Thematic Booklet 16

Biofuel Feedstock Production in South Africa and Climate Change

R.E. Schulze (Ed)

A Selection of Extracts from

HANDBOOK ON ADAPTATION TO CLIMATE CHANGE FOR FARMERS, OFFICIALS AND OTHERS IN THE AGRICULTURAL SECTOR OF SOUTH AFRICA

Chapters A1, J5 and Appendices
DISCLAIMER

While every reasonable effort has been made by the authors to obtain objective and realistic results in this study, neither the authors, the School of Bioresources Engineering and Environmental Hydrology nor the University of KwaZulu-Natal, nor the Department of Agriculture, Forestry and Fisheries nor any of their employees, make any warranty, express or implied, or assume any legal liability or responsibility for the accuracy, completeness or usefulness of any information, product or process disclosed by this report.
Background to the Handbook’s Thematic Booklets

The “Handbook on Adaptation to Climate Change for Farmers, Officials and Others in the Agricultural Sector of South Africa” contains 47 Chapters in 11 Sections and is over 670 pages in length. For greater ease of use, the full document is also presented in the form of 16 thematic booklets, of which this is one. The Chapters making up this specific booklet are listed on the cover page. Each booklet, in addition to its theme chapters, also contains the introductory Chapter A1, the concluding Chapter K1 and Appendices (Chapters A5 and A6) on tools used in the analyses as well as clarifications of terms commonly used in climate change studies. In the table of contents below these chapters are highlighted. Please note that page numbers in this thematic booklet do not correspond with those in the full Handbook.

HANDBOOK ON ADAPTATION TO CLIMATE CHANGE FOR FARMERS, OFFICIALS AND OTHERS IN THE AGRICULTURAL SECTOR OF SOUTH AFRICA

Thematic Booklets

Booklet 1 Agriculture and Climate Change in South Africa: On Vulnerability, Adaptation and Climate Smart Agriculture
Booklet 2 Agriculture’s Natural Capital in South Africa 1: The Biophysical Environment
Booklet 3 Agriculture’s Natural Capital in South Africa 1: Weather and Climate – Now and into the Future
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SETTING THE SCENE

CHAPTER A1   ON OBSERVATIONS, CLIMATE CHALLENGES, THE SOUTH
AFRICAN AGRICULTURE SECTOR AND CONSIDERATIONS FOR AN
ADAPTATION HANDBOOK

R.E. Schulze

Setting the Scene

What are We Already Observing in Regard to Our Climate? A Global Perspective

What are We Observing in Regard to Our Climate? A South African Perspective

Figure A1.1  Annual CO$_2$ emissions (in Gigatons) into the atmosphere (top) and annual
(red pluses) as well as decadal (red bars) global temperature differences relative to the 20th century average (bottom), showing 2015 to be the hottest
year on record (Sources: USGS and NOAA, 2016)

Figure A1.2  Annual mean temperature anomalies (base period 1961-1990) of 20 climate
stations in South Africa for the period 1961-2014, with the red line indicating the linear trend and the black line the 5-year moving average (SAWS, 2015)

Climate and Climate Change as Drivers of Agricultural Production in South Africa

The Climate Hand We have been Dealt with

Climate as a Driver of Agricultural Production in South Africa

Climate Change: The Added Challenge

A Little More on the Science of Climate Change from a South African Perspective

Climate Projections into the Future

Figure A1.3  Increases in GHG emissions in the recent past (left), with more detail on
recent global monthly mean CO2 concentrations in the atmosphere (Sources:

Figure A1.4  Representative Concentration Pathways (Source: IPCC, 2014)

Why a Focus in South Africa on the Agricultural Sector?

First, What Does Our National Climate Change Response Strategy State from an
Overall Perspective?

Secondly, What are Our National Climate Change Response Strategy’s More
Specific Mandates on South Africa’s Agriculture and Forestry?

The South African Farming Scene: The Complexity of Farming Types in South Africa

A Typology of Farming Systems

Figure A1.5  A typology of South African farming systems (Original conception: Jordaan,
Ncube and Schulze, 2014; later published in Ncube and Lagardien, 2015)

Subsistence Farmers
Smallholder Farmers
Emerging Farmers
Semi-Commercial Farmers
Commercial Farmers

Figure A1.6  Trends in commercial farming units in South Africa over time (DAFF
Abstracts of Agricultural Statistics, 2013)

What Needs to be Considered in a Handbook on Adaptation to Climate Change in the
Agriculture Sector of South Africa?
The Geographical Area Covered in this Handbook

Figure A1.7  Provinces, countries, major roads and towns
Table A1.1  Areal information (Sources: Statistics SA, 2013)

The Scope Covered in this Handbook

In Conclusion: What to Expect and Not to Expect from the Handbook

Further Reading

Please cite as follows:
Schulze, R.E. 2016. On Observations, Climate Challenges, the South African Agriculture Sector and Considerations for an Adaptation Handbook. In: Schulze, R.E. (Ed.) Handbook for Farmers, Officials and Other Stakeholders on Adaptation to Climate Change in the Agriculture Sector within South Africa. Section A: Agriculture and Climate Change in South Africa: Setting the Scene, Chapter A1.
A1 ON OBSERVATIONS, CLIMATE CHALLENGES, THE SOUTH AFRICAN AGRICULTURE SECTOR AND CONSIDERATIONS FOR AN ADAPTATION HANDBOOK

Setting the Scene

The world’s climate is changing fast, and will continue to do so for the foreseeable future, no matter what measures are now taken. The effects of climate change on agriculture should therefore be seen in terms of both

• productivity of farming operations, and
• the risk of disruption of production,

with implications for food security and income for millions of households in South Africa. The increase in average temperature that characterises climate change, when taken together with changing rainfall patterns, is likely to shift optimum growing areas for key crops, generate an increase in the frequency and severity of extreme and moderate weather events, and result in pests and diseases finding new ranges. This converts into increased vulnerability in agriculture over the medium to long term and poses new risks to farming and food production unless measures are taken now already to strengthen the resilience of production systems and to learn to adapt to cope with climate change – a recognition that has led to the concept of “climate smart agriculture”.

The above realisation becomes even more relevant because agriculture is generally considered to be one of the most high-performance motors of growth in national and global economies, and it has been shown that in developing countries such as South Africa, agricultural growth:

• contributes more than most other sectors to overall growth of revenue in those rural environments where the major part of the vulnerable populations live and work,
• stimulates growth in the other sectors of the economy by amplifying the demand for goods and services produced within the agricultural sector, and
• reduces levels of poverty, famine and malnutrition by increasing the supply of food and improving access to a better diet.

Early planning to adapt to the risks of climate change, and also being aware of the opportunities that climate change may have to offer, will help minimize the impacts on farm productivity and protect farm operations.

This Handbook is designed as a starting point for identifying decisions which need to be made to help farmers and officials be better prepared for the projected consequences of climate change and to support farmers to adapt timeously.

What are We Already Observing in Regard to Our Climate? A Global Perspective

The effects of climate change resulting from steady increases in carbon dioxide (CO₂) emissions into the atmosphere (Figure A1.1 top) can no longer be denied or ignored, with 2015 having been the planet’s warmest year on record (Figure A1.1 bottom) since these started in the 1860s, and up to the end of 2015, 14 of the 15 hottest years on record had been in this century. All South Africans, including farmers and ranchers, are already facing devastating impacts of climate – from severe floods to extreme heat and drought to increased challenges due to wildfires, disease and pests. That is why the South African government is taking action to cut the carbon pollution that drives climate change and protect our communities from its impacts.
Figure A1.1  Annual CO₂ emissions (in Gigatons) into the atmosphere (top) and annual (red pluses) as well as decadal (red bars) global temperature differences relative to the 20ᵗʰ century average (bottom), showing 2015 to be the hottest year on record (Sources: USGS and NOAA, 2016)

What are We Observing in Regard to Our Climate? A South African Perspective

While not as steady as the global temperature trend, South Africa's temperature is also showing an overall upward trend in temperatures (Figure A1.2).

Figure A1.2  Annual mean temperature anomalies (base period 1961-1990) of 20 climate stations in South Africa for the period 1961-2014, with the red line indicating the linear trend and the black line the 5-year moving average (SAWS, 2015)
Climate and Climate Change as Drivers of Agricultural Production in South Africa

The Climate Hand We have been Dealt with
South Africa’s climate has many influences ranging from seasonal synoptic circulations and frontal systems, the El-Niño-Southern Oscillation, the inter-Tropical Convergence Zone, occasional Tropical cyclones, coastal cut-off lows and many more. Jointly, these have provided South Africa not only with summer, winter and all year rainfall regions, but also with one of the world’s most variable climates. Living with, and managing the impacts of, climate variability on agricultural systems has thus always been a major challenge.

As a result of the above,

- Over 80% of the RSA's land surface may be classified semi-arid to arid, with only 18% being dry sub-humid to sub-humid; the potential for crop production is therefore limited;
- In fact, of the RSA’s total surface area, only ~ 13% can be used for arable crop production, and of that, only 22% has high potential, with less than 10% of the total arable land under irrigation.
- The most limiting factor in agriculture is available water, with rainfall generally low and erratic for rain fed agriculture, while the relatively small irrigated sector utilises ~ 60% of the RSA’s stored water.

Climate as a Driver of Agricultural Production in South Africa
There are many “drivers” of the agricultural sector in South Africa, each of which can have wide-ranging repercussions not only in the production of food, fibre and forests, but also on GDP, employment or foreign exchange earnings. One such “driver” that varies markedly from year to year, and within any given year, is climate.

Climate is vital for the selection of appropriate crops for a given locality or site, irrespective of whether farmers are planning for maximum economic returns or for sustaining their immediate family’s livelihood, and the more detailed the knowledge, the more intelligently the land use can be planned on all scales, be they at the macro, farm or plot scales.

Climate information is equally important for optimising seasonal and longer term agricultural practices as it is for day-to-day operational planning ranging from when and how much to irrigate, to timing of fertilizer application, the selection of cultivars / varieties or to deciding when to plant.

The influence exercised by climate on living organisms is, however, exceedingly complex, not only because the individual climatic variables play important roles, but also because of the constant interaction between the variables.

Climate Change: The Added Challenge
Now, in addition to the highly variable and challenging climate described above, there is increasing evidence that changes in temperatures, rainfall patterns, wind fields and climate extremes are already occurring that cannot be explained by natural causes alone, and that there is a strong human “fingerprint” at the cause of these change. These climatic changes affect agricultural activities and output, and they are projected to change non-uniformly in magnitude, direction and variability over the next few decades, not only on a global scale, but more specifically so regionally and locally within South Africa. Again, such human-induced climate change is projected to occur in addition to the already high natural climate variability which we experience, and in addition to the other stresses that beset the agriculture sector in South Africa.

Climate change will likely cause a range of impacts on South African agriculture with a consequent need for adaptation responses to emergent risks and opportunities. This
Handbook is intended to be a step towards effective climate change adaptation responses across South African agriculture.

Climate change, often perceived and described by many simply as “global warning”, has climatic ramifications well beyond merely averaged temperature increases, and through higher order perturbations in rainfall and temperature characteristics these changes present serious challenges to agriculture and forestry, which are the providers of food, feed, fibre, timber and energy, and which contribute significantly to the GDPs of economies worldwide, either directly or through knock-on effects. As such, climate change is causing grave concern at all levels of society worldwide because plants and animals may not be able to cope with, and adapt to, the progressive and projected changes in climate as well as we humans can, and this poses a serious threat to ecosystems. Climate change dynamics are extremely complex and not yet well enough understood, especially regarding the extent, timing and impacts of projected changes. South Africa’s already high risk climatic environment by virtue of its straddling the 20-35°S latitudinal range which is transitional to winter, all year and summer rainfall producing synoptic regimes, renders it particularly sensitive and vulnerable to geographical shifts in climates. What is currently known, however, points to many serious effects that climate change can have on South Africa’s food security, socio-economic activities, human health, water resources, extreme weather events, low lying areas and infrastructure. The effects are not necessarily always negative, however, and positive spin-offs are likely to occur. These need to be identified and maximised.

As agriculture and forestry are the mainstay of livelihoods and economic growth, the South African national Department of Agriculture, Forestry and Fisheries (DAFF), together with other non-governmental role players (NGOs) in the broader agricultural sector, has been proactive in initiating sector related climate change strategies and scenarios to promote climate change awareness and knowledge, advocate sustainable terrestrial and aquatic ecosystems-based production practices which minimise emissions of greenhouse gases, conserve the sector's natural environments, promote adaptation and mitigate effects of climate change as far as possible. This Handbook is the outcome of one such DAFF initiative.

Rather than dealing only with short-term weather events such as droughts, floods, heat waves and cold spells, farmers must now respond to climatic changes that will alter irrevocably the way they farm. Around the world, and for us specifically in this country, farmers urgently need to understand better the projected impacts of climate change in order for them to become innovative so that they will be able to produce enough to support themselves and the ever-growing local, regional and global population. Their added challenge is to do so in ways that will protect the environment, especially soil and water, and minimise agriculture’s contribution to climate change.

**A Little More on the Science of Climate Change from a South African Perspective**

*Climate Projections into the Future*

Climates are changing as a result of an increase in concentrations of greenhouse gases (GHGs; mainly carbon dioxide CO$_2$, methane CH$_4$ and nitrous oxide N$_2$O) in the earth’s atmosphere (Figure A1.3). This increase has occurred over the past two centuries, and has been accelerating more recently, due to anthropogenic (human driven) factors, particularly industrialisation through burning of fossil fuels such as coal, oils and natural gases mainly for energy generation, but also to unsustainable land use systems, increases in livestock and clearing of forests, all resulting in increasing the concentration of GHGs.

Such GHG emitting activities have significantly increased the atmosphere’s absorption of the earth’s outgoing infrared radiation, thereby enhancing the existing greenhouse effect, and then re-radiating part of it back to earth, resulting in the rising trend in global temperatures
shown in Figure A1.1. Climate change thus refers to the changes of climate which are attributed directly or indirectly to human activities that alter the composition of the global atmosphere. This change in climate is superimposed onto natural climate variability which is experienced world-wide, but which is particularly severe over South Africa.

Future climate projections (which are NOT forecasts nor predictions) are scenario descriptions of possible future conditions based on the current understanding of the physics of the atmosphere, on assumptions about changing GHG emissions and their atmospheric concentrations, as well as on assumptions of future technological, economic and demographic trends. The skill of projections (i.e. their accuracy) depends strongly on how far into the future projections are made, which of a number of possible future GHG emissions pathways is considered (the thicker lines in Figure A1.4), and on the climate variable considered (e.g. temperature projections are generally thought to be more skilful than rainfall projections). Deriving key regional messages about future potential change thus requires assessing multiple lines of evidence. Climate projections are therefore assessed in this Handbook from a range of climate models generically termed GCMs, i.e. General Circulation Models or Global Climate Models, as it is not possible to identify a “best” model for all relevant climate variables for South Africa (Schulze, 2012). This range of outcomes from different GCMs for a specific future pathway is shown by the different thin coloured lines in Figure A1.4 for each of the thicker coloured lines of an emissions pathway.

Projections of impacts in the agricultural sector in South Africa (and other sectors as well) are often complicated by different scientists applying different sets of climate scenarios and using different modelling approaches, thus making it challenging to extract coherent key
messages. The various climate projections used in the agricultural impact studies presented in this Handbook have been based, in many of the case studies, on the Intergovernmental Panel on Climate Change’s (IPCC) Special Report on Emission Scenarios (SRES) so-called A2 emission scenario, which is essentially a “business as usual” scenario representing CO₂ equivalent levels of above 500 ppm by 2050. Other case studies have used outputs from GCMs which are driven by the various so-called RCPs, or Representative Concentration Pathways (thick lines in Figure A1.4). Again, the “business as usual” RCP8.5 has been used as all the latest carbon emissions point in that direction (see 2014 estimate on the RCP8.5 trajectory in Figure A1.4), certainly for the forthcoming few decades which are considered in this Handbook.

![Representative Concentration Pathways](image.png)

**Figure A1.4** Representative Concentration Pathways (Source: IPCC, 2014)

Future rainfall projections remain challenging,
- first, because rainfall is a derived rather than a direct output from GCMs and,
- secondly, because complex rainfall-generating processes such as cloud formation and land surface-atmosphere interactions are not yet fully understood and resolved in climate models.

Overall, projections for South Africa’s winter rainfall region in the southwest of the country suggest future rainfall decreases, while summer rainfall region projections deviate less from present rainfall, with possible increases in rainfall amounts. In summary, some key findings, elaborated upon in other sections, show the following:
- All regions are very likely to be warmer in the future.
- Patterns of projected decreases in winter rainfall in the southwest occur across many GCMs.
- Similarly, projected increases in summer rainfall in the east seem stable and physically consistent with the projected circulation changes; however, there remains uncertainty in the magnitude of responses and with some local scale deviations.
- There is uncertainty about the location of the boundary between regions that show less rainfall in the west and similar or more rainfall in the east.
- The roles of mountain ranges and topography are critically important, especially in enhancing the projected east coast increases in precipitation and ameliorating the projected rainfall reductions on the Cape Mountains in the southwest of the country.
Why a Focus in South Africa on the Agricultural Sector?

First, What Does Our National Climate Change Response Strategy State from an Overall Perspective?

South Africa’s official standpoint at this point in time (2016) on adapting to climate change is encapsulated in the National Climate Change Response Strategy (NCCRS) of 2011. Here is a broad view that this document takes on responses to climate change:

• Ecosystems provide important services to society, and agricultural ecosystems include the provision of food, wood, fibre and fuel, in all of which water is also utilised.

• The rate of change to the earth’s climate compromises the ability of service providing ecosystems, including agriculture, to function effectively, and the rate can exceed the capacity of ecosystems to adapt.

• South Africa’s agriculture is highly vulnerable and exposed to the impacts of climate change due, on the one hand, to our socio-economic context (e.g. the many land-dependent rural poor) and, on the other hand, to an already high risk natural environment (including high season to season climate variability, extreme weather events, times of severe water stress).

• Agriculture urgently has to strengthen its resilience to climate change impacts and has to develop and implement policies, measures, mechanisms and infrastructure that protects its various components (commercial, emerging, rainfed, irrigated, crops, livestock, plantation forestry etc.).

• This strengthening of resilience is to be done cognisant of
  - the Intergovernmental Panel on Climate Change’s (IPCC’s) conclusions on unequivocal global warming forced by anthropogenic (human) activities;
  - the threat that climate change becomes to undermining South Africa’s positive development goals;
  - our continued legally binding obligations to strengthening and ensuring full implementation of our international commitments to, for example, the United Nations Framework Convention on Climate Change (UNFCCC) and the (now superseded) Kyoto Protocol through, for example,
    ▫ Formulating, implementing, publishing and regularly updating policies, measures and programmes to mitigate our emissions of Greenhouse Gases (GHGs) and to adapt to the adverse effects of inevitable climate change;
    ▫ Monitoring and periodically reporting to the international community the country’s GHG inventory (which includes agriculture’s contribution);
    ▫ Managing, conserving and enhancing GHG sinks and reservoirs sustainably, including those from agricultural (terrestrial) ecosystems and forests;
    ▫ Developing a climate change response plan to address, inter alia, the agriculture sector, also in its integration with land protection / rehabilitation and water resources;
    ▫ Mainstreaming climate change considerations into social, economic and environmental policy;
    ▫ Further developing and supporting research and systematic observation, as well as research and technical capacities within South Africa and beyond its borders; and
    ▫ Developing and implementing education, training and public awareness programmes on climate change within the broader agriculture sector and highlighting its effects in order to promote and facilitate scientific, technical and managerial skills as well as providing public access to information, public awareness of and participation in addressing climate change.

Secondly, What are Our National Climate Change Response Strategy’s More Specific Mandates on South Africa’s Agriculture and Forestry?
In both the agriculture and commercial forestry sectors there exists synergy and overlap between adaptation and mitigation measures.

Climate-resilient sectoral plans such as the one on Agriculture, Forestry and Fisheries have the potential to directly address the plight of those most impacted by climate change, e.g. the rural poor.

Climate resilience needs to address issues of strategic national importance, e.g. to food security and its links to water, health (human, livestock and plant) and land reform.

Being the largest consumer of water in South Africa (mainly through irrigation), agriculture is vulnerable to changes in water availability as well as to increased water pollution and soil erosion, from a combination of projected spatial changes in rainfall patterns, increases in intense rainfall events and increased evapotranspiration.

Under-resourced, small scale and subsistence farmers are particularly vulnerable to the impacts of climate change.

Commercial agriculture is a significant contributor to GDP and to employment. With its full contribution, including multipliers, agriculture contributes up to 12% of South Africa’s GDP and 30% of its national employment. Crop failures through the vagaries of climate can thus have a significant impact on the nation’s economy.

The following should be considered, either directly or indirectly, in an agriculture adaptation plan in light of projected climate change:
- Climate-resilient agricultural responses depend on the recognition that agriculture provides not only food, but also other environmental and socio-economic benefits.
- Important as input-intensive commercial agriculture is, it can sometimes have negative environmental, social and economic externalities, and these may be exacerbated by climate change.
- The appropriate use of small-scale labour-intensive agriculture techniques and its various overall benefits (e.g. job creation, empowerment, food security, contribution to biodiversity) should also be considered from a climate change perspective.
- Modelling of climate change scenarios is vital to informing land use planning decisions in agriculture in as much as they determine the mix of livestock and crop cultivation, as well as the types of crops that are likely to be commercially viable under projected future climate scenarios.
- Impacts of alien invasive plant species, which reduce streamflow and may consequently compromise already scarce water resources as well as reducing biodiversity, need to be evaluated through a climate change lens.
- The overall role of carbon sequestration in agriculture needs to be reviewed. More specifically, the role of natural and plantation forests functioning as carbon sinks, thereby reducing the effects of enhanced GHG emissions in the atmosphere, need to be assessed.
- The potential for sustainable biofuel production under conditions of climate change, and its possible impacts on food security, needs to be evaluated.
- Issues surrounding grassland degradation through injudicious grazing and burning regimes, as well as the reversal of those negative effects through veld rehabilitation, need to be addressed from a climate change perspective.

The South African Farming Scene: The Complexity of Farming Types in South Africa

The RSA has a distinct dual agricultural economy, comprising of a well-developed commercial sector which produces ~ 95% of the marketed agricultural output, and a predominantly subsistence oriented sector residing mainly in what were, historically, the so-called “homelands”, although an emerging sector is now evolving out of the subsistence sector.

A Typology of Farming Systems

Many farming typologies have been developed to try and capture the complexities of the South African farming types. The one shown below in Figure A1.5, and also now published
in Ncube and Lagardien (2015) is used in this Handbook. It distinguishes, in the first instance, between freehold and communal farmers, and amongst the freehold between commercial (small vs. large family vs. company owned), emerging (owned vs. leased), subsistence and contract farmers while the communal farmers are sub-classified into subsistence, commercial and contract farmers, all of whom are associated with different farming activities.

![Figure A1.5](image-url) A typology of South African farming systems (Original conception: Jordaan, Ncube and Schulze, 2014; later published in Ncube and Lagardien, 2015)

Working definitions, taken from DAFF (2013), of some (but not all) of the farmer types listed in Figure A1.5 are as follows:

**Subsistence Farmers**
Subsistence farming is self-sufficiency household farming wherein farmers produce mainly for household consumption and production is based on the family requirements rather than markets. Production is further reduced by limited technology and access to resources. Subsistence farmers are resource poor farmers producing mainly for household consumption and according to their family food requirements rather than markets.

**Smallholder Farmers**
Smallholder farmers produce for household consumption and markets, subsequently earning ongoing revenue from their farming businesses, which form a source of income for the family. Farming is not always the main source of income, however, and diverse non-farm sources of income exist to sustain the family. They have the potential to expand their farming operations and to become commercial farmers, but need access to comprehensive support (technical, financial and managerial instruments).
Emerging Farmers
Emerging farmers are part of the smallholder farmers. The term “emerging” farmer is used with different connotations depending on the institution being consulted. Farmers (and some institutions) do not like the term, and farmers often see themselves as being “in transition” towards becoming commercial farmers.

Semi-Commercial Farmers
Semi-commercial farmers produce on medium sized holdings and grow at least one commercial product that may be sold at the farm gate or to the distributors.

Commercial Farmers
Commercial farming is defined as the established farming venture undertaken by an individual or business entity for the purpose of the production and sale of agricultural products to make a profit. A dilemma is emerging in that fewer and fewer commercial farmers (~61 000 in 1996; ~ 46 000 in 2002; ~ 40 000 in 2007) have to feed a steadily increasing and rapidly urbanising South African population, with the decline in commercial farming units having been most acute in Limpopo (Figure A1.6).

What Needs to be Considered in a Handbook on Adaptation to Climate Change in the Agriculture Sector of South Africa?

The vulnerability of South Africa’s agriculture sector to climate, and the potential impacts of climate change on components of the sector, form the backdrop in this Handbook on assessing what to adapt to, and how to adapt. Therefore, one needs to consider responses to the

- **magnitudes of change**, i.e. how much the change is projected to be and how much impact that can have, where the magnitude of an impact is determined by
  - its scale, e.g. the area affected or the number of people / animals affected and
  - its intensity, i.e. the degree of damage caused, with the most widely used quantitative measures for climate impacts being
  - monetary units such as welfare, income or revenue losses,
  - costs of anticipating and adapting to certain biophysical impacts,
  - estimates of peoples’ willingness to pay to avoid (or accept as compensation for) certain climate impacts, or the
  - number of people affected by certain impacts such as food and water shortages, morbidity and mortality from diseases, and forced migration;
• **direction**, i.e. is it a positive or negative change, and what that implies;

• **timing**, i.e.
  - when, in the course of a year, the change is projected to occur and how that affects management decisions, or
  - whether a harmful impact is more likely to happen sooner rather than in the more distant future;

• **rate**, i.e.
  - how rapidly change is projected to occur in years or decades ahead, and
  - how that affects priorities of action,
  - with adverse impacts which occur suddenly (and/or surprisingly) being perceived as more significant than the same impacts occurring gradually, because the potential for adaptation for both human and natural systems would be much more limited in the former case, and
  - with very rapid change in a non-linearly responding system (such as the availability of water for agriculture) possibly exacerbating other vulnerabilities (e.g. impacts on agriculture and nutrition which aggravate human vulnerability to disease), particularly where such rapid change curtails the ability of systems to prevent and prepare for particular kinds of impacts;

• **location**, i.e. where will it occur first or most severely by considering, *inter alia*, income, gender and age in addition to regional, national and sectoral groupings;

• **persistence and reversibility**, i.e. where impacts could become important due to persistence of, say, the emergence of near-permanent drought conditions or intensified cycles of extreme heat waves or flooding that were previously regarded as “one-off” events;

and, as has been shown in various more technical reports (for example, Schulze, 2012), the

• **levels of confidence / uncertainty** of projected impacts in regard to likelihood of impacts and confidence, where
  - likelihood is the probability of an outcome occurring and
  - confidence is either the subjective or a statistically more objective, assessment that any statement about an outcome may prove correct;

and in regard to this Handbook, the

• **potential for adaptation**, which differs between and within regions and sectors, and where the potential considers not only the technical feasibility of certain adaptations, but also the availability of required human resources, the costs and side-effects of adaptation, the knowledge about those adaptations, their timeliness, the (dis-)incentives for adaptation actors to actually implement them, and their compatibility with individual or cultural preferences; and the

• **importance of the system at risk**, in this instance agriculture in South Africa, in regard to the value attached to the system by different societies, be that value related to infrastructure, the uniqueness of a habitat or an ecosystem or agricultural commodity, or the livelihoods of many people depending crucially on the functioning of the system (IPCC, 2007; Schulze, 2012).

These are some of the challenges which this Handbook wishes to address.

**The Geographical Area Covered in this Handbook**

While the Handbook’s title refers to *South Africa*, the geographical entity covered in this Handbook comprises the Republic of South Africa with its nine provinces (viz. Limpopo, Mpumalanga, North West, Northern Cape, Gauteng, Free State, KwaZulu-Natal, Eastern Cape and Western Cape) plus the Kingdoms of Swaziland and Lesotho. Where a focus is specifically on the Republic of South Africa, the abbreviation RSA is used, with the term “South” used here in preference to “southern”, as the latter has a different political connotation (e.g. as in SADC, which includes over a dozen member states). The provinces
of the RSA plus the two other countries, as well as major roads and towns, are shown in Figure A1.7 while information on areas is given in Table A1.1.

![Figure A1.7 Provinces, countries, major roads and towns](image)

**Table A1.1** shows the Northern Cape to be the largest of the nine provinces at 363 389 km², while Gauteng is 19 times smaller at only 18 760 km². The total study area is 1 223 201 km², of which the RSA covers just over 96 %.

**Table A1.1**  Areal information (Sources: Statistics SA, 2013)

<table>
<thead>
<tr>
<th>Province / Country</th>
<th>Area (km²)</th>
<th>Area of Total (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Limpopo</td>
<td>119 606</td>
<td>9.4</td>
</tr>
<tr>
<td>Mpumalanga</td>
<td>81 816</td>
<td>6.4</td>
</tr>
<tr>
<td>North West</td>
<td>118 710</td>
<td>9.3</td>
</tr>
<tr>
<td>Northern Cape</td>
<td>363 389</td>
<td>28.6</td>
</tr>
<tr>
<td>Gauteng</td>
<td>18 760</td>
<td>1.5</td>
</tr>
<tr>
<td>Free State</td>
<td>129 437</td>
<td>10.2</td>
</tr>
<tr>
<td>KwaZulu-Natal</td>
<td>91 481</td>
<td>7.2</td>
</tr>
<tr>
<td>Eastern Cape</td>
<td>170 616</td>
<td>13.4</td>
</tr>
<tr>
<td>Western Cape</td>
<td>129 386</td>
<td>10.2</td>
</tr>
<tr>
<td>RSA (total)</td>
<td>1 223 201</td>
<td>96.3</td>
</tr>
<tr>
<td>Swaziland</td>
<td>17 404</td>
<td>1.4</td>
</tr>
<tr>
<td>Lesotho</td>
<td>29 558</td>
<td>2.3</td>
</tr>
<tr>
<td><strong>Totals</strong></td>
<td>1 270 163</td>
<td>100.0</td>
</tr>
</tbody>
</table>

**The Scope Covered in this Handbook**
In this Handbook the following Sections have been covered, each with a number of Chapters making up the Section, viz. 

- **Section A: Agriculture and Climate Change in South Africa: Setting the Scene**  
  (including Chapters on Vulnerability, Adaptation, Tools Used, Terminology)

- **Section B: Agriculture’s Natural Capital in South Africa: A Climate Change Perspective**  
  (including Chapters on Concepts, Terrain, Climates – Present & Future, Climate Zones, Soils, Water)

- **Section C: Crops in South Africa and Climate Change**  
  (including Chapters on Maize, Wheat, Sugarcane, Soybeans, Grain Sorghum, Taro, Bambara Groundnuts)

- **Section D: Natural Grasslands and Pastures in South Africa and Climate Change**  
  (including Chapters on Natural Grasslands, Pasture Grasses)

- **Section E: Horticultural Crops in South Africa and Climate Change**  
  (including Chapters on Potatoes, Viticulture, Bananas, Citrus Fruits)

- **Section F: Livestock in South Africa and Climate Change**  
  (including Chapters on Dairy Cattle, Pigs, Wildlife Ranching, Fodder Banking)

- **Section G: Tree Crop Systems in South Africa and Climate Change**  
  (including Chapters on Optimum & Sub-Optimum Growth Areas, What Can be Grown Successfully Where, Specific Species, Streamflow Reduction)

- **Section H: Irrigation in South Africa and Climate Change**  
  (including Chapters on Net Irrigation Requirements, Percolation Losses)

- **Section I: Hazards and Climate Change in South Africa**  
  (including Chapters on Fire, Pests)

- **Section J: Overarching Adaptation Perspectives in South Africa and Emerging Issues**  
  (including Chapters on Early Warning Systems, Indigenous Knowledge, Perceptions of Smallholder Farmers, Human Discomfort, Biofuels)

Past experience demonstrates that all these agricultural sectors have sensitivity to climate variations ranging from minor to substantial. Consequently, there are many management responses to climate variability and these provide the basis of many initial adaptation strategies. This aspect is covered in each of the chapters. Also included, as seen above, are cross-cutting issues such as those related to water resources, as well as overarching perspectives and what are seen as emerging challenges, as these are perceived to be highly sensitive to potential climate changes and they have significant implications for components of the agricultural sector.

**In Conclusion: What to Expect and Not to Expect from the Handbook**

This Handbook, written specifically for farmers, officials and other stakeholders in the South African agriculture sector, should be used with the following in mind:

- It is a Handbook and not a scientific document in the purist sense of the word, thus written without equations and without major sections on methodology, and with only key references given for further reading by interested parties.

- The Handbook is nevertheless informed by sound science and it was inevitable that some Chapters appear to be more scientific than others.

- It should ideally be viewed as a “living and dynamic document” with the impacts maps to be replaced by updated ones as and when new information on climate projections comes to light.

- Individual Chapters, although being parts of broader Sections, are written as entities in themselves, although users can refer to prior Chapters on tools and methods.

- The Handbook’s existing chapter content should be updated as and when feedback on adaptation options / strategies is obtained from the wider South African agricultural fraternity (farmers, farmer unions, government, specialised sectors).
• It is in many ways thus a “work in progress” with numerous field and horticultural crops, as well as other broader facets of climate change in the agricultural sector, still to be covered.
• Any feedback to improve subsequent versions of this Handbook are welcome!

Further Reading

DAFF, 2013. Definitions of Farming Categories. Department of Agriculture, Forestry and Fisheries, Pretoria, RSA.
Background

What is Biofuel?
- Sugar-to-Bioethanol Production
- Starch-to-Bioethanol Production
- Vegetable Oil-to-Biodiesel Production
- By-Products of Biofuel Production

In Summary

Biofuel Feedstocks of Importance Globally

Biofuel Feedstocks of Importance in South Africa

Table J5.1 List of facilities which have applied to the Department of Energy for a licence to produce biofuels (DoE, 2014)

Biofuels Regulatory Framework

Acknowledging Impacts of Climate Change on Feedstock Cultivation and Aims of this Chapter

Method Used to Estimate Crop Yield
- The AQUACROP Model
- Model Calibration
- Attainable Yield
- National Level Simulations

Method Used to Estimate Crop Water Use

Method Used to Estimate Crop Water Use Efficiency

Method Used to Estimate Crop Season Length

Climate Change and Potential Biodiesel Production: The Case of Soybeans

Soybean Yields under Historical Climatic Conditions

From Present to the Intermediate Future: Absolute Changes in Soybean Yields

Figure J5.1 Mean seasonal yield (dry t/ha) for soybean planted in November and estimated using historical climate data (left), and absolute differences (dry t/ha; average of GCM ensemble) between soybean yields simulated for the present and intermediate future climates (right), derived with the AQUACROP model using climate inputs from multiple GCMs

Water Use Efficiencies of Soybean under Historical Climatic Conditions

From Present to the Intermediate Future: Absolute Changes in the WUE of Soybeans

Figure J5.2 Mean seasonal water use efficiency (WUE, kg dry matter/m³ water) for soybeans planted in November and estimated using historical climate data (left) and absolute differences (kg dry matter/m³ water; average of GCM ensemble) between soybean WUEs simulated for the present and intermediate future climates (right), derived with the AQUACROP model using climate inputs from multiple GCMs
Soybean Season Lengths under Historical Climatic Conditions

From Present to Intermediate Future: Absolute Changes in Soybean Season Lengths

Figure J5.3 Average length of the growing season (days; from planting to maturity date) for soybean planted in November and estimated using historical temperature data (left) and reduction (days) in soybean growing season length (right), calculated from present and intermediate future climate scenarios (right) and derived with the AQUACROP model using climate inputs from multiple GCMs.

Climate Change and Potential Bioethanol Production: The Case of Grain Sorghum

Grain Sorghum Yields under Historical Climatic Conditions

From Present to Intermediate Future: Absolute Changes in Yields of Grain Sorghum

Figure J5.4 Mean seasonal yield (dry t/ha) for grain sorghum planted in November and estimated using historical climate data (left), and absolute differences (dry t/ha; average of GCM ensemble) between grain sorghum yields simulated for the present and intermediate future climates (right), derived with the AQUACROP model using climate inputs from multiple GCMs.

Water Use Efficiency of Grain Sorghum under Historical Climatic Conditions

Figure J5.5 Mean seasonal water use efficiency (WUE, kg dry matter/m$^3$ water) for grain sorghum planted in November and estimated using historical climate data (left) and absolute differences (kg dry matter/m$^3$ water; average of GCM ensemble) between grain sorghum WUE simulated for the present and intermediate future climates (right), derived with the AQUACROP model using climate inputs from multiple GCMs.

From Present to the Intermediate Future: Absolute Changes in the WUE of Grain Sorghum

Sorghum Season Length under Historical Climatic Conditions

From Present to Intermediate Future: Absolute Changes in the Length of the Grain Sorghum Growing Season

Figure J5.6 Average length of the growing season (days; from planting to maturity date) for grain sorghum planted in November and estimated using historical temperature data (left) and reduction (days) in grain sorghum growing season length (right), simulated with the AQUACROP model from present and intermediate future climate scenarios and using climate inputs from multiple GCMs.

Climate Change and Potential Bioethanol Production: The Case of Sugarcane

Sugarcane Yields under Historical Climatic Conditions

From Present to Intermediate Future: Absolute Changes in Sugarcane Yields

Figure J5.7 Mean annual yield (t/ha) for sugarcane planted in April and estimated using historical climate data (left), and absolute differences (dry t/ha; average of GCM ensemble) between sugarcane yields simulated for the present and intermediate future climates (right), derived with the AQUACROP model using climate inputs from multiple GCMs.

Water Use Efficiency of Sugarcane under Historical Climatic Conditions

From Present to the Intermediate Future: Absolute Changes in the WUE of Sugarcane

Figure J5.8 Mean annual water use efficiency (WUE, kg dry matter/m$^3$ water) for sugarcane planted in April and estimated using historical climate data (left) and absolute differences (kg dry matter/m$^3$ water) between sugarcane WUE simulated for the present and intermediate future climates (right), derived with the AQUACROP model using climate inputs from multiple GCMs.

Length of Sugarcane Harvest Cycle under Historical Climatic Conditions

Figure J5.9 Average length of the dryland harvest cycle (days; planting to maturity date) for sugarcane planted in April and estimated using historical temperature data (left) and reduction (days) in the sugarcane harvest cycle (right),
simulated for the present and intermediate future climate scenarios and using climate inputs from multiple GCMs

**From Present to Intermediate Future: Absolute Changes in the Length of the Sugarcane Harvest Cycle**

Conclusions on Findings from the Case Studies

Biofuel Production as a Climate Change Mitigation Opportunity

On Crop Production for Biofuels and Adaptation to Climate Change

Further Implications of Climate Change for the Biofuels Industry
- **Risks Associated with Increasing Yield Variability**
- **Location of Processing Plants**
- **New Crop Varieties**
- **Production from Designated Areas and Groups**
- **Cost-Benefit Analysis**
- **Eliminating Areas with Unviable Yields**
- **Selection of GCMs**

Further Reading

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**Please cite as follows:**


**Background**

Globally, there is increasing concern over converging problems such as rising energy demands, fluctuating fossil fuel costs, worsening soil degradation, growing water scarcity, declining water quality and continuing biodiversity loss. Biofuel production has emerged as a possible "panacea" for a range of global energy, environmental and rural development issues. Hence, global interest in biofuels has grown rapidly over the past decade.

In South Africa, the intention is to produce biofuel from crops (or feedstocks) containing
- sugar (e.g. from sugarcane),
- starch (e.g. from grain sorghum), or
- vegetable oil (e.g. from soybean).

The envisaged demand for biofuel feedstock is intended to bring, *inter alia*, fallow land in the former homeland areas back into agricultural production. This will help to alleviate poverty in rural communities that grow the required feedstock. However, the solution also requires additional infrastructure (in particular roads) to be built in rural areas in order to improve market access.

Since South Africa is a water scarce country, it is important to grow feedstocks that have minimal water use and high yield potential. It is also important to understand the impact of accelerating climate change and climate variability on crop yield and water use. It is inevitable that combined changes in atmospheric CO\(_2\) concentrations, air temperature and rainfall patterns will affect feedstock (and thus biofuel) production in the future. The aim of this Chapter in the Handbook is to provide an overview of the emerging biofuels industry in South Africa.

**What is Biofuel?**

Biofuel is liquid transport fuel at is produced from biomass. There are two main forms of biofuel, *viz*:
- bioethanol, which is processed mainly from crops containing sugar or starch and is blended with petrol at a depot or refinery, and
- biodiesel, which is manufactured from crops containing vegetable oil and is blended with diesel.

Sugar, starch and vegetable oil are converted into biofuels using what is known as first generation biofuel technology.

**Sugar-to-Bioethanol Production**

Sugar juice is extracted (or pressed) from the feedstock to create soluble sugar which is then converted to bioethanol through the process of fermentation. The fermentation reaction is caused by yeast, or bacteria, which feed on the sugars to produce bioethanol and carbon dioxide. Fermentation produces bioethanol broth, from which bioethanol is separated out (the bioethanol recovery step) from the other components. A final dehydration step removes any remaining water from the bioethanol.

**Starch-to-Bioethanol Production**

The starch (e.g. grain sorghum) is first milled to improve the efficiency of the bioethanol production process. Dilute sulphuric acid is then mixed with the milled feedstock to initiate a chemical reaction called hydrolysis. During this process, the complex sugars are converted into soluble sugars. Enzymes are added to start the ferment process. The production of
bioethanol then follows the same process as described above (cf. sugar-to-bioethanol production).

**Vegetable Oil-to-Biodiesel Production**
Vegetable oil is removed from oilseed by crushing or chemical extraction. Biodiesel is made by the trans-esterification of vegetable oil with an alcohol catalyst, such as methanol. Glycerine is formed which must be separated (i.e. washed) from the biodiesel.

**By-Products of Biofuel Production**
A by-product of the sugarcane-to-bioethanol process is bagasse, which is burnt to generate heat energy and electricity which is then used by the processing plant (co-generation). In contrast, the starch-to-bioethanol process requires the input of fossil-based fuel, typically coal to fire the boilers.

The conversion of maize (and grain sorghum) into bioethanol produces a by-product called distiller’s dried grains and solubles (DDGS). It is pressed into pellets and used to make animal feed, which is then sold back to the agriculture sector. The processing of sugarbeet and sweet sorghum into bioethanol also produces animal feed, but to a lesser extent.

When soybean is converted to biodiesel, protein-rich oilcake is produced which is used in animal feeds. Glycerine is another by-product which has many uses in the food and beverage industry, as well as in pharmaceutical and personal care products.

A biodiesel processing facility is cheaper to construct than a bioethanol plant. In addition, it is cheaper and more efficient to convert sugar crops into bioethanol than compared to starch crops, owing to the added cost of the hydrolysis (i.e. starch to sugar) process.

**In Summary**
Although biofuel is seen as a sustainable source, or renewable fuel, it cannot completely substitute fossil-based fuels. This is due mainly to the significant cropping area and water required to produce sufficient biofuel feedstocks in order to meet the demand for liquid transport fuel. However, biofuels can contribute in reducing the overall consumption of, and dependency on, fossil fuels.

**Biofuel Feedstocks of Importance Globally**
Currently, sugar extracted from sugarcane underpins bioethanol production in Brazil, which is the world’s largest producer of both sugar and of bioethanol. Starch from maize is the foundation of a significant proportion of US biofuel targets. Similarly, maize currently is the main crop for fuel bioethanol production in China. Soybean is the dominant feedstock in both the USA and South America, whilst canola (rapeseed) underpins the European market. On the other hand, palm oil is the preferred feedstock in Indonesia and Malaysia.

**Biofuel Feedstocks of Importance in South Africa**
A list of companies which have applied to the Department of Energy for licenses to produce biofuel in South Africa is given in Table J5.2. The table highlights eight biofuel manufacturers who are planning to produce more than 1 300 million litre of biofuel per annum. The preferred bioethanol feedstocks include grain sorghum, sugarbeet and sugarcane. Similarly, the preferred biodiesel feedstocks include canola and soybean.

The construction of the above-mentioned processing plants has been deferred due to the government’s delay in finalising the regulated pricing and financial support mechanisms for licensed biofuel producers. At present (2016) there are no plans to build a biofuel processing plant in Mpumalanga, which is a concern for the local government there.
Table J5.2  List of facilities which have applied to the Department of Energy for a licence to produce biofuels (DoE, 2014)

<table>
<thead>
<tr>
<th>Company</th>
<th>Biofuel</th>
<th>Feedstock</th>
<th>Capacity (Ml/yr)</th>
<th>Location</th>
<th>Province</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mabele Fuels</td>
<td>Bioethanol</td>
<td>Sorghum</td>
<td>150</td>
<td>Bothaville</td>
<td>Free State</td>
</tr>
<tr>
<td>Arengo 316</td>
<td>Bioethanol</td>
<td>Sorghum</td>
<td>90</td>
<td>Cradock</td>
<td>Eastern Cape</td>
</tr>
<tr>
<td>Arengo 316</td>
<td>Bioethanol</td>
<td>Sugarbeet</td>
<td>90</td>
<td>Cradock</td>
<td>Eastern Cape</td>
</tr>
<tr>
<td>Ubuhle RE</td>
<td>Bioethanol</td>
<td>Sugarcane</td>
<td>50</td>
<td>Jozini</td>
<td>KwaZulu-Natal</td>
</tr>
<tr>
<td>E10 Petroleum</td>
<td>Bioethanol</td>
<td>Sugarcane</td>
<td>4</td>
<td>Germiston</td>
<td>Gauteng</td>
</tr>
<tr>
<td>PhytoEnergy</td>
<td>Biodiesel</td>
<td>Canola</td>
<td>455</td>
<td>Port Elizabeth</td>
<td>Gauteng</td>
</tr>
<tr>
<td>Rainbow Nation</td>
<td>Biodiesel</td>
<td>Soybean</td>
<td>288</td>
<td>Port Elizabeth</td>
<td>Eastern Cape</td>
</tr>
<tr>
<td>Basfour 3528</td>
<td>Biodiesel</td>
<td>Soybean</td>
<td>170</td>
<td>Berlin</td>
<td>Eastern Cape</td>
</tr>
<tr>
<td>Exol Oils</td>
<td>Biodiesel</td>
<td>Waste oil</td>
<td>12</td>
<td>Krugersdorp</td>
<td>Gauteng</td>
</tr>
</tbody>
</table>

Biofuels Regulatory Framework

It is the responsibility of the Department of Energy (DoE) to determine the price of biofuels that offer “reasonable” returns for manufacturers. The petroleum industry will pay this price for bioethanol and biodiesel purchased from the licensed producers. In January 2014, DoE released its draft position paper on the biofuels regulatory framework (DoE, 2014).

The pricing framework is based on grain sorghum as the reference feedstock to represent the production of bioethanol from starch. Similarly, soybean was selected as the reference for determining the costs associated with biodiesel production from vegetable oil. The sugar industry argued that the costs of bioethanol production from sugar-based feedstocks is cheaper than starch-based crops (e.g. grain sorghum) crops. Hence, the regulatory framework should include sugarcane to represent these feedstocks.

Acknowledging Impacts of Climate Change on Feedstock Cultivation and Aims of this Chapter

South Africa’s 20-Year Liquid Fuels Infrastructure Road Map acknowledges the potential impacts that climate change may have on crop production and used biofuel production as the example. The report also highlighted the need to monitor the changing climate in order to devise appropriate mitigation strategies. The role of computer simulation modelling to assess the likely impacts of climate change was also emphasised.

The aim of this Chapter is to determine the optimum growing areas, yields and water use efficiencies (WUEs) of soybean, grain sorghum and sugarcane in South Africa under historical climate conditions, and how these growing areas may shift geographically and the yields and WUEs may change under projected climate changed conditions. Note that for the three crops more detail on the crops per se, their production in South Africa and adaptation to climate change is given in three individual Chapters in Section C on “Crops and Climate Change” since these biofuel feedstocks are also important food crops.

The methods used to derive crop yield, water use and season length are discussed next.

Method Used to Estimate Crop Yield

The AQUACROP model was used to estimate the attainable yield of the three selected strategic biofuel feedstocks, viz. soybean, grain sorghum and sugarcane, also in relation to their seasonal water use.
**The AQUACROP Model**

*AQUACROP* was developed by the Food and Agricultural Organisation (FAO) and designed to simulate yield response of a range of crops to water availability (Steduto *et al.*, 2009; 2012). The model is particularly suited to conditions where water is a key limiting factor in crop production.

*AQUACROP* is a water productivity model that simulates biomass production based on the amount of water transpired by the green canopy cover. Canopy cover development (biomass production) is based on thermal time. Temperature governs thermal time as well as pollination success. In addition, low temperatures limit biomass production. Water stress affects the transpiration rate via the crop water productivity parameter, which is a measure of water use efficiency. However, like most crop models, *AQUACROP* does not account for the effects of pests and diseases on crop response. The model requires daily rainfall, minimum and maximum temperature as well as reference crop evaporation as climatic input data.

The model is, furthermore, well suited for the analysis of climate change impacts on crop productivity, water requirements and water consumption, for it allows for the assessment of crop responses under different climate change scenarios in terms of altered water and temperature regimes as well as elevated CO₂ concentrations in the atmosphere.

**Model Calibration**

The *AQUACROP* model (version 4.0) has already been parameterised for a number of crops, of which sugarcane, sugarbeet, grain sorghum, soybean and sunflower are considered suitable feedstocks for biofuel production. Where possible, the model was further calibrated for selected feedstocks to better represent local growing conditions in South Africa. This is discussed further in each individual Chapter in **Section C** for the specific crops.

**Attainable Yield**

Attainable yield refers to the utilisable portion of the biomass that contains sugar (i.e. stem or tuber), starch (i.e. grain) or vegetable oil (i.e. seed). The yield is expressed as mass of dry matter per unit area, i.e. dry kg per hectare or kg/ha.

**National Level Simulations**

The *AQUACROP* model was linked to the South African Quinary Catchments Database (Schulze *et al.*, 2010) that exists for South Africa, Lesotho and Swaziland. This historical climate database consists of 50 years (1950-1999) of daily climate data (rainfall, maximum and minimum temperature as well as reference crop evaporation) for each of the 5 838 Quinary Catchments covering the region. The climate database also contains 20 years of projected climate data for two periods, viz. the “present” (1971-1990) and an “intermediate future” (2046-2065). The climate projections were derived from four global climate models (GCMs), with climate outputs statistically downscaled to the 5 838 Quinaries. The climate scenarios were then used as input to *AQUACROP* to assess the likely impact of a changing climate on crop yield, water use efficiency and growing season length.

The Quinary Catchments Database also contains a soils database of soil water retention parameters and soil thicknesses for two horizons, and the area weighted values are deemed to be representative of each entire Quinary. However, *AQUACROP* also requires saturated hydraulic conductivity which was derived using a pedo-transfer function for each Quinary.

The model was run to determine the attainable yield, water use efficiency and growing season length for a single season. The process was then repeated to obtain simulated data for the following season. The crop yield, water use efficiency and length of growing season for each consecutive season was then analysed to calculate a range of statistics.
This procedure was then repeated for each of the 5,838 Quinary Catchments and again for each selected feedstock. Owing to the large number of model runs, the plug-in\(^1\) version of the AQUACROP model was used. The methodology was fully automated to reduce its computational complexity, thus minimising the time required to complete a national run (Kunz et al., 2015b; Kunz et al., 2015c).

**Method Used to Estimate Crop Water Use**

Crop water use is defined as total evaporation (often termed “actual evapotranspiration”) from the cropped surface, which is accumulated over the full productive cycle (i.e. crop growing season). Total evaporation is the sum of transpired water from the crop and the evaporation of soil water. Crop water use is expressed as a volume of water in m\(^3\). It is a standard output of the AQUACROP model.

**Method Used to Estimate Crop Water Use Efficiency**

As noted above, AQUACROP was used to provide estimates of attainable yield (\(Y\)) and crop water use (\(ET\)) for selected feedstocks. Water use efficiency (\(WUE\)) was then calculated at a national scale as follows:

\[ WUE = \frac{Y}{ET} \]

\(WUE\) is therefore expressed in kg/m\(^3\). This metric is useful for assessing which feedstock uses water more efficiently (i.e. gives “more crop per drop”). \(WUE\) is also a standard output of the AQUACROP model.

**Method Used to Estimate Crop Season Length**

The length of the growing season is defined as the number of days between the planting date and the crop maturity date. A set planting date was selected for each feedstock and used for all areas (i.e. same planting date across all Quinaries).

The expected harvest date is determined in AQUACROP by calculating growing degree days (GDDs) for each day after planting. When sufficient GDDs have been accumulated for the crop to mature, the expected harvest date is determined. The length of the crop cycle in GDDs is a parameter required by the model and is specific for each crop. Hence, the growing season length was determined using thermal time (not calendar time) and varies in length depending on the temperature of each Quinary.

**Climate Change and Potential Biodiesel Production: The Case of Soybeans**

There are plans in South Africa to produce 458 million litres of biodiesel from soybean. This will require the production of ~2.476 million tons of crop from a total planted area of approximately 1.456 million ha (Kunz et al., 2015c). The by-product of biodiesel production from soybean is an oil-rich feedcake, which will reduce the country’s need to import this product to satisfy local demand.

**Soybean Yields under Historical Climatic Conditions**

The mean seasonal yield of soybean was calculated from 49 seasonal estimates derived for rainfed growing conditions, as shown in **Error! Reference source not found.**. The map shows that the highest yields are attainable along the eastern (and southern) seaboard due to the distribution of summer rainfall. However, large parts of the country’s interior region, especially towards the western areas, are considered too dry for rainfed feedstock cultivation. **Error! Reference source not found.** (left) shows the high yielding areas to be in Mpumalanga and KwaZulu-Natal. It is interesting to note that the Eastern Cape shows greater potential to produce soybean than the Free State.

\(^1\) [http://www.fao.org/nr/water/docs/AquaCropPlugInV40.doc](http://www.fao.org/nr/water/docs/AquaCropPlugInV40.doc)
From Present to the Intermediate Future: Absolute Changes in Soybean Yields

The simulated changes in seasonal soybean yield from the present to the intermediate future which is projected to result from climate change is expressed in absolute terms (i.e. t/ha) in Error! Reference source not found. (right). The map shows that, on average, yields are expected to increase by 1-2 t/ha in KwaZulu-Natal and in the Eastern Cape. However, the central region of Mpumalanga and especially the inland areas of the Eastern Cape (south of the Lesotho border), which currently experience relatively low temperatures, may experience much larger yield increases in future, as depicted on the map.

Figure J5.1 Mean seasonal yield (dry t/ha) for soybean planted in November and estimated using historical climate data (left), and absolute differences (dry t/ha; average of GCM ensemble) between soybean yields simulated for the present and intermediate future climates (right), derived with the AQUACROP model using climate inputs from multiple GCMs

Water Use Efficiencies of Soybean under Historical Climatic Conditions

Mean seasonal WUEs for soybean are presented in Error! Reference source not found. for historical (i.e. baseline) climatic conditions (left map). The map shows that soybean is most water use efficient (i.e. producing most “crop per drop”) when cultivated along the southern coastal areas of KwaZulu-Natal as well as along the coastal areas of the Eastern Cape. In addition, the crop also exhibits efficient water use in the central parts of the Limpopo and Mpumalanga provinces. Such areas also exhibit the lowest variation in inter-seasonal yield (map not shown here, but in Section C).

The map also highlights the large parts of the interior and western regions of South Africa that are not suited to soybean production. Such areas are either too cold and / or too dry for viable crop production. The variability in WUE (and yield) in these regions is high. As a general rule of thumb, WUE is maximised in areas where the crop yield is highest and the inter-seasonal variability in yield is lowest.

From Present to the Intermediate Future: Absolute Changes in the WUE of Soybeans

The simulated increases in soybean WUEs which may result from climate change are expressed in absolute terms (i.e. kg dry matter/m³ water) in Error! Reference source not found. (right). The WUE of soybean is relatively low (≤ 1.5 dry kg/m³) for the historical climate, with a small increase (i.e. 0.2-0.3 kg/m³) expected over the majority of KwaZulu-Natal, as a result of climate change, but with WUEs increasing by 0.3-0.5 kg/m³ in the northeastern parts of the Eastern Cape, and parts of Lesotho, the eastern Free State and Mpumalanga.
Figure J5.2  Mean seasonal water use efficiency (WUE, kg dry matter/m³ water) for soybeans planted in November and estimated using historical climate data (left) and absolute differences (kg dry matter/m³ water; average of GCM ensemble) between soybean WUEs simulated for the present and intermediate future climates (right), derived with the AQUACROP model using climate inputs from multiple GCMs.

Soybean Season Lengths under Historical Climatic Conditions

Figure J5.3 (left) shows that the average length of soybean’s growing season ranges from 125 to 150 days (i.e. 4-5 months) in the hotter parts of the country. However, soybean produced in these areas (e.g. northern coastal area of KwaZulu-Natal) is likely to be affected by soybean rust (a fungal infection), especially during hot and humid growing conditions (Caldwell et al., 2002). As temperatures decreases, the growing season length extends up to 6 months (< 180 days). For the colder interior regions of the country, the crop cycle length may be 7 months or longer.

From Present to Intermediate Future: Absolute Changes in Soybean Season Lengths
The simulated reduction in soybean’s growing season (in days), which may result from climate change, is given in Figure J5.3 (right). For Mpumalanga, where the majority of soybean is currently produced, farmers may expect the growing season to shorten by up to 90 days (i.e. 3 months) into the intermediate future. The reduction in growing season length may even be larger for certain parts of the Free State. In KwaZulu-Natal, a 30-day reduction in crop cycle length may be expected.

Climate Change and Potential Bioethanol Production: The Case of Grain Sorghum

From the 1997/98 season grain sorghum production has been declining steadily in South Africa. Hence, the grain sorghum industry requires an alternative market for their product, which the emerging biofuels market should provide. There are plans to produce 240 million litres of bioethanol from grain sorghum. This will require the production of approximately 600 000 tons of crop from a total planted area of about 217 000 ha (Kunz et al., 2015c).

Grain Sorghum Yields under Historical Climatic Conditions
The mean seasonal yield of grain sorghum was calculated from 49 seasonal estimates derived for rainfed growing conditions, with results mapped in Figure J5.4 (left). The map shows that the highest yields are attainable along the eastern (and southern) seaboard due
to the distribution of summer rainfall. As noted for soybean, large parts of the country’s western region are considered too dry for rainfed feedstock cultivation.

Figure J5.3 Average length of the growing season (days; from planting to maturity date) for soybean planted in November and estimated using historical temperature data (left) and reduction (days) in soybean growing season length (right), calculated from present and intermediate future climate scenarios (right) and derived with the AQUACROP model using climate inputs from multiple GCMs.

From Present to Intermediate Future: Absolute Changes in Yields of Grain Sorghum
The simulated increases in seasonal grain sorghum yields, in t/ha, which may result from climate change, is shown in Figure J5.4 (right). The map shows that the interior of the country is projected to benefit, mainly from the warmer anticipated future climate. The central region of Mpumalanga and the inland areas of the Eastern Cape may experience yield increases of 5 t/ha or more.

Figure J5.4 Mean seasonal yield (dry t/ha) for grain sorghum planted in November and estimated using historical climate data (left), and absolute differences (dry t/ha; average of GCM ensemble) between grain sorghum yields simulated for the present and intermediate future climates (right), derived with the AQUACROP model using climate inputs from multiple GCMs.

Water Use Efficiency of Grain Sorghum under Historical Climatic Conditions
Mean seasonal WUE for grain sorghum is presented in Figure J5.5 (left) for historical (baseline) climatic conditions. Assuming that low WUE (i.e. 0.1-0.5 dry kg/m³) implies the
crop is unsuitable for production, it is evident that areas suitable for soybean cultivation can also grow grain sorghum. However, sorghum can produce “more crop per drop” than soybean. The map again shows that WUEs are highest when grain sorghum is cultivated along the coastal areas of KwaZulu-Natal and the Eastern Cape.

Figure J5.5  Mean seasonal water use efficiency (WUE, kg dry matter/m³ water) for grain sorghum planted in November and estimated using historical climate data (left) and absolute differences (kg dry matter/m³ water; average of GCM ensemble) between grain sorghum WUE simulated for the present and intermediate future climates (right), derived with the AQUACROP model using climate inputs from multiple GCMs

From Present to the Intermediate Future: Absolute Changes in the WUE of Grain Sorghum
The projected changes in WUE for grain sorghum that may result from climate change is illustrated in Figure J5.5 (right). The largest increases are projected for inland areas. In particular, the map highlights a region in the Eastern Cape (and south of Lesotho) where a substantial increase in WUEs is projected. This region is currently too cold for viable grain sorghum production and will benefit from the warmer conditions anticipated in the future.

Sorghum Season Length under Historical Climatic Conditions
The average length of grain sorghum’s growing season ranges from 100 to 180 days (i.e. 3-6 months), as indicated in Figure J5.6 (left). At higher altitudes (i.e. cooler mountainous areas), the growing season length extends beyond 7 months (> 210 days). However, some of these areas (e.g. in KwaZulu-Natal and Mpumalanga) may yield 12 t/ha or more of grain.

From Present to Intermediate Future: Absolute Changes in the Length of the Grain Sorghum Growing Season
The simulated reduction in grain sorghum’s growing season (in days) is given in Figure J5.6. On average, a 15- to 30-day reduction in crop cycle length may be expected. However, the season may shorten by more than 90 days (3 months) in some areas, which is significant.

Climate Change and Potential Bioethanol Production: The Case of Sugarcane
There are on-going investigations in South Africa into sugarcane varieties that are suitable for energy production, with plans also afoot to produce 54 million litres of bioethanol from sugarcane. This will require the production of approximately 675 000 tons of crop from a total planted area of about 11 000 ha (Kunz et al., 2015c).
Sugarcane Yields under Historical Climatic Conditions
As a point of departure, characteristics of dryland sugarcane production, simulated with the AQUACROP sugarcane model, are shown for historical climatic conditions (1950-1999) in Figure J5.7 (left), with areas shaded in red considered unsuitable for dryland cane production on climatic grounds (annual rainfall and winter temperatures too low). As expected from a tropical/sub-tropical crop, mean annualised yields are highest along the coast of KwaZulu-Natal and the Eastern Cape and the wetter/warmer parts of Swaziland and Mpumalanga, with yields dropping off drastically into the drier and cooler inland areas (Figure J5.7 left), to the extent that at under 25-30 t/ha/yr it is uneconomical to grow sugarcane, even for purposes of bioethanol production.

From Present to Intermediate Future: Absolute Changes in Sugarcane Yields
The main features when comparing dryland sugarcane yields derived from outputs of multiple GCMs as inputs to the AQUACROP cane model between the present (1971-1990) and intermediate future (2046-2065) periods (Figure J5.7 right) is an expansion into the interior of climatically suitable production areas and with that also an increase in yields inland, as shown in Chapter C4 on “Sugarcane and Climate Change”.

The projected changes in yields, illustrated in t/ha/yr in the right map of Figure J5.7, show the greatest increases to generally occur in the inland areas which often are now on the cool side, but with global warming will have higher yield responses.

Water Use Efficiency of Sugarcane under Historical Climatic Conditions
The WUE of sugarcane grown under historical climatic conditions exceeds 3 kg dry matter/m³/yr only along the coastal areas of the Eastern Cape and KwaZulu-Natal, with the WUE tapering off very rapidly inland to being ~ 1.5-2.0 kg/m³ in the Midlands of KwaZulu-Natal and the cane producing areas of Swaziland and Mpumalanga to < 0.5 kg/m³ in the interior of the country where yields would, in any event, be < 10 t/yr (Figure J5.8 left).

From Present to the Intermediate Future: Absolute Changes in the WUE of Sugarcane
Into the intermediate future where sugarcane would be grown either as a crop for sugar production or as a biofuel crop, there is a general increases in WUE of the order of 0.3-0.5
kg/m$^3$ (Figure J5.8 right), with some higher increases in the inland surrounding Lesotho, but where for other reasons cane would not be grown as a biofuel crop even in a warmer future.

**Figure J5.7** Mean annual yield (t/ha) for sugarcane planted in April and estimated using historical climate data (left), and absolute differences (dry t/ha; average of GCM ensemble) between sugarcane yields simulated for the present and intermediate future climates (right), derived with the AQUACROP model using climate inputs from multiple GCMs.

**Figure J5.8** Mean annual water use efficiency ($WUE$, kg dry matter/m$^3$ water) for sugarcane planted in April and estimated using historical climate data (left) and absolute differences (kg dry matter/m$^3$ water) between sugarcane $WUE$ simulated for the present and intermediate future climates (right), derived with the AQUACROP model using climate inputs from multiple GCMs.

**Length of Sugarcane Harvest Cycle under Historical Climatic Conditions**

Given the warm/wet conditions near the coast, the length of the sugarcane harvest cycle is shortest along the north coast of KwaZulu-Natal and the warm inland areas at ~1 year, lengthening to around 2 years in cooler inland areas (Figure J5.9 left map).

**From Present to Intermediate Future: Absolute Changes in the Length of the Sugarcane Harvest Cycle**

A major feature of cane production into a warmer future is the reduction in the harvest-to-harvest cycle by 50 to 150 days (2-5 months) along the coast and up to 150-222 days, i.e. 5-7 months in inland areas (Figure J5.9 right map).
Figure J5.9  Average length of the dryland harvest cycle (days; planting to maturity date) for sugarcane planted in April and estimated using historical temperature data (left) and reduction (days) in the sugarcane harvest cycle (right), simulated for the present and intermediate future climate scenarios and using climate inputs from multiple GCMs

Conclusions on Findings from the Case Studies

The rainfed cultivation of biofuel feedstocks on currently under-utilised arable land is recommended to help ensure the sustainable production of biofuel in South Africa. The results for three selected feedstocks (soybean, grain sorghum and sugarcane) all showed positive climate change effects on crop production. Increases in crop yield and water use efficiency were simulated for the majority of South Africa, when model output for the present climate was compared to that derived using the future climate scenario. In addition, the length of the growing season is expected to shorten. The results from this study are similar to those obtained by Vanuytrecht et al. (2014), where AQUACROP was used to evaluate the impact of climate change on maize yield and season length for two locations in Belgium.

The efficiency with which water is converted to yield has become a critical benchmark for crop production and resource use efficiency. This metric is useful in assessing which feedstock uses water more efficiently (i.e. gives “more crop per drop”). Areas exhibiting highest WUE may indicate where the feedstock is best suited for cultivation. Although a larger portion of South Africa’s land area is better suited to soybean (and grain sorghum) rather than sugarcane production, it is evident that sugarcane is more efficient in terms of crop yield per unit of water use. The south coast areas of KwaZulu-Natal exhibit the highest WUE for all three strategic feedstocks. Hence, land use planners should strive towards minimising the permanent loss of farmland in this region to urbanisation or urban expansion.

It is important to note that WUE maps can be misinterpreted. A relatively high WUE can be calculated for a crop in a particular area, but may result from very low crop evapotranspiration (and thus a low simulated yield). It is therefore recommended that WUE be interpreted in conjunction with yield. Furthermore, WUE metric is highly influenced by agronomic factors that affect crop growth (and thus yield).

Biofuel Production as a Climate Change Mitigation Opportunity
Biofuel production provides a climate change mitigation opportunity, since it may offer new business opportunities for growth in rural areas. However, the policy environment in South Africa must be supportive of smallholder production and marketing of agricultural products. Hence, biofuel-related policies will need to be designed carefully if they are to serve the rural poor and smallholder farmers (FAO, 2008).

**On Crop Production for Biofuels and Adaptation to Climate Change**

Rising air temperatures as well as increased variability in rainfall and higher frequency of extreme events are is likely to affect agriculture. According to the FAO (FAO, 2008), smallholder and subsistence farmers in Sub-Saharan Africa show extremely low resilience to climate change impacts. In general, their adaptive capacity is constrained by their low level of livelihood assets. Therefore, these farmers are most vulnerable to possible climate change and, in particular, to extreme events.

The development of crop varieties that take advantage of shorter growing seasons and possibly drier growing conditions should help farmers adapt to the changing climate. However, owing to the timeline required to develop and market new crop varieties (order of decades), immediate action is therefore required to accelerate the introduction of new and improved varieties.

A shift from conventional to conservation agriculture is a medium- to long-term adaptation strategy due to the "lag" time for tangible benefits to appear. Smallholder farmers often abandon conservation agriculture because the associated benefits are not immediate. Thus, farmer support programmes and agricultural extension services need to promote it amongst farmers. Farmers may also need financial support, or assistance in kind, in order to adopt conservation agriculture practices (FAO, 2008).

The FAO also recognises the benefits of rainwater harvesting as another adaptation strategy, as it increases resilience to (and reduces the risk of) higher rainfall variability in the future. Water harvesting is most needed in areas prone to dry spells, in order to supplement rainfall (FAO, 2008).

Not all mitigation and adaptation strategies may have the same relevance and potential for intervention in all settings. Agro-climatic conditions, prevailing livelihood and local socio-economic conditions will influence intervention programmes. For example, conservation agriculture practices are most relevant in the cooler, temperate area that produce maize or sugarbeet. The FAO (FAO, 2008) concluded that 58% of the rural population in Sub-Saharan Africa could benefit from some type of investment in water. Water will remain a major factor affecting the livelihoods of rural people in the region. Investments in water are therefore needed to build resilience and reduce vulnerability.

**Further Implications of Climate Change for the Biofuels Industry**

The emerging biofuels industry in South Africa is faced with multiple challenges, some of which may be exacerbated by a changing climate. Based on findings presented in this Chapter, farmers can expect the growing season to shorten and climatic conditions to become hotter in the future. Elsewhere in this Handbook, evidence suggests that the climate will become more variable, with extreme events occurring more frequently. Although crop yields are projected to increase, the variation in inter-seasonal crop yields will also change, with a possible increase in crop failures owing to extreme growing conditions.

**Risks Associated with Increasing Yield Variability**

The biofuel industry will need to ascertain the consequence of, and risks associated with, increasing crop yield variability. This is particularly important for sugar-based crops, which
Unlike starch-based crops, cannot be stored and processed into biofuel at a later stage. Hence, the profitability of a sugar-to-ethanol processing plant is highly dependent on the continuous supply of high quality (i.e. high sugar content) feedstock. Crop failures due to heat waves and/or drought conditions in the future, will have major financial implications for bioethanol plants reliant on sugar-based feedstock crops (e.g. sugarcane, sugarbeet or even sweet sorghum). More frequent flooding events, which prevent the transport of these feedstocks from the farm to the processing plant, will disrupt biofuel production, and will therefore also have an impact on profit margins. Lessons can be learnt from both the South African timber and sugar industries with regard to feedstock supply risk and appropriate contingency plans.

**Location of Processing Plants**

Another important point to note for ethanol production from sugar is the location of the processing plant, which must take cognisance of potential impacts of climate change on suitable areas for crop growth. As a result mainly of transport costs, sugar crops should be cultivated within an 80 km radius of the biofuel manufacturing facility. If the surrounding farmland is negatively impacted by the changing climate (i.e. increased frequency of crop failures due to extreme events), then the future viability of the processing plant could be jeopardised.

With regard to ethanol production from starch-based crops, it is imperative that the processing plant is situated in close vicinity to a major railway line. This will facilitate the rail transport of grains from storage silos located elsewhere in the country, since the cost of road transport is economically unviable. Furthermore, rail (not road) is preferred for transporting the end-product (i.e. biofuel) from the manufacturer to refineries and depots for blending with fuel produced from imported crude oil or syncrude (i.e. fuel from coal and natural gas). In the future, areas suitable for grain production are expected to shift towards the interior of the country. The potential impact of this important finding on the proposed location of grain sorghum-based processing plants (i.e. Bothaville in the Free State; Cradock in the Eastern Cape) needs careful assessment.

**New Crop Varieties**

As noted earlier, farmers will need to plant crop varieties that cope better with heat stress and shorter growing seasons. Owing to the timeline required to develop such varieties (order of decades), the industry needs to invest in breeding programmes timely. It is evident that the preferred feedstocks for biofuel production in South Africa are grain sorghum, soybean and canola. Hence, immediate action is required to accelerate the introduction of new and improved varieties.

**Production from Designated Areas and Groups**

The biofuels industry is encouraged to produce feedstock under rainfed conditions using currently under-utilised arable land. Pending biofuel policy makes reference to “designated areas”, which discourages the use of currently productive commercial farmland for biofuel feedstock cultivation. In addition, a biofuel manufacturer must source at least 10% of its required feedstock from smallholder or emerging farmers. It remains unclear how emerging farmers will participate in the biofuels supply chain. The government favours the use of cooperatives to help integrate small-scale farmers into the biofuel supply chain. However, a study in 2010 concluded that the current Cooperative Act of South Africa will need to be amended in order to attract investments from private companies.

Small-scale farmers in KwaZulu-Natal predominantly grow staple crops such as maize, dry beans and potatoes. Hence, these rural farmers have little to no experience growing biofuel feedstocks such as soybean, canola or grain sorghum. This places considerable burden on agricultural extension services to promote and facilitate the cultivation of biofuel feedstocks.
Climate change and its potential impact on cultivar choice and management practice needs to be well understood, in order for such extension services to be beneficial.

**Cost-Benefit Analysis**

A cost-benefit analysis is needed by the industry to ascertain the economic viability of producing feedstock on fragmented smallholdings, each typically less than 2 ha in size. Studies conducted to date in South Africa suggest that potential income derived from soybean cultivation by small-scale farmers is insufficient to incentivise a rural community to grow this feedstock. Owing to issues related to economies of scale, non-farming rural households must be allowed to transfer their land use rights to other households that want to grow biofuel feedstock. This is important since an increase in farming area is typically associated with improved profit margins.

Thresholds of minimum crop yields are needed to eliminate areas where low yields are not considered economically viable for biofuel production. For example, the cultivation of 0.5-1.0 t/ha of soybean may provide adequate food security for a rural household, but insufficient income to promote the sale of the crop to a biofuel manufacturer. In addition, the production of feedstock on land considered “marginal” means greater risk of climate change impacts and more land area required to produce a certain quantity of feedstock.

**Eliminating Areas with Unviable Yields**

It is important to note that the crop simulation model (*AQUACROP*) was run at a national scale for both the historical and projected future climates, in order to quantify the simulated changes in crop yields. If the threshold yields mentioned in the previous paragraph were known, then areas with economically unviable yields could be eliminated from the maps. This would help to identify regions considered suitable for crop growth, both current and in the future. Although Kunz *et al.* (2015c) produced land suitability maps for various biofuel feedstocks (including soybean, grain sorghum and sugarcane), they did not consider the impact of climate change.

**Selection of GCMs**

Finally, the GCMs used in this study were considered the best available at the time of analysis. The selection of other GCMs in the ensemble would likely produce different results spatially. However, it is expected that similar trend would be predicted, i.e. increasing crop yields and shorter growing seasons.

**Further Reading**


SECTION K  WHERE TO FROM HERE?

CHAPTER K1  IN THE FINAL ANALYSIS... WHERE TO FROM HERE?

R.E. Schulze

Where to From Here?

Economic Perspectives

Relevant Issues on the Way Forward

Other Key Questions

Continuing to Monitor, Analyse and Learn

Further Reading

Please cite as follows:
Schulze, R.E. 2016. In the Final Analysis... Where to From Here? In: Schulze, R.E. Handbook for Farmers, Officials and Other Stakeholders on Adaptation to Climate Change in the Agriculture Sector within South Africa. Section K: Where to From Here? Chapter K1.
Where to From Here?

An obvious question which arises at the conclusion to this Handbook is “Where to from here?” Listed below are some issues that require further attention:

• climate change impacts on South Africa’s agriculture sector must be viewed as part of a continuum of climate related impacts, which cross the spectrum from the
  - immediate future, with timeframes from the “now” state of climate from the near real time and to lead times of a few days only, and in which operational decisions of immediacy need to be made, to the
  - near future, in which tactical decisions for the next weeks and months up to a season ahead need to be made, to the more
  - long term future, which has been the focus of this Handbook and which requires strategic decisions to be made with timeframes of years to decades, and which include mainstreaming climate change more explicitly into legislation and policy, and through that also into practice; that
• outputs from more, and from the next generation of, appropriately downscaled and bias corrected GCMs based on a range of emissions scenarios, need to be evaluated and many sections of this Handbook need to be re-assessed with outputs from those GCMs so as to gain further confidence in results for South Africa; that
• in addition to assessing projected changes to crop yields or shifts in optimum growing areas solely from a perspective of climatic suitability, some real world constraints and factors be introduced, for example, in regard to
  - physical constraints, factors such as slope gradients, soil suitability, occurrence of wetlands, floodplain buffer zones and the like,
  - developmental constraints, considerations on existing urban areas, mines, roads, rail lines and their reserves, or proclaimed conservation areas (e.g. game reserves, heritage sites etc) which cannot be used for agricultural expansion,
  - economic constraints, such as crop prices, or the cost effectiveness of producing alternative crops etc, or
  - political constraints, such as potential impacts of land transformation on national and local food security under conditions of climate change.

Furthermore, other

• higher order consequences of ramifications and knock-on effects of climate change in the agricultural sector of South Africa need be addressed through sector and region targeted workshops with farmers and officials on both adaptive (autonomous) management options (i.e. learning by experiencing) and on planned adaptation strategies.

Economic Perspectives

From an economic perspective a number of issues raise their head as being important:

• It will be important to undertake impact and adaptation studies “beyond the farm gate” of crop yields into crop related value chain analyses of those components where climate and climate change are relevant.
• Additionally, large-scale and long time-horizon estimates of potential damages associated with climate change are useful in assessing the order of magnitude of what climate change could cost on a sectoral basis (e.g. the agriculture sector as a whole or specific crops / commodities) as well as on a geographical basis (e.g. the costs to individual farmers, to provinces within South Africa, or to the country as a whole, or to the SADCC region).
• When the certainty of impacts of projected climate change on South Africa’s agricultural sector becomes better understood as we head into the future, attention has to turn to a more detailed and holistic view of the economic consequences of climate change that focus even more on the benefits of adapting vs. the potential costs of not adapting, than has been the case in this Handbook.

Relevant Issues on the Way Forward

Howden et al. (2007) raise very relevant issues regarding the way forward, and some of those which are relevant to the South African situation are highlighted here:

• **Baseline Studies as a Point of Departure**
  Robust estimates of baseline impacts are necessary before reliable assessments of the costs and benefits of adaptations can be made.

• **Improved Understanding**
  There is substantial room for improving our understanding of how combinations of various factors such as CO\(_2\), temperature and rainfall, as well as pests and diseases affect various agricultural systems and how management responses will interact with these.

• **Adaptive Capacity**
  - Agriculture in South Africa remains sensitive to climate variability and the capacity to manage this risk is highly variable from location to location and from farming sector to farming sector within the country.
  - Given that climate change is highly likely going to be expressed, *inter alia*, through changes in variability into the future and to individual events (e.g. exceedance of critical thresholds), enhancing the capacity to manage climate risk is a core adaptation strategy.
  - The ability to map this adaptive capacity would provide critical information for policy and the agriculture sector to better target capacity-development programmes. However, this adaptive capacity mapping and analysis needs to be refined to being localised and tuned to the needs of specific agricultural commodities and issues such as needs of, for example, subsistence farmers vs. those of commercial farmers.
  - Developing adaptive capacity involves increasing the “climate knowledge” of farmers, commodity sectors and decision makers alike, so that they become more cognisant of climate impacts on their systems and of how to use management options to intervene, thereby reducing negative impacts and optimising opportunities that might arise.
  - It also means moving the focus from adaptation to climate change towards management of climate risk, i.e. integrating climate change into a broader research domain.

• **Effectiveness of Adaptation vs. Rates of Adaptation**
  The results of adaptation will be a function of both the likely technical *effectiveness* of adaptations and the *rates* at which they can be adopted. However, there is a paucity of studies in South Africa (or globally for that matter) that have assessed these two components in a thorough way, especially for higher levels of climate change and for more vulnerable systems.

• **Stakeholder Engagement**
  In particular there is a need to engage with stakeholders in a structured way to assess how fast adaptation options can be adopted. These could focus on the acceptability of adaptation options in terms of the factors important to the stakeholders and their perceptions of synergies and barriers. Particular interest to major commercial players within the South African agriculture sector may be on issues concerning:
  - the costs and benefits of adaptation when both market and non-market values are taken into account,
  - the feasibility and costs of simultaneously reducing greenhouse gas emissions and adapting to climate change,
- the effect of limitations in capital and other resources such as irrigation water, energy and fertilizer and pesticides (due to environmental concerns), and
- the adoption rates of adaptation in highly impacted areas if food prices were to decline as a result of positive climate change impacts, and / or land use intensification in temperate regions, or if demand for biofuels increases competition for land.

Other Key Questions

Some other key questions, which have important implications for both research and public policy in South Africa, have also been identified:

• One central question is on the mix between adaptation in agriculture that is specifically driven by policy decisions vs. adaptation that takes place autonomously in response to the conditions that farmers, and the sector as a whole, experience. In South African agriculture this mix will depend critically on how well information (for example, from this Handbook) can be assimilated by both farmer and policy maker, and acted upon, again by both farmer and policy maker. This implies making use of
  - workshops at provincial, farmer association and farming commodity (e.g. the dairy industry) levels, and
  - the literature read by the farmer on the ground, e.g. Farmers Weekly
  - and learning as much from those workshops as teaching / informing.

• A second, more conceptual, key question is whether climate change poses a discontinuous set of challenges which are different from those faced by, for example, poor livelihood farmers who are vulnerable to both environmental and economic stressors. This question is related to the broader one on how adaptation fits into the more overarching question of economic and social development. The question is essentially whether the move out of the poverty trap and into a position of more wealth is a more effective adaptation strategy than specific environmental and infrastructure investments and actions. In South Africa this move will depend on a number of factors, including farmers (especially subsistence farmers) being subject to cultural constraints, being hampered by poor service delivery by government and on the nature of the disruption of environmental services by climate change.

• A third question posed in the policy and economic literature is whether adaptation is merely a substitute for mitigation, or whether it complements mitigation by asking whether efforts to reduce the risks of climate change through adaptation reduce (or increase) the value of reducing greenhouse gases. In a lesser developed South African context the more appropriate question posed is rather, which is a higher priority for the use of the relatively scarce domestic resources available in our country to address the risks of climate change: mitigation or adaptation?

• The priority for South Africa’s agricultural sector at this point in time must surely be adaptation.

Continuing to Monitor, Analyse and Learn

In the final analysis, and reiterating partially what has already been mentioned indirectly above,

• when assessing the risks of climate change and developing effective response strategies, we have to take into account the many uncertainties in the underlying socio-economic, political and technological drivers of climate change, as well fundamental uncertainties in understanding the climate system.

• Given these uncertainties there is a need for directed focus in management, science and policy to continue to monitor, analyse and learn, so as to iteratively and effectively adjust one’s planning and decisions to the actual climate changes that are likely to be experienced by the various South African farming communities in the coming decades.

Further Reading
Appendix 1: Tools Used in this Handbook

R.E. Schulze

Spatial Databases 1: The Concept of Quinary Catchments

*Before Quinaries*

Figure A5.1 Primary and Quaternary catchments covering the RSA, Lesotho and Swaziland (After Midgley et al., 1994)

*The Development of Quinary Catchments*

Figure A5.2 Flowpaths between Quinary and Quaternary Catchments

Figure A5.3 Delineation of the RSA, Lesotho and Swaziland into 5 838 agriculturally and hydrologically relatively homogeneous Quinary Catchments (Schulze and Horan, 2010)

Further Reading

Spatial Databases 2: From Quinaries to a Quinary Catchments Database

*Daily Rainfall Input per Quinary Catchment under Baseline Historical Conditions*

*Daily Temperature Input per Quinary Catchment*

*Soils Information*

*Baseline Land Cover Information*

Further Reading

Climate Databases: Present and Future Climate Scenarios Based on Global Climate Models (GCMs)

*The ‘Generic’ Dilemma of Projecting Future Climates with GCMs*

*Uncertainties Inherent in GCMs*

*Addressing Shortcomings of GCMs for Applications in this Handbook*

Further Reading

Climate Change Scenarios Used in this Study

*Introduction*

*The GCMs Used*

Further Reading

Simulation Models: Crop Yield Models

*What are Crop Yield Models?*

*On Issues of Model Complexity in Crop Yield Models and the Approaches Adopted in this Study*

Table A5.1 Attributes of biomass/crop yield models of different complexity (After Schulze et al., 1995)

*The Smith Rule Based Suite of Models: Application of a Simple Crop Yield Model*

Box A5.1 Estimation of Dryland Winter Wheat Yield, Based on Smith’s Climatic Criteria

*The DSSAT Crop Systems Model: Application of a Complex Crop Yield Model*

*APSIM, the Agricultural Production Systems Simulator: Application of a Further Complex Crop Yield Model*

*The AQUACROP Model*

Further Reading

Simulation Models: The ACRU Agro-Hydrological Model

*Background 1: The Use of Models to Evaluate Agro-Hydrological Responses*

*Background 2: From Model Input to Model Output*

*Concepts of the ACRU Model*

Figure A5.4 ACRU: Concepts of the modelling system (Schulze, 1995)

Figure A5.5 ACRU: Model structure (Schulze, 1995)

Further Reading
In a Handbook on adaptation to climate change in the South African agriculture sector a number of “tools” are used in various assessments. These are outlined below.

**Spatial Databases 1: The Concept of Quinary Catchments** [Schulze and Horan, 2010]

**Before Quinaries**
Forerunners to the present Department of Water and Sanitation delineated the RSA, Swaziland and Lesotho into 22 Primary Catchments, which in turn were disaggregated into Secondary, then Tertiary and finally, into 1,946 interlinked Quaternary Catchments (QCs), as shown in Figure A5.1. This “fourth level” of discretisation has, to date, constituted the most detailed spatial level of operational catchment in the DWS for general planning purposes.

![Figure A5.1 Primary and Quaternary catchments covering the RSA, Lesotho and Swaziland (After Midgley et al., 1994)](image1)

**The Development of Quinary Catchments**
Schulze and Horan (2010) showed that many fourth level Quaternary Catchments in southern Africa are physiographically too diverse for agricultural and hydrological responses from them to be considered relatively homogeneous. By applying Jenks’ optimisation procedures available within the ArcGIS software suite, a three-fold altitude break based sub-delineation of QCs into fifth level Quinary Catchments (the Upper, Middle and Lower Quinaries of a QC) was then carried out. These Quinary Catchments were then configured within the QC configuration, such that the outflow of the Upper Quinary enters the Middle, which in turn flows into the Lower Quinary. However, the Lower Quinary outflow of a QC does not enter the Upper Quinary of the next downstream Quaternary Catchment, because that QC’s Upper Quinary may be at a higher altitude than the Lower Quinary of the immediate upstream Quaternary. Therefore, the outflow of the Lower Quinary has been configured to rather enter the downstream Quaternary at its exit (Schulze and Horan, 2010). A schematic of the flowpath configuration between Quinaries and Quaternaries is illustrated in Figure A5.2.

![Figure A5.2 Flowpaths between Quinary and Quaternary Catchments](image2)

The sub-delineation of Quaternary into Quinary Catchments resulted in 5,838 hydrologically interlinked and cascading Quinaries (Figure A5.3) covering the RSA, Lesotho and Swaziland. These have been demonstrated to be physiographically considerably more homogeneous than the
Quaternaries (Schulze and Horan, 2010) and on a national and smaller scale are considered to be relatively homogeneous hydrological as well as agricultural response zones.

Figure A5.3  Delineation of the RSA, Lesotho and Swaziland into 5 838 agriculturally and hydrologically relatively homogeneous Quinary Catchments (Schulze and Horan, 2010)

Further Reading

Spatial Databases 2: From Quinaries to a Quinary Catchments Database [Further Information: Schulze et al., 2010]

Following the delineation of the southern African countries of the RSA, Lesotho and Swaziland into Quinary Catchments, a Quinary Catchments Database, QnCDB, was established. A summary of the key climatic and catchment input into the QnCDB, and the link to the ACRU agro-hydrological model (see later in this Chapter) is described below.

Daily Rainfall Input per Quinary Catchment under Baseline Historical Conditions
Rainfall is generally considered to be the most important input into any agricultural or hydrological model. Methods for the estimation of daily rainfall values for simulations under baseline historical climatic conditions are described below.

A comprehensive database (1950-1999) of quality controlled (and infilled where necessary) rainfall data consisting of > 300 million rainfall values from 12 153 daily rainfall stations in southern Africa was compiled by Lynch (2004). From that database, a rainfall station had to be selected for each of the 5 838 Quinary Catchments, with that station’s data considered representative of the daily rainfall of that Quinary (see Schulze et al., 2010 for details). In total 1 240 high quality rainfall driver stations selected to generate the 50 years of daily rainfall for each of the 5 838 Quinary Catchments. The
selection of driver stations was followed by the determination of multiplicative month-by-month rainfall adjustment factors (from the one arc minute raster of median monthly rainfalls created by Lynch, 2004) for each Quinary Catchment and these were then applied to the driver station’s daily records in order to render the driver station’s daily rainfall to be more representative of that of the Quinary. This resulted in a unique 50 year daily rainfall record for each of the 5 838 Quinaries for application with the ACRU model (Schulze, 1995).

**Daily Temperature Input per Quinary Catchment**

Daily maximum and minimum temperature values facilitate estimations to be made, either implicitly or explicitly, of solar radiation, vapour pressure deficit and potential evaporation. Using these variables, in addition to rainfall, as input into agricultural and hydrological models, the generation of crop yields, soil moisture content, runoff and / or irrigation demand becomes possible. A summary of the methodology for estimations of daily maximum and minimum temperature values, as described in detail by Schulze et al. (2010) under baseline historical climatic conditions, is given below.

Procedures outlined in detail by Schulze and Maharaj (2004) enable the generation of a 50 year historical time series (1950-1999) of daily maximum and minimum temperatures at any unmeasured location in the RSA, Lesotