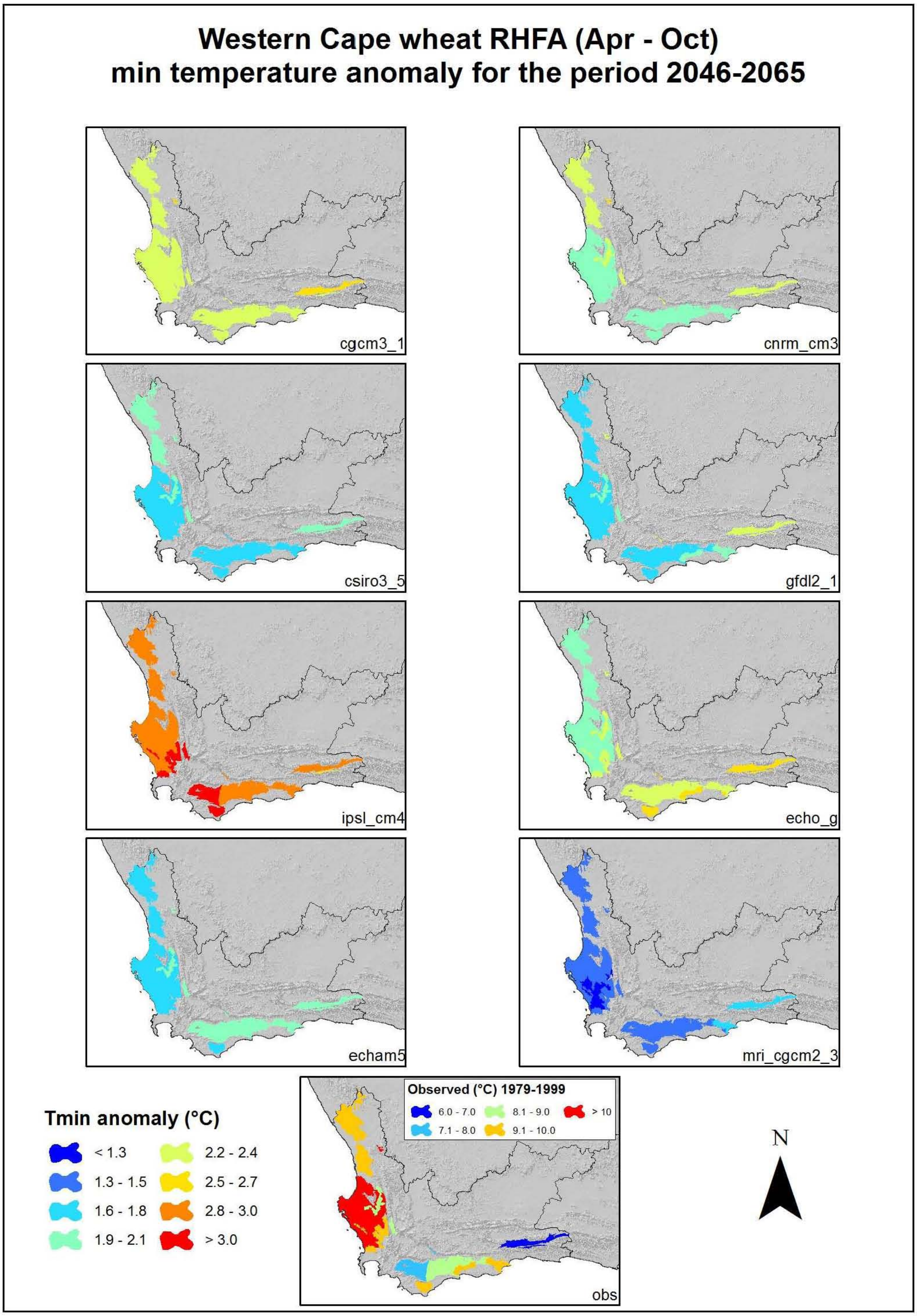
## Appendix II - Maps and tables of Western Cape downscaled GCM climate projection anomalies for 2046 – 2065 for April to October.



Appendix Figure 22. Maps showing downscaled GCM precipitation average anomalies for Apr-Oct 2046-2065. Observed mean precipitation for Apr to Oct is shown in the bottom map.



Appendix Figure 23. Maps showing downscaled GCM maximum temperature average anomalies for Apr-Oct 2046-2065. Observed average maximum temperature for Apr to Oct is shown in the bottom map.



Appendix Figure 24. Maps showing downscaled GCM minimum temperature average anomalies for Apr-Oct 2046-2065. Observed average minimum temperature for Apr to Oct is shown in the bottom map.

Appendix Table 1. Average (Apr-Oct) downscaled GCM minimum temperature anomalies for 2046 – 2065.

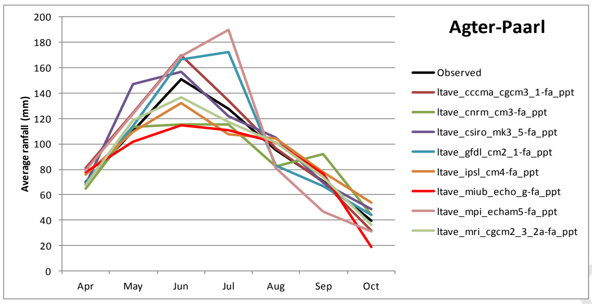
| RHFA | Observed (°C) | Average minimum temperature anomalies (Δ°C) for April - October (2046 - 2065) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | cgcm3_1 | cnrm_cm3 | csiro3_5 | echam5 | echo_g | gfdl2_1 | ipsl_cm4 | mri_cgcm2_3 |
| Agter-Paarl | 9.6 | 2.2 | 2.1 | 1.6 | 1.8 | 2.3 | 1.8 | 3.2 | 1.4 |
| Bo-Langkloof | 6.4 | 2.4 | 2.2 | 1.8 | 2.0 | 2.5 | 2.1 | 2.7 | 1.6 |
| Bredasdorp/Strandveldvlakte | 9.2 | 2.2 | 2.0 | 1.6 | 1.8 | 2.4 | 1.7 | 3.1 | 1.4 |
| Gemengde Boerderygebied | 9.6 | 2.2 | 2.1 | 1.6 | 1.8 | 2.3 | 1.8 | 3.2 | 1.4 |
| Gourits-Rooiruens | 9.3 | 2.3 | 2.0 | 1.6 | 1.9 | 2.4 | 1.9 | 2.8 | 1.5 |
| Gouritzriviervallei | 9.6 | 2.3 | 2.0 | 1.6 | 1.9 | 2.4 | 2.0 | 2.7 | 1.5 |
| Graafwater/Sandveld | 9.1 | 2.3 | 2.1 | 1.8 | 1.8 | 2.0 | 1.8 | 2.9 | 1.3 |
| Hardeveld | 9.6 | 2.4 | 2.4 | 1.9 | 1.8 | 2.1 | 1.8 | 2.8 | 1.3 |
| Hermon/Gouda | 9.9 | 2.2 | 2.1 | 1.8 | 1.7 | 2.1 | 1.8 | 3.0 | 1.3 |
| Hoe Reenval Saaigebied | 10.4 | 2.1 | 2.0 | 1.6 | 1.6 | 2.0 | 1.5 | 2.9 | 1.2 |
| Kamanassie | 6.3 | 2.4 | 2.2 | 1.9 | 2.0 | 2.5 | 2.2 | 2.7 | 1.6 |
| Kleinberg/Suurrug | 9.4 | 2.3 | 2.0 | 1.6 | 1.9 | 2.4 | 1.9 | 2.8 | 1.5 |
| Koringberg/Rooi Karoo Saaigebied | 8.9 | 2.4 | 2.2 | 2.0 | 1.9 | 2.2 | 2.0 | 3.0 | 1.4 |
| Malgas/Heidelbergvlakte | 9.0 | 2.3 | 2.0 | 1.6 | 1.9 | 2.4 | 2.0 | 2.9 | 1.4 |
| Middel Swartland Saaigebied | 10.1 | 2.2 | 2.0 | 1.6 | 1.6 | 2.1 | 1.6 | 3.0 | 1.3 |
| Ruens East | 8.8 | 2.2 | 2.0 | 1.6 | 1.9 | 2.4 | 1.8 | 2.9 | 1.4 |
| Ruens West | 8.0 | 2.3 | 1.9 | 1.6 | 1.9 | 2.4 | 1.8 | 3.1 | 1.4 |
| Sandveld Saaigebied | 10.0 | 2.2 | 2.0 | 1.6 | 1.6 | 2.0 | 1.6 | 2.8 | 1.3 |
| Stockwell | 7.9 | 2.3 | 2.2 | 1.8 | 2.1 | 2.5 | 2.1 | 3.0 | 1.5 |
| Tulbagh/Wolseley | 8.4 | 2.4 | 2.2 | 1.9 | 1.9 | 2.2 | 2.0 | 3.0 | 1.4 |
| Urionskraal | 10.4 | 2.5 | 2.4 | 2.0 | 1.9 | 2.2 | 2.2 | 2.9 | 1.5 |

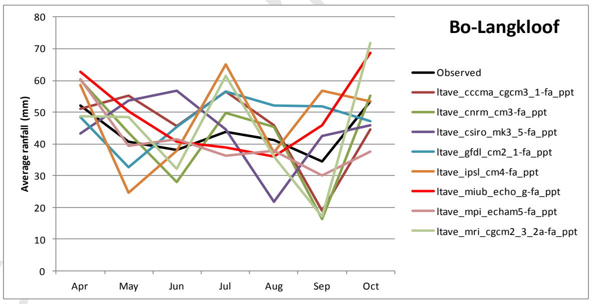
Appendix Table 2. Average (Apr-Oct) downscaled GCM maximum temperature anomalies for 2046 – 2065.

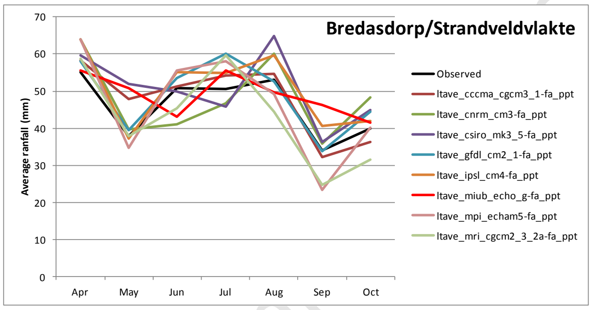
| RHFA | Observed (°C) | Average maximum temperature anomalies (Δ°C) for April - October (2046 - 2065) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | cgcm3_1 | cnrm_cm3 | csiro3_5 | echam5 | echo_g | gfdl2_1 | ipsl_cm4 | mri_cgcm2_3 |
| Agter-Paarl | 21.2 | 2.2 | 2.1 | 1.4 | 1.6 | 2.3 | 1.3 | 3.3 | 1.4 |
| Bo-Langkloof | 18.0 | 2.2 | 2.0 | 1.6 | 1.9 | 2.1 | 1.5 | 2.7 | 1.4 |
| Bredasdorp/Strandveldvlakte | 19.3 | 2.1 | 1.9 | 1.4 | 1.7 | 2.2 | 1.3 | 2.9 | 1.3 |
| Gemengde Boerderygebied | 21.2 | 2.2 | 2.1 | 1.4 | 1.6 | 2.3 | 1.3 | 3.3 | 1.4 |
| Gourits-Rooiruens | 20.4 | 2.1 | 1.8 | 1.4 | 1.8 | 2.1 | 1.4 | 2.7 | 1.4 |
| Gouritzriviervallei | 19.2 | 2.1 | 1.9 | 1.4 | 1.8 | 2.2 | 1.5 | 2.6 | 1.4 |
| Graafwater/Sandveld | 22.4 | 2.4 | 2.2 | 1.6 | 1.7 | 2.1 | 1.4 | 3.2 | 1.4 |
| Hardeveld | 22.8 | 2.5 | 2.5 | 1.9 | 1.7 | 2.1 | 1.5 | 3.1 | 1.5 |
| Hermon/Gouda | 20.3 | 2.3 | 2.1 | 1.6 | 1.7 | 2.1 | 1.4 | 3.2 | 1.4 |
| Hoe Reenval Saaigebied | 20.1 | 2.1 | 2.0 | 1.4 | 1.4 | 2.0 | 1.2 | 3.1 | 1.3 |
| Kamanassie | 18.5 | 2.2 | 2.1 | 1.6 | 1.9 | 2.1 | 1.6 | 2.7 | 1.5 |
| Kleinberg/Suurrug | 20.3 | 2.1 | 1.8 | 1.4 | 1.8 | 2.2 | 1.4 | 2.7 | 1.4 |
| Koringberg/Rooi Karoo Saaigebied | 21.9 | 2.4 | 2.3 | 1.8 | 1.8 | 2.3 | 1.5 | 3.2 | 1.5 |
| Malgas/Heidelbergvlakte | 19.9 | 2.1 | 1.9 | 1.4 | 1.8 | 2.2 | 1.4 | 2.8 | 1.4 |
| Middel Swartland Saaigebied | 20.4 | 2.2 | 2.1 | 1.5 | 1.6 | 2.2 | 1.3 | 3.3 | 1.4 |
| Ruens East | 20.1 | 2.1 | 1.9 | 1.3 | 1.8 | 2.1 | 1.4 | 2.9 | 1.3 |
| Ruens West | 20.5 | 2.1 | 1.9 | 1.4 | 1.8 | 2.2 | 1.2 | 3.1 | 1.3 |
| Sandveld Saaigebied | 19.4 | 2.1 | 1.9 | 1.5 | 1.4 | 2.0 | 1.3 | 3.1 | 1.2 |
| Stockwell | 21.0 | 2.2 | 2.1 | 1.5 | 1.9 | 2.2 | 1.5 | 2.8 | 1.4 |
| Tulbagh/Wolseley | 20.4 | 2.4 | 2.2 | 1.6 | 1.8 | 2.2 | 1.5 | 3.1 | 1.5 |
| Urionskraal | 22.3 | 2.5 | 2.5 | 1.8 | 1.9 | 2.2 | 1.7 | 3.3 | 1.6 |

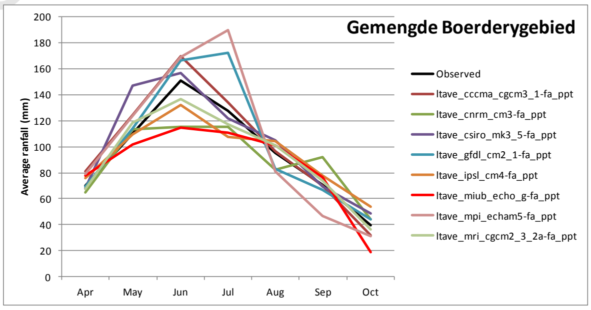
## Appendix III - Average future April-October monthly rainfall for 2046 - 2065 for each RHFA as projected by the 8 downscaled GCMs.

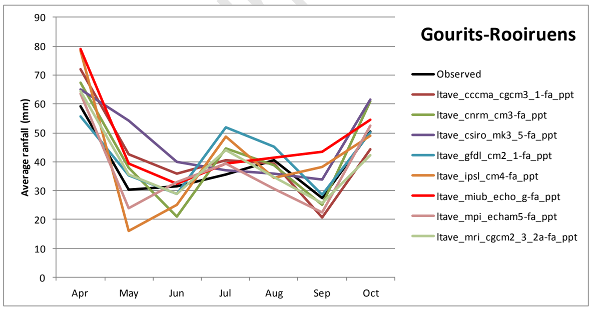
(The observed rainfall (1979 - 1999) is included for comparative purposes. To help constrain rainfall model bias, future rainfall is determined by calculating the difference between the each downscaled GCM's simulated future and control result, and adding that anomaly back onto the observed). Note when making any comparisons that the range on the Y-axis may vary considerably.

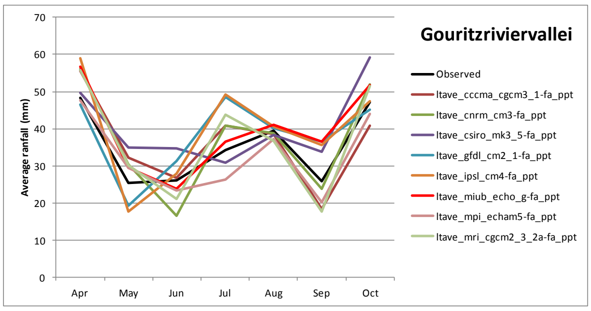


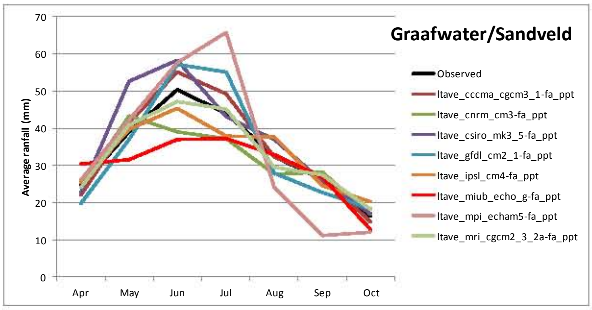


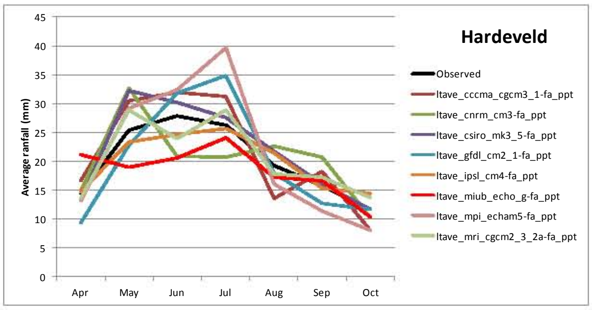


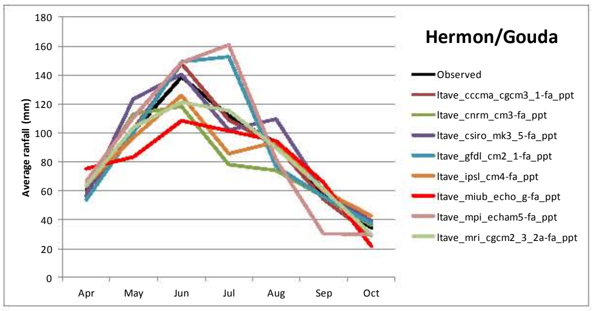


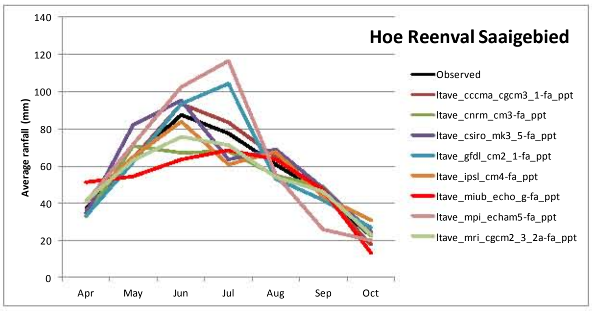


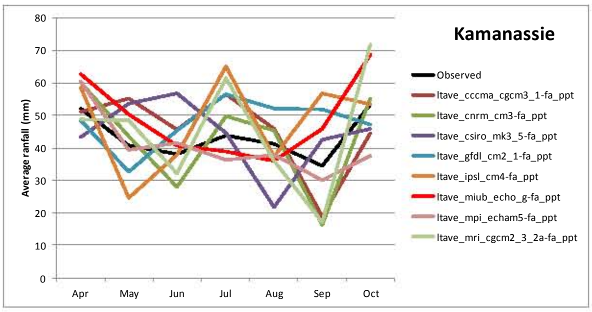


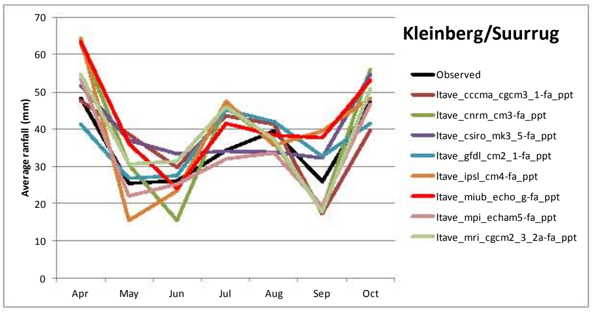

Graafwater/Sandveld
Average ranfall (mm)
0
10
20
30
40
50
60
70
Apr
May
Jun
Jul
Aug
Sep
Oct
Observed
ltave_cccma_cgcm3_1-fa_ppt
ltave_cnrm_cm3-fa_ppt
ltave_csiro_mk3_5-fa_ppt
ltave_gfdl_cm2_1-fa_ppt
ltave_ipsl_cm4-fa_ppt
ltave_miub_echo_g-fa_ppt
ltave_mpi_echam5-fa_ppt
ltave_mri_cgcm2_3_2a-fa_ppt

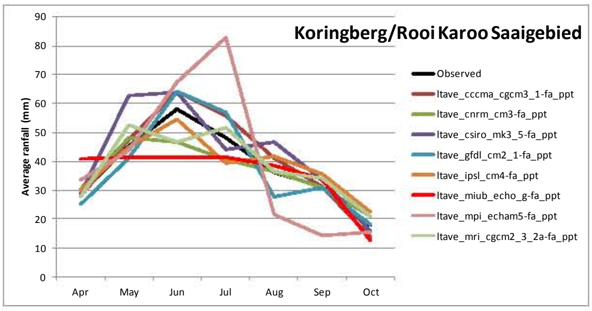

Hardeveld
Average ranfall (mm)
0
5
10
15
20
25
30
35
40
45
Apr
May
Jun
Jul
Aug
Sep
Oct
Observed
ltave_cccma_cgcm3_1-fa_ppt
ltave_cnrm_cm3-fa_ppt
ltave_csiro_mk3_5-fa_ppt
ltave_gfdl_cm2_1-fa_ppt
ltave_ipsl_cm4-fa_ppt
ltave_miub_echo_g-fa_ppt
ltave_mpi_echam5-fa_ppt
ltave_mri_cgcm2_3_2a-fa_ppt

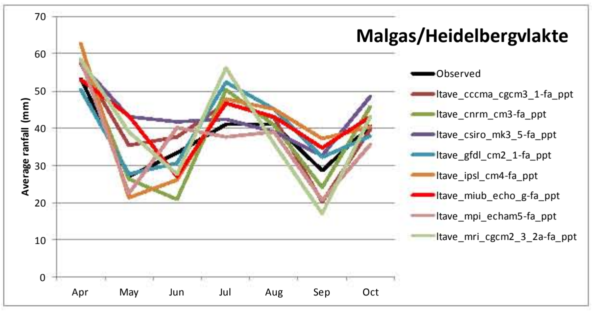

Hermon/Gouda
Average ranfall (mm)
0
20
40
60
80
100
120
140
160
180
Apr
May
Jun
Jul
Aug
Sep
Oct
Observed
ltave_cccma_cgcm3_1-fa_ppt
ltave_cnrm_cm3-fa_ppt
ltave_csiro_mk3_5-fa_ppt
ltave_gfdl_cm2_1-fa_ppt
ltave_ipsl_cm4-fa_ppt
ltave_miub_echo_g-fa_ppt
ltave_mpi_echam5-fa_ppt
ltave_mri_cgcm2_3_2a-fa_ppt

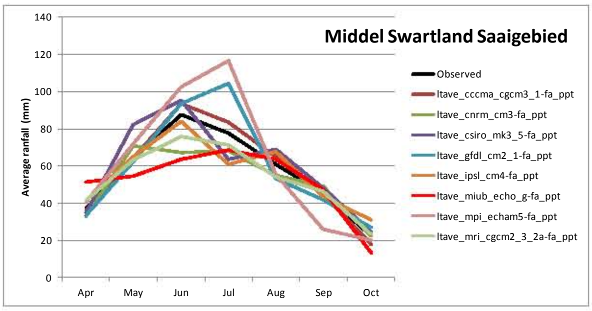

Hoe Reenval Saaigebied
Average ranfall (mm)
0
20
40
60
80
100
120
140
Apr
May
Jun
Jul
Aug
Sep
Oct
Observed
ltave_cccma_cgcm3_1-fa_ppt
ltave_cnrm_cm3-fa_ppt
ltave_csiro_mk3_5-fa_ppt
ltave_gfdl_cm2_1-fa_ppt
ltave_ipsl_cm4-fa_ppt
ltave_miub_echo_g-fa_ppt
ltave_mpi_echam5-fa_ppt
ltave_mri_cgcm2_3_2a-fa_ppt

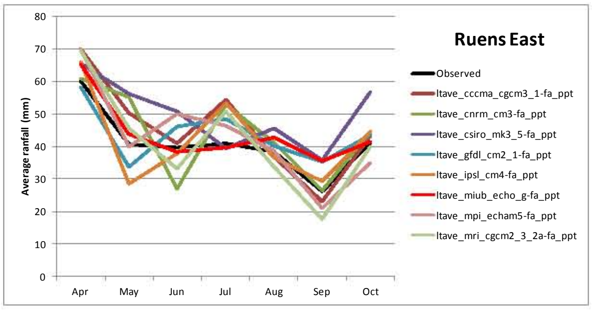

Kamanassie
Average ranfall (mm)
0
10
20
30
40
50
60
70
80
Apr
May
Jun
Jul
Aug
Sep
Oct
Observed
ltave_cccma_cgcm3_1-fa_ppt
ltave_cnrm_cm3-fa_ppt
ltave_csiro_mk3_5-fa_ppt
ltave_gfdl_cm2_1-fa_ppt
ltave_ipsl_cm4-fa_ppt
ltave_miub_echo_g-fa_ppt
ltave_mpi_echam5-fa_ppt
ltave_mri_cgcm2_3_2a-fa_ppt

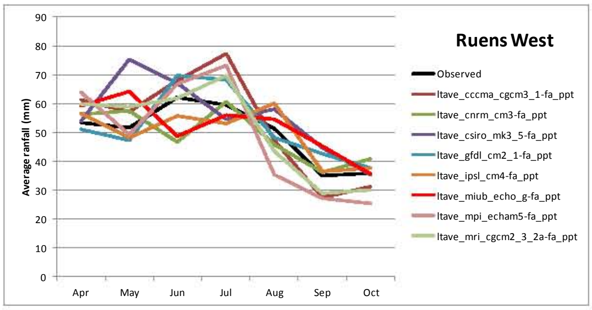

Kleinberg/Suurrug
Average ranfall (mm)
0
10
20
30
40
50
60
70
Apr
May
Jun
Jul
Aug
Sep
Oct
Observed
ltave_cccma_cgcm3_1-fa_ppt
ltave_cnrm_cm3-fa_ppt
ltave_csiro_mk3_5-fa_ppt
ltave_gfdl_cm2_1-fa_ppt
ltave_ipsl_cm4-fa_ppt
ltave_miub_echo_g-fa_ppt
ltave_mpi_echam5-fa_ppt
ltave_mri_cgcm2_3_2a-fa_ppt

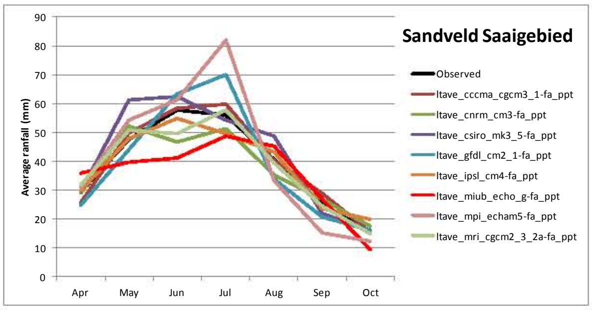

Koringberg/Rooi Karoo Saaigebied
Average ranfall (mm)
0
10
20
30
40
50
60
70
80
90
Apr
May
Jun
Jul
Aug
Sep
Oct
Observed
ltave_cccma_cgcm3_1-fa_ppt
ltave_cnrm_cm3-fa_ppt
ltave_csiro_mk3_5-fa_ppt
ltave_gfdl_cm2_1-fa_ppt
ltave_ipsl_cm4-fa_ppt
ltave_miub_echo_g-fa_ppt
ltave_mpi_echam5-fa_ppt
ltave_mri_cgcm2_3_2a-fa_ppt

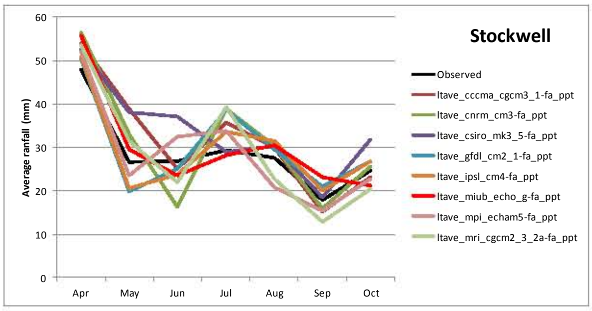

Malgas/Heidelbergvlakte
Average ranfall (mm)
0
10
20
30
40
50
60
70
Apr
May
Jun
Jul
Aug
Sep
Oct
Observed
ltave_cccma_cgcm3_1-fa_ppt
ltave_cnrm_cm3-fa_ppt
ltave_csiro_mk3_5-fa_ppt
ltave_gfdl_cm2_1-fa_ppt
ltave_ipsl_cm4-fa_ppt
ltave_miub_echo_g-fa_ppt
ltave_mpi_echam5-fa_ppt
ltave_mri_cgcm2_3_2a-fa_ppt

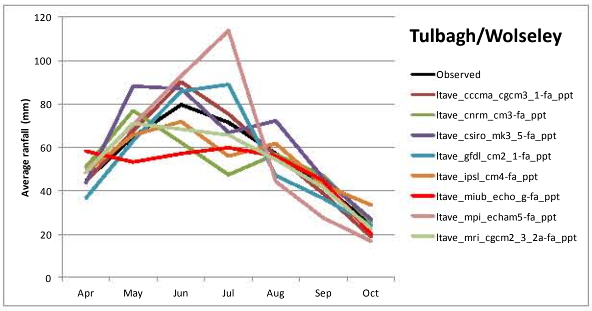

Middel Swartland Saaigebied
Average ranfall (mm)
0
20
40
60
80
100
120
140
Apr
May
Jun
Jul
Aug
Sep
Oct
Observed
ltave_cccma_cgcm3_1-fa_ppt
ltave_cnrm_cm3-fa_ppt
ltave_csiro_mk3_5-fa_ppt
ltave_gfdl_cm2_1-fa_ppt
ltave_ipsl_cm4-fa_ppt
ltave_miub_echo_g-fa_ppt
ltave_mpi_echam5-fa_ppt
ltave_mri_cgcm2_3_2a-fa_ppt

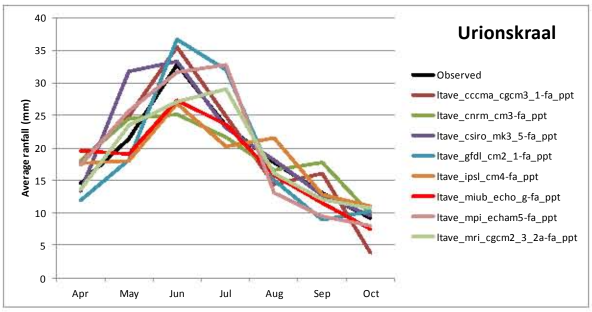

Ruens East
Average ranfall (mm)
0
10
20
30
40
50
60
70
80
Apr
May
Jun
Jul
Aug
Sep
Oct
Observed
ltave_cccma_cgcm3_1-fa_ppt
ltave_cnrm_cm3-fa_ppt
ltave_csiro_mk3_5-fa_ppt
ltave_gfdl_cm2_1-fa_ppt
ltave_ipsl_cm4-fa_ppt
ltave_miub_echo_g-fa_ppt
ltave_mpi_echam5-fa_ppt
ltave_mri_cgcm2_3_2a-fa_ppt


Ruens West
90
80
70
60
50
40
30
20
10
0
Average ranfall (mm)
Apr
May
Jun
Jul
Aug
Sep
Oct
Observed
ltave_cccma_cgcm3_1-fa_ppt
ltave_cnrm_cm3-fa_ppt
ltave_csiro_mk3_5-fa_ppt
ltave_gfdl_cm2_1-fa_ppt
ltave_ipsl_cm4-fa_ppt
ltave_miub_echo_g-fa_ppt
ltave_mpi_echam5-fa_ppt
ltave_mri_cgcm2_3_2a-fa_ppt

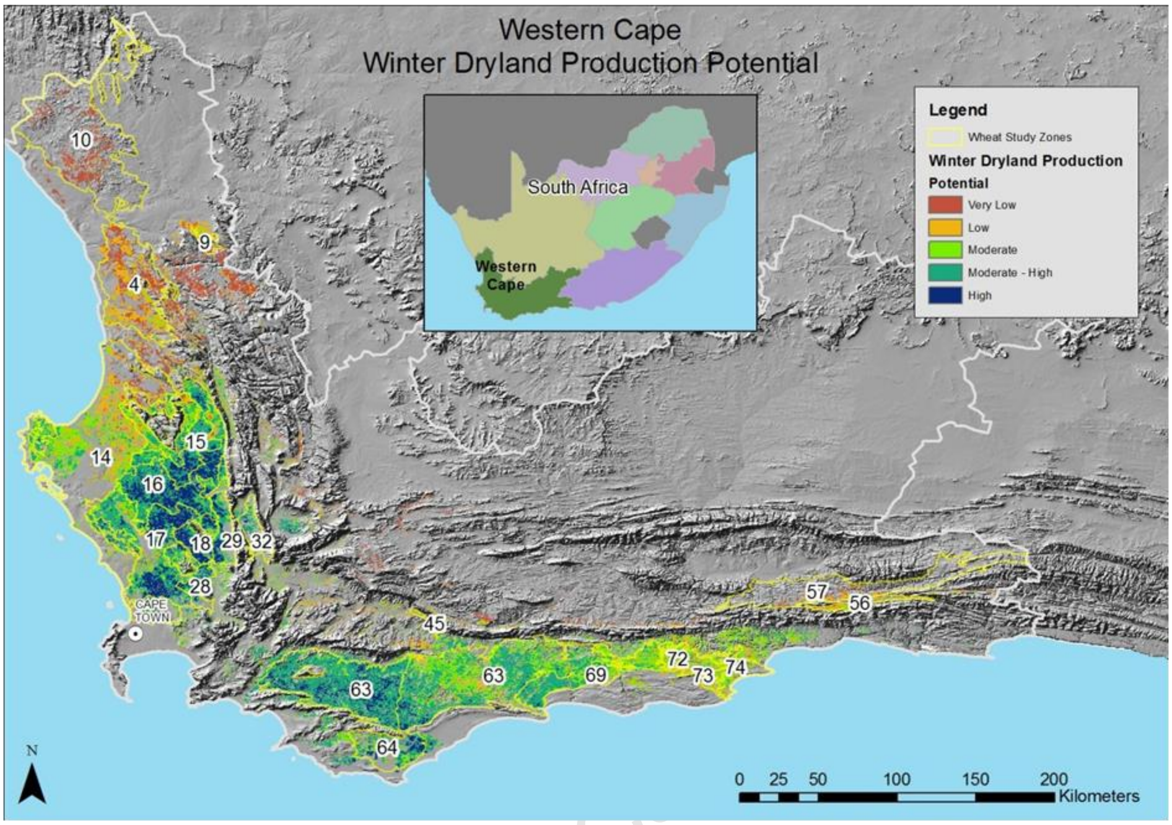

Sandveld Saaigebied
90
80
70
60
50
40
30
20
10
0
Average ranfall (mm)
Apr
May
Jun
Jul
Aug
Sep
Oct
Observed
ltave_cccma_cgcm3_1-fa_ppt
ltave_cnrm_cm3-fa_ppt
ltave_csiro_mk3_5-fa_ppt
ltave_gfdl_cm2_1-fa_ppt
ltave_ipsl_cm4-fa_ppt
ltave_miub_echo_g-fa_ppt
ltave_mpi_echam5-fa_ppt
ltave_mri_cgcm2_3_2a-fa_ppt


Stockwell
60
50
40
30
20
10
0
Average ranfall (mm)
Apr
May
Jun
Jul
Aug
Sep
Oct
Observed
ltave_cccma_cgcm3_1-fa_ppt
ltave_cnrm_cm3-fa_ppt
ltave_csiro_mk3_5-fa_ppt
ltave_gfdl_cm2_1-fa_ppt
ltave_ipsl_cm4-fa_ppt
ltave_miub_echo_g-fa_ppt
ltave_mpi_echam5-fa_ppt
ltave_mri_cgcm2_3_2a-fa_ppt


Tulbagh/Wolseley
120
100
80
60
40
20
0
Average ranfall (mm)
Apr
May
Jun
Jul
Aug
Sep
Oct
Observed
ltave_cccma_cgcm3_1-fa_ppt
ltave_cnrm_cm3-fa_ppt
ltave_csiro_mk3_5-fa_ppt
ltave_gfdl_cm2_1-fa_ppt
ltave_ipsl_cm4-fa_ppt
ltave_miub_echo_g-fa_ppt
ltave_mpi_echam5-fa_ppt
ltave_mri_cgcm2_3_2a-fa_ppt

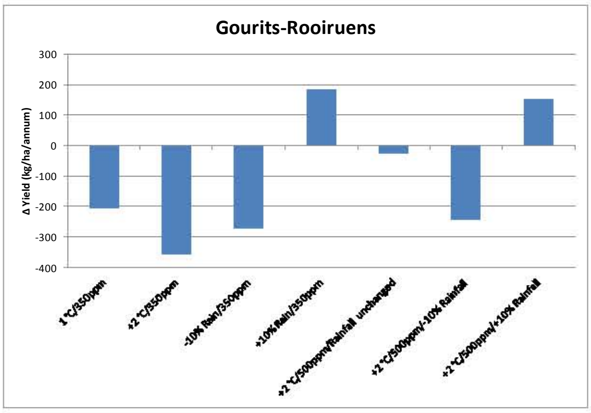

Urionskraal
40
35
30
25
20
15
10
5
0
Average ranfall (mm)
Apr
May
Jun
Jul
Aug
Sep
Oct
Observed
ltave_cccma_cgcm3_1-fa_ppt
ltave_cnrm_cm3-fa_ppt
ltave_csiro_mk3_5-fa_ppt
ltave_gfdl_cm2_1-fa_ppt
ltave_ipsl_cm4-fa_ppt
ltave_miub_echo_g-fa_ppt
ltave_mpi_echam5-fa_ppt
ltave_mri_cgcm2_3_2a-fa_ppt

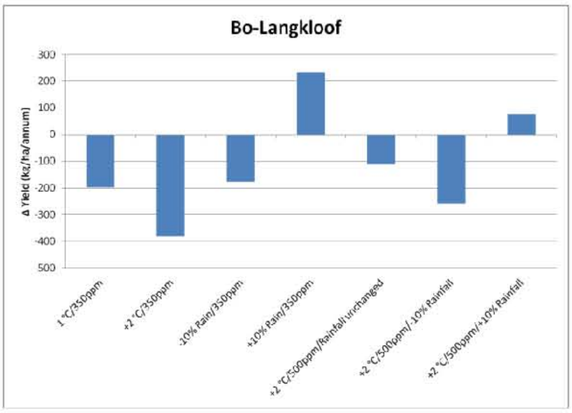
## Appendix IV - Western Cape winter dryland production potential

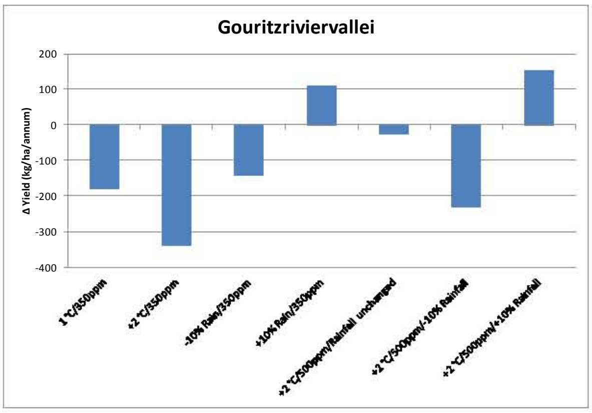


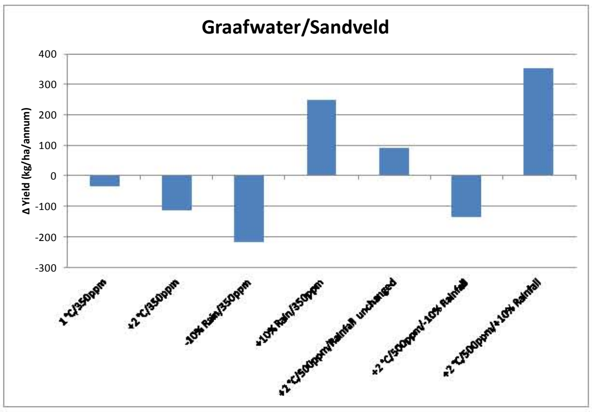
Appendix Figure 25. Current winter dryland production potential (Wallace, unpublished). The RHFA zone number is given on the map.

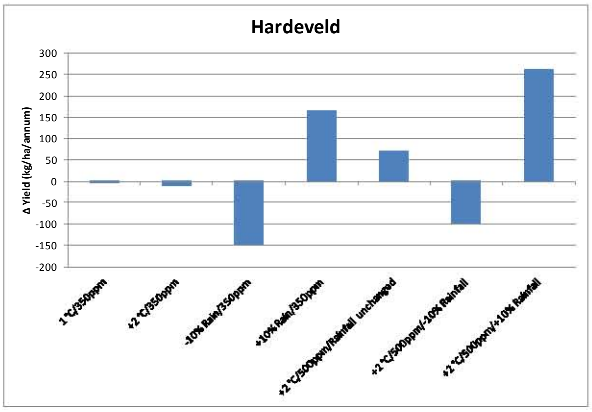
# Appendix V - Sensitivity impact model output graphs for the secondary wheat zones

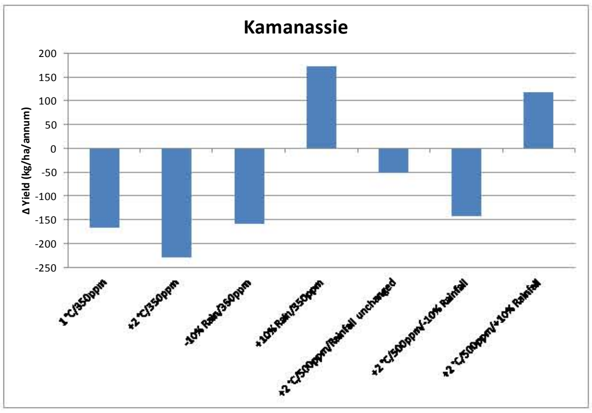


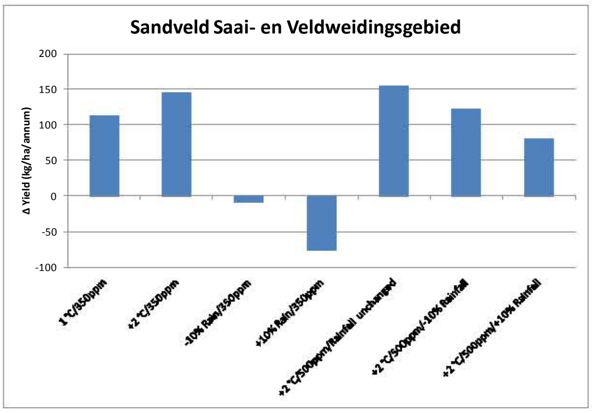


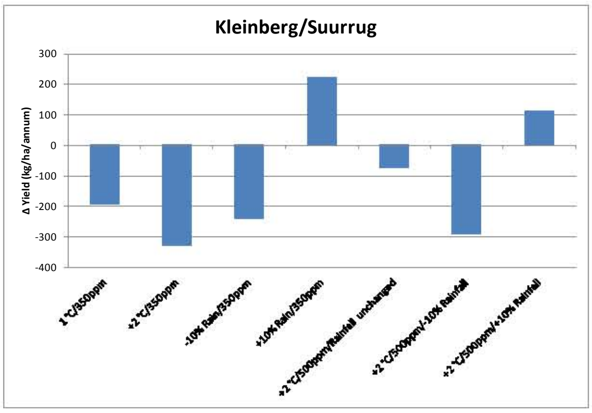


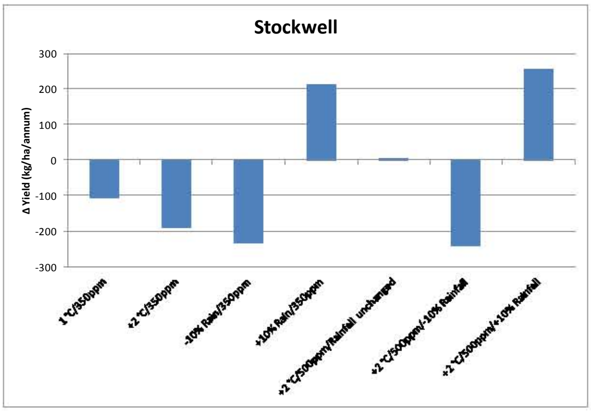


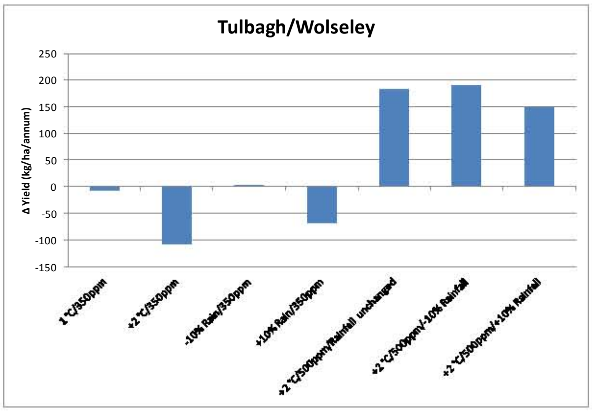


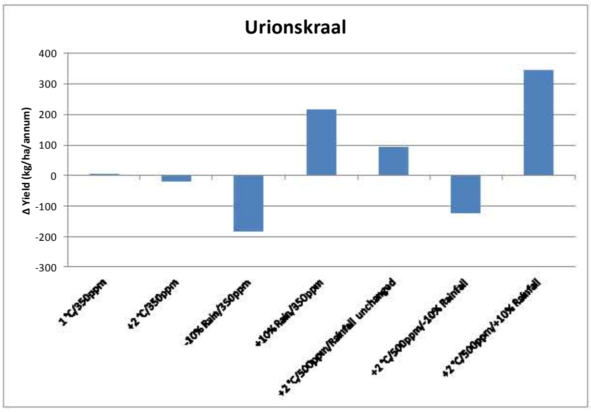







Stockwell
Δ Yield (kg/ha/annum)
300
200
100
0
-100
-200
-300
1 °C/350ppm
+2 °C/350ppm
-10% Rain/350ppm
+10% Rain/350ppm
+2 °C/500ppm/Rainfall unchanged
+2 °C/500ppm/-10% Rainfall
+2 °C/500ppm/+10% Rainfall

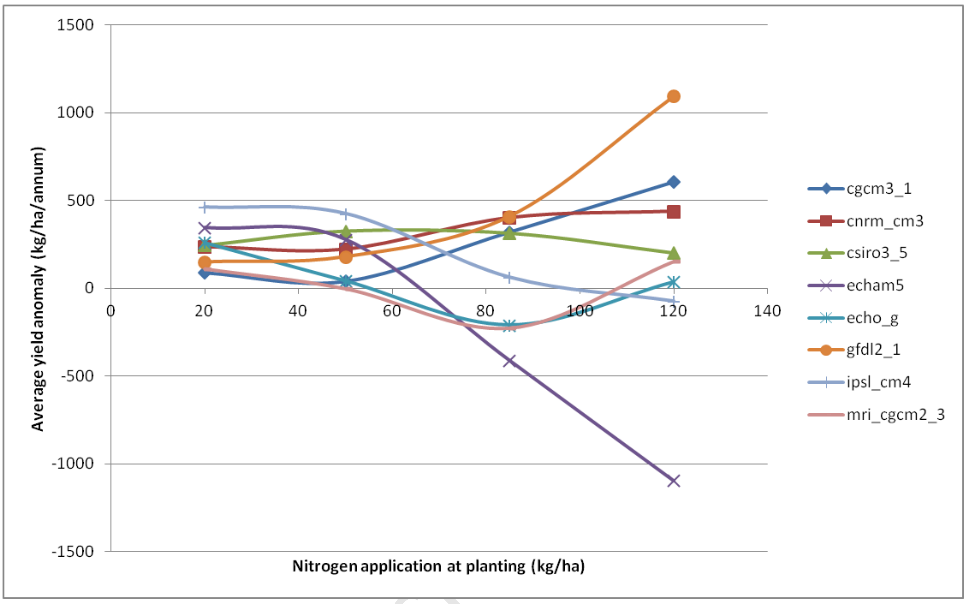

Tulbagh/Wolseley
Δ Yield (kg/ha/annum)
250
200
150
100
50
0
-50
-100
-150
1 °C/350ppm
+2 °C/350ppm
-10% Rain/350ppm
+10% Rain/350ppm
+2 °C/500ppm/Rainfall unchanged
+2 °C/500ppm/-10% Rainfall
+2 °C/500ppm/+10% Rainfall


Urionskraal
Δ Yield (kg/ha/annum)
400
300
200
100
0
-100
-200
-300
1 °C/350ppm
+2 °C/350ppm
-10% Rain/350ppm
+10% Rain/350ppm
+2 °C/500ppm/Rainfall unchanged
+2 °C/500ppm/-10% Rainfall
+2 °C/500ppm/+10% Rainfall

Appendix VI - Introductory discussion and plots of yield anomalies versus different nitrogen application levels for APSIM modelled RHFA yield as driven by each of the 8 downscaled GCMs climate data.

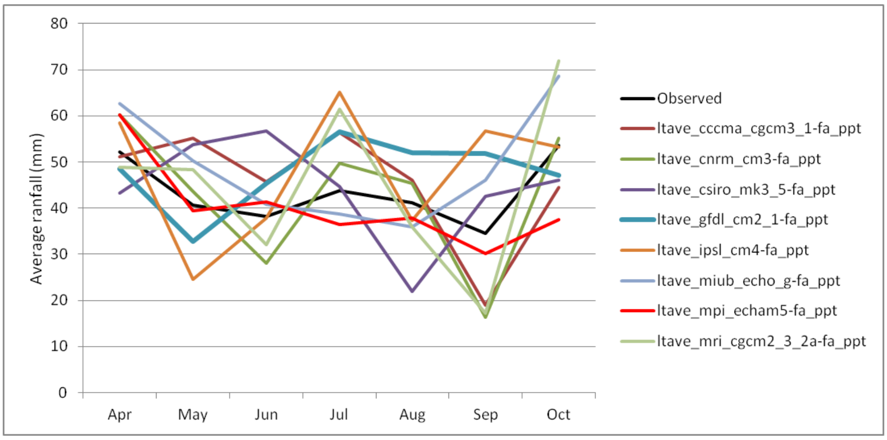
**Discussion on variation on N response within the modelled ensemble:**

Bo-Langkloof had the highest range and standard deviation in the yield projection ensemble. A plot of all deviations from the "observed" for each level of N for Bo-Langkloof is presented in Appendix Figure 26.



Appendix Figure 26. Plot of Bo-Langkloof yield anomalies versus four different nitrogen application levels for APSIM modelled yield driven by each of the 8 downscaled GCMs. Note: *The insertion of lines does not imply any trend, but is added only to assist in visual presentation of the scatter.*

In this RHFA, the gfdl2_1 model produced the highest and the echam5 model the lowest yields. Comparing this to modelled future precipitation – the echam5 downscaling indeed projected the lowest seasonal rainfall, whilst the gfdl2_1 is 2nd highest where it appears that a favourable seasonal distribution curve may have had a beneficial influence, as relatively higher rainfall is maintained during the critical anthesis and grain filling stages from August to October (Appendix Figure 27).

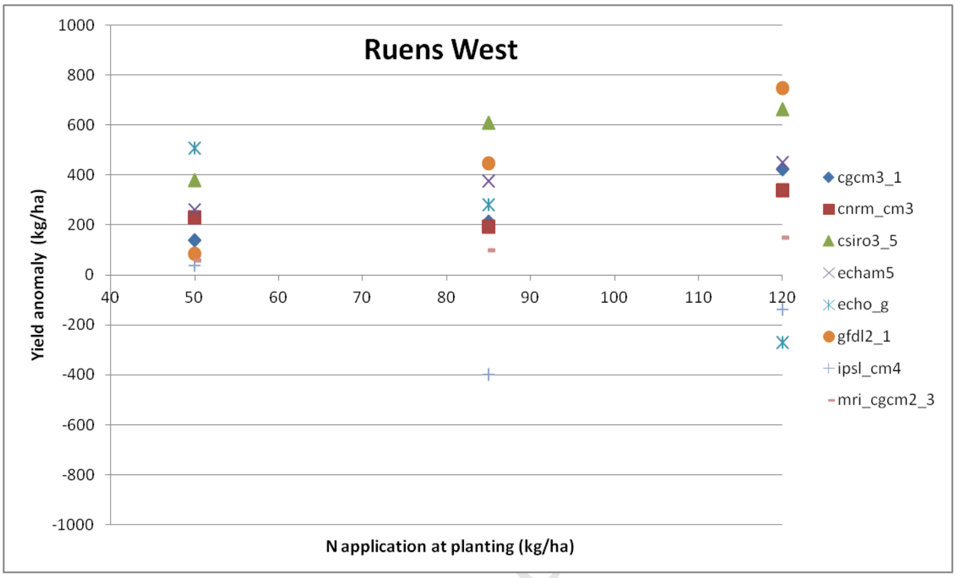


Appendix Figure 27. Average growing season monthly rainfall for 2046 - 2065 as projected by the 8 downscaled GCMs. The observed rainfall (1979 - 1999) is shown for comparative purposes. (To help constrain rainfall model bias, future rainfall is determined by calculating the difference between the simulation's future and control, and adding that anomaly back on to the observed)

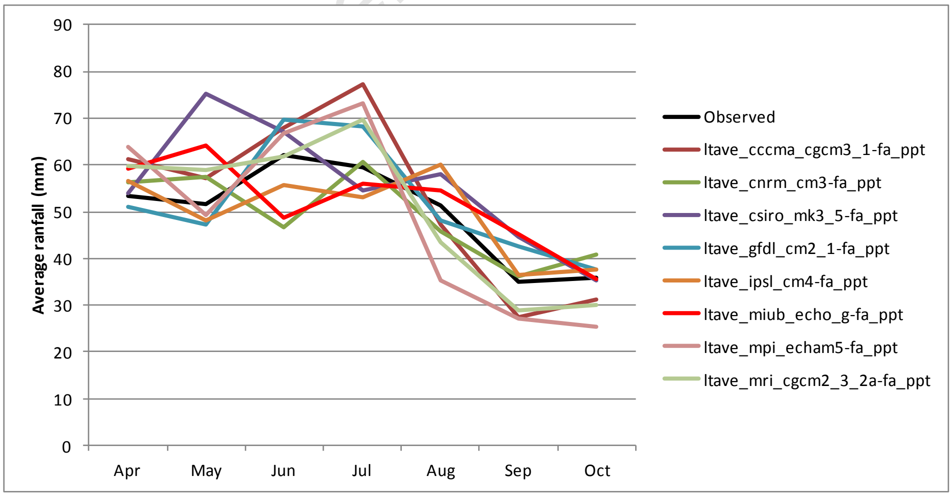
The Bo-Langkloof seemed to be an outlier in its extreme response to the high N application. Gourits-RooiRûens and Gouritzriviervallei both showed increasing yield at the higher N levels forced by the GCM which projected the highest rainfall for the July, August period (gfdl2_1). The low response to high N in Kamanassie again seemed to be a response to the lowest rainfall projection (echam5). Graafwater/Sandveld responded favourably to the rainfall projection (echam5) which was highest during June/July, although not the highest over the whole season) and showed a negative response to high N at the lowest seasonal rainfall projection (echo_g). This rainfall relationship did not hold for the Sandveld Saaigebied however, where the strongest N responses were produced by one of the lower rainfall projections (echo_g) or in Tulbagh/Wolseley, where the responses seemed unrelated to rainfall scenario.

Agter-Paarl and Gemengde Boerderygebied showed similar marked reduction in N response under the ipsl_cm4 projection. This may be a consequence of the corresponding rainfall being the lowest in the ensemble for July, indicating poor rainfall distribution was projected – possible as a result of dry spells – leading up to anthesis.

Initial inspection of the N-response graph of Rûens West (Appendix Figure 28. Plot of Rûens West yield anomalies vs. three different nitrogen application levels for APSIM modelled yield driven by each of the 8 downscaled GCMs.), one of the highest yielding wheat areas, appears to show good overall response to higher N applications. The quartile responses (in terms of percentages of each N application's baseline yield) however, indicate otherwise. Although most of the yield responses increase towards higher N levels in terms of kg/ha, these increases are small in relation to the percentages of the high baseline yields in this zone. The negative response under the echo_g projection may once again be a response to the low rainfall projected for June and July.



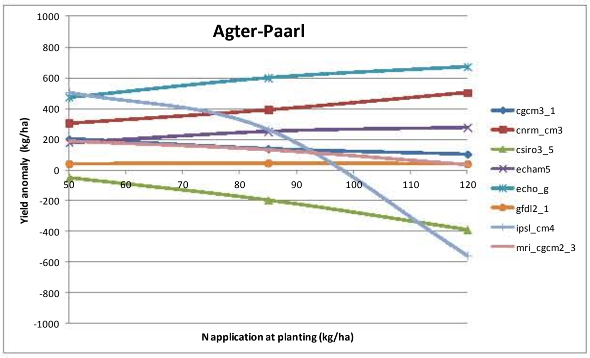
Appendix Figure 28. Plot of Rûens West yield anomalies vs. three different nitrogen application levels for APSIM modelled yield driven by each of the 8 downscaled GCMs.

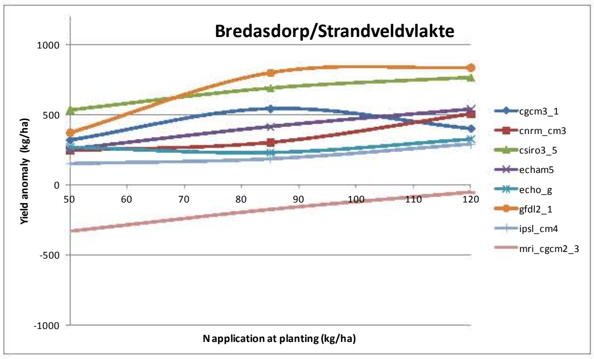


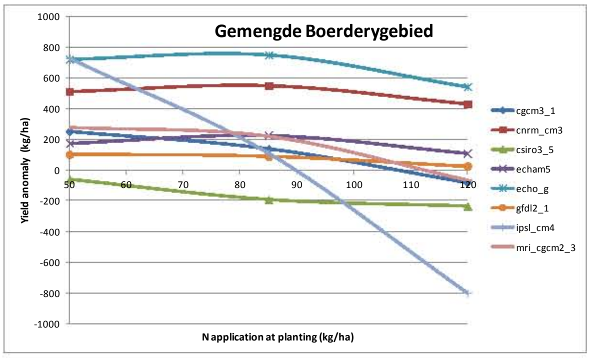
Appendix Figure 29. Average growing season monthly rainfall for 2046 – 2065 as projected by the 8 downscaled GCMs. The observed rainfall (1979 - 1999) is shown for comparative purposes

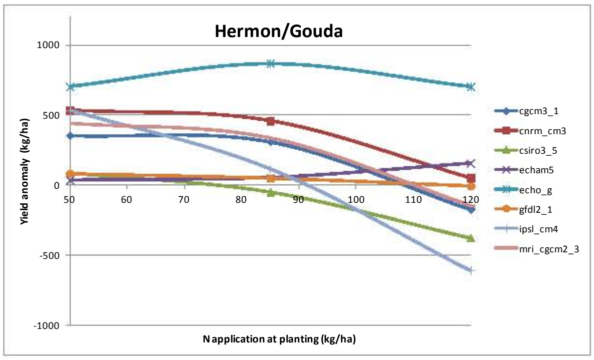
Primary wheat production RHFAs: plots showing responses (yield anomalies) at 3 different N levels (50; 85 and 120 kg/ha) at planting:

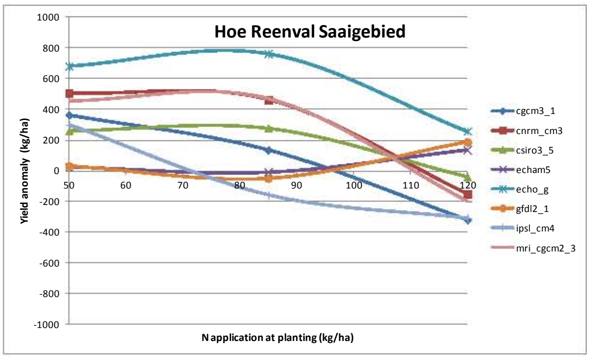
***Note***: *The insertion of lines does not imply a trend, but are added only to assist in visual presentation of the scatter.*

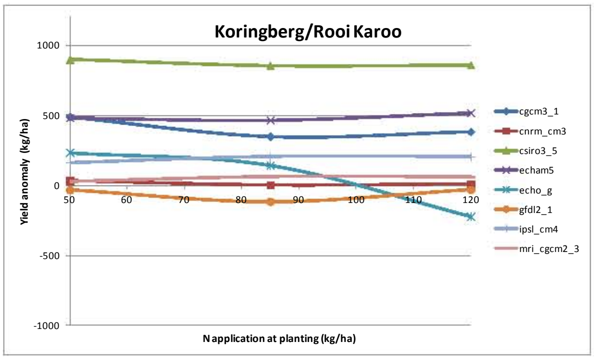


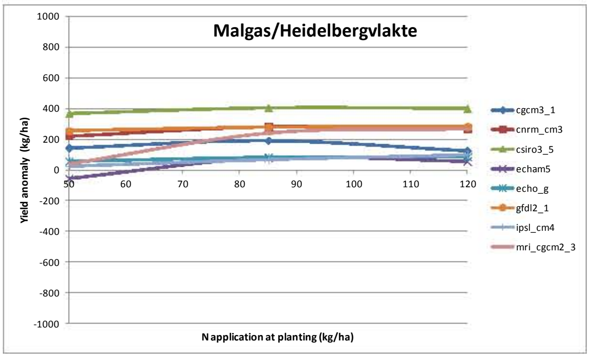


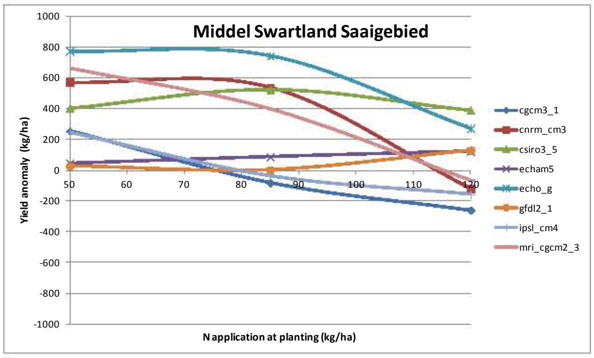


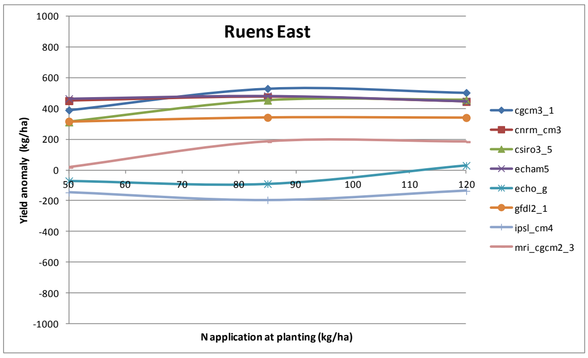


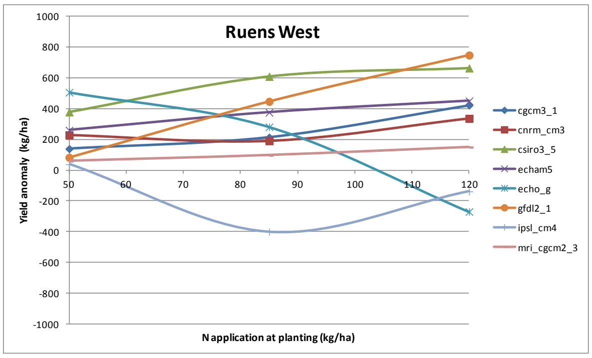






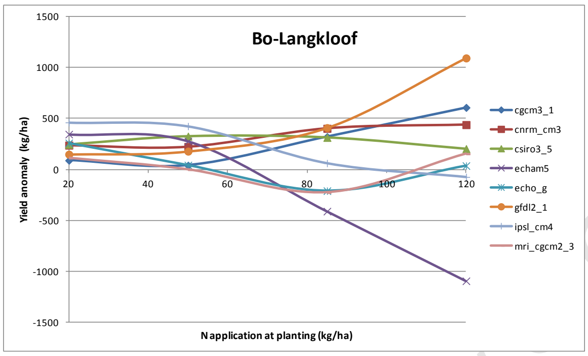


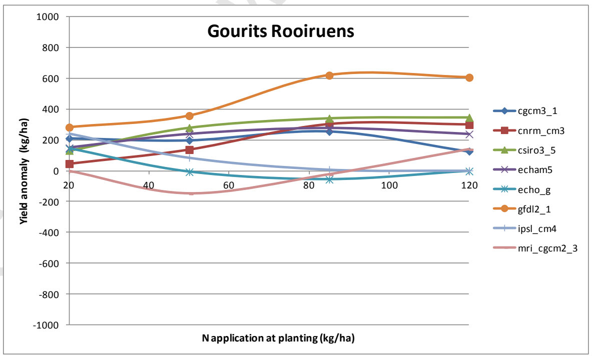


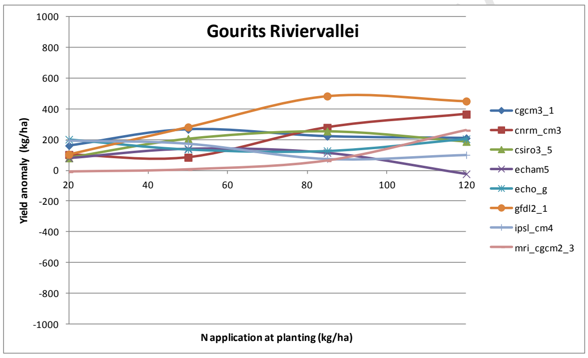


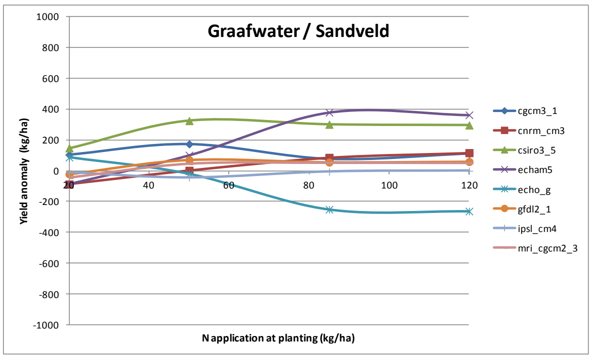
Secondary wheat production RHFAs: plots showing responses (yield anomalies) at 4 different N levels (20; 50; 85 and 120 kg/ha) at planting:

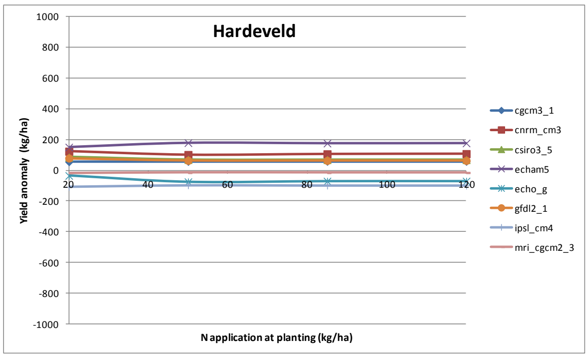
***Note***: *The insertion of lines does not imply a trend, but are added only to assist in visual presentation of the scatter.*

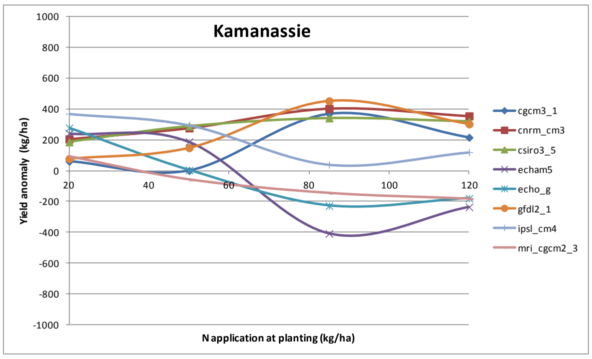


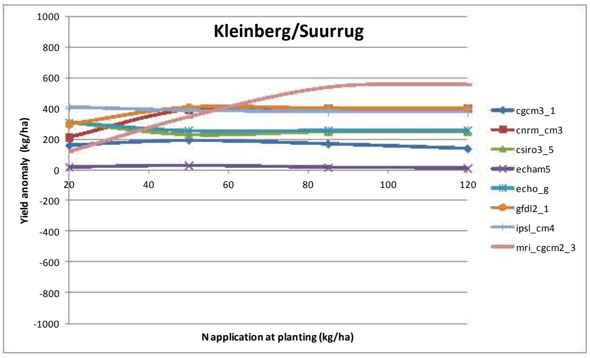


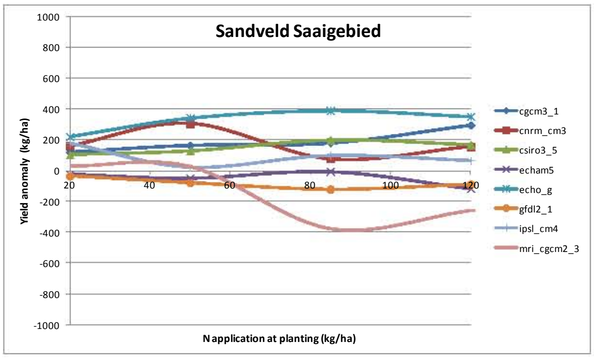


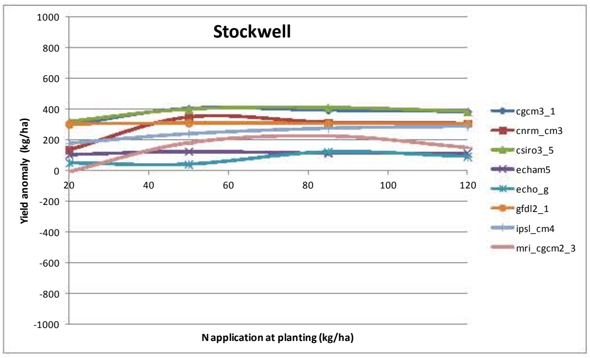


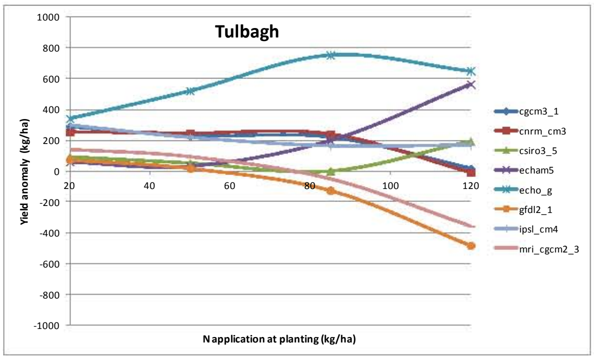


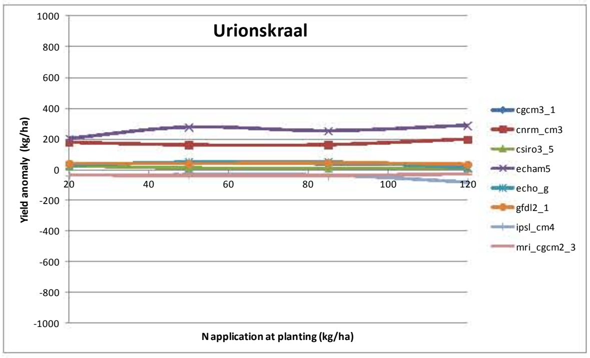



Kleinberg/Suurrug
Yield anomaly (kg/ha)
1000
800
600
400
200
0
-200
-400
-600
-800
-1000
20
40
60
80
100
120
N application at planting (kg/ha)
cgcm3_1
cnrm_cm3
csiro3_5
echam5
echo_g
gfdl2_1
ipsl_cm4
mri_cgcm2_3

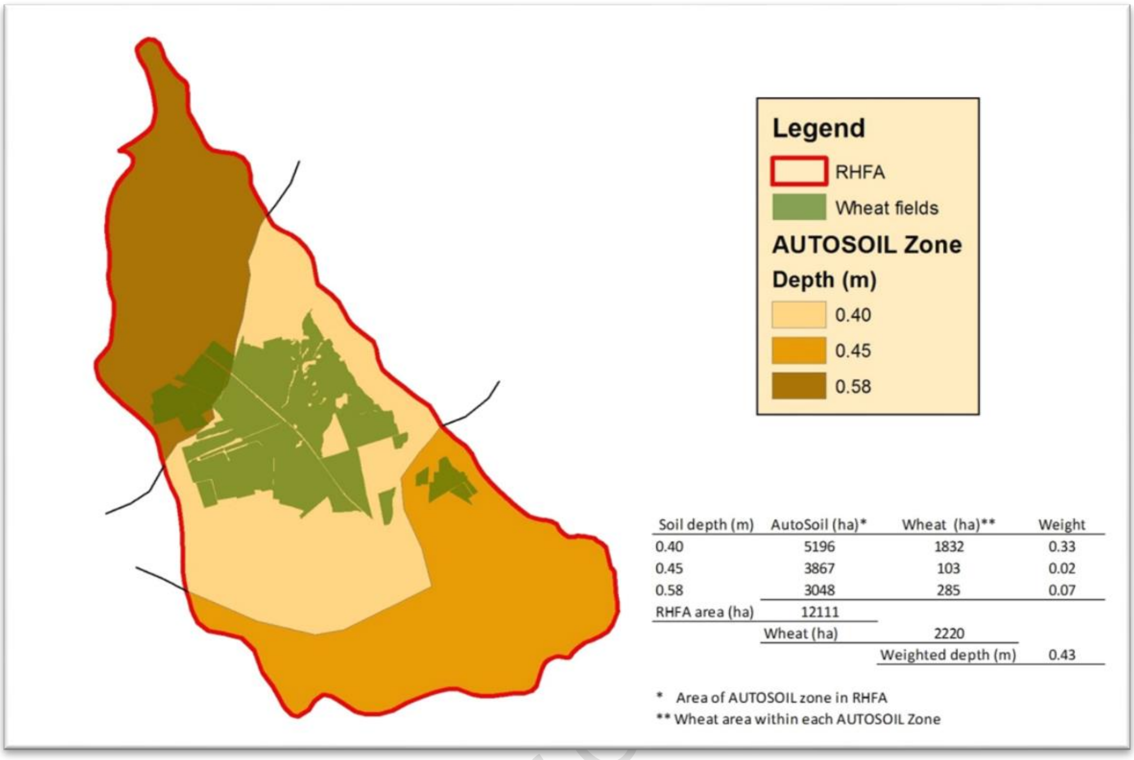

Sandveld Saaigebied
Yield anomaly (kg/ha)
1000
800
600
400
200
0
-200
-400
-600
-800
-1000
20
40
60
80
100
120
N application at planting (kg/ha)
cgcm3_1
cnrm_cm3
csiro3_5
echam5
echo_g
gfdl2_1
ipsl_cm4
mri_cgcm2_3


Stockwell
Yield anomaly (kg/ha)
1000
800
600
400
200
0
-200
-400
-600
-800
-1000
20
40
60
80
100
120
N application at planting (kg/ha)
cgcm3_1
cnrm_cm3
csiro3_5
echam5
echo_g
gfdl2_1
ipsl_cm4
mri_cgcm2_3


Tulbagh
Yield anomaly (kg/ha)
1000
800
600
400
200
0
-200
-400
-600
-800
-1000
20
40
60
80
100
120
N application at planting (kg/ha)
cgcm3_1
cnrm_cm3
csiro3_5
echam5
echo_g
gfdl2_1
ipsl_cm4
mri_cgcm2_3


Urionskraal
Yield anomaly (kg/ha)
1000
800
600
400
200
0
-200
-400
-600
-800
-1000
20
40
60
80
100
120
N application at planting (kg/ha)
cgcm3_1
cnrm_cm3
csiro3_5
echam5
echo_g
gfdl2_1
ipsl_cm4
mri_cgcm2_3

# Appendix VII - Soil area-weighting methodology and parameterisation



| Soil depth (m) | AutoSoil (ha)* | Wheat (ha)** | Weight |
|---|---|---|---|
| 0.40 | 5196 | 1832 | 0.33 |
| 0.45 | 3867 | 103 | 0.02 |
| 0.58 | 3048 | 285 | 0.07 |
| RHFA area (ha) | 12111 | | |
| | Wheat (ha) | 2220 | |
| | | Weighted depth (m) | 0.43 |

* Area of AUTOSOIL zone in RHFA

** Wheat area within each AUTOSOIL Zone

Appendix Figure 30. Graphic showing an example of the methodology used to assign area-weighted soil water-holding capacity values (e.g. depth shown in this example) for each RHFA according to the proportion of mapped wheat fields within each intersected AUTOSOIL zone per RHFA.

Appendix Table 3. Table showing the soil water-holding parameters derived from the area-weighting methodology and the corresponding maximum and minimum RHFA values per parameter.

| **RHFA** | **LL1** | MIN | MAX | **LL2** | MIN | MAX | **DUL1** | MIN | MAX | **DUL2** | MIN | MAX | **Depth** | **MIN** | **MAX** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | m/m | | | | | | | **cm** | |
| Agter-Paarl | **0.15** | 0.086 | 0.177 | **0.21** | 0.165 | 0.246 | **0.23** | 0.185 | 0.248 | **0.28** | 0.244 | 0.302 | **45** | 34 | 68 |
| Bo-Langkloof | **0.12** | 0.069 | 0.137 | **0.16** | 0.077 | 0.170 | **0.20** | 0.163 | 0.220 | **0.24** | 0.181 | 0.251 | **50** | 8 | 54 |
| Bredasdorp/Strandveldvlakte | **0.12** | 0.077 | 0.163 | **0.18** | 0.122 | 0.217 | **0.20** | 0.176 | 0.238 | **0.24** | 0.215 | 0.282 | **50** | 19 | 54 |
| Gemengde Boerderygebied | **0.12** | 0.065 | 0.173 | **0.17** | 0.089 | 0.237 | **0.21** | 0.166 | 0.245 | **0.25** | 0.193 | 0.296 | **70** | 4 | 108 |
| Gourits-Rooiruens | **0.15** | 0.098 | 0.166 | **0.20** | 0.139 | 0.219 | **0.23** | 0.192 | 0.240 | **0.27** | 0.230 | 0.283 | **65** | 25 | 75 |
| Gouritzriviervallei | **0.12** | 0.096 | 0.143 | **0.12** | 0.103 | 0.179 | **0.20** | 0.189 | 0.224 | **0.22** | 0.208 | 0.255 | **50** | 45 | 107 |
| Graafwater/Sandveld | **0.08** | 0.065 | 0.136 | **0.09** | 0.069 | 0.136 | **0.12** | 0.111 | 0.217 | **0.14** | 0.135 | 0.205 | **90** | 13 | 119 |
| Hardeveld | **0.08** | 0.074 | 0.083 | **0.08** | 0.076 | 0.083 | **0.17** | 0.167 | 0.174 | **0.18** | 0.180 | 0.184 | **55** | 36 | 60 |
| Hermon/Gouda | **0.14** | 0.085 | 0.177 | **0.21** | 0.143 | 0.251 | **0.23** | 0.183 | 0.250 | **0.28** | 0.232 | 0.305 | **60** | 45 | 86 |
| Hoe Reenval Saaigebied | **0.10** | 0.064 | 0.173 | **0.16** | 0.092 | 0.241 | **0.20** | 0.166 | 0.245 | **0.24** | 0.196 | 0.298 | **70** | 15 | 118 |
| Kamanassie | **0.12** | 0.098 | 0.141 | **0.13** | 0.120 | 0.160 | **0.20** | 0.190 | 0.222 | **0.22** | 0.213 | 0.242 | **50** | 0 | 58 |
| Kleinberg/Suurrug | **0.10** | 0.054 | 0.162 | **0.16** | 0.098 | 0.218 | **0.20** | 0.162 | 0.237 | **0.24** | 0.204 | 0.284 | **55** | 20 | 113 |
| Koringberg/Rooi Karoo | **0.15** | 0.073 | 0.183 | **0.21** | 0.101 | 0.259 | **0.23** | 0.171 | 0.258 | **0.28** | 0.203 | 0.311 | **60** | 18 | 104 |
| Malgas/Heidelbergvlakte | **0.17** | 0.130 | 0.190 | **0.20** | 0.132 | 0.239 | **0.24** | 0.215 | 0.257 | **0.27** | 0.221 | 0.297 | **45** | 37 | 53 |
| Middel Swartland Saaigebied | **0.12** | 0.064 | 0.183 | **0.18** | 0.085 | 0.259 | **0.21** | 0.167 | 0.258 | **0.25** | 0.188 | 0.311 | **75** | 14 | 119 |
| Ruens East | **0.15** | 0.090 | 0.210 | **0.17** | 0.102 | 0.288 | **0.23** | 0.184 | 0.271 | **0.25** | 0.196 | 0.331 | **45** | 8 | 75 |
| Ruens West | **0.13** | 0.080 | 0.147 | **0.15** | 0.085 | 0.184 | **0.21** | 0.174 | 0.227 | **0.23** | 0.184 | 0.258 | **55** | 35 | 63 |
| Sandveld Saai | **0.09** | 0.040 | 0.178 | **0.12** | 0.060 | 0.215 | **0.18** | 0.120 | 0.253 | **0.22** | 0.000 | 0.282 | **90** | 0 | 120 |
| Stockwell | **0.13** | 0.118 | 0.136 | **0.16** | 0.112 | 0.170 | **0.22** | 0.205 | 0.225 | **0.24** | 0.207 | 0.242 | **60** | 33 | 68 |
| Tulbagh/Wolseley | **0.13** | 0.105 | 0.139 | **0.16** | 0.130 | 0.169 | **0.22** | 0.194 | 0.232 | **0.24** | 0.221 | 0.250 | **50** | 41 | 80 |
| Urionskraal | **0.14** | 0.072 | 0.152 | **0.20** | 0.086 | 0.225 | **0.22** | 0.172 | 0.240 | **0.27** | 0.190 | 0.285 | **70** | 24 | 79 |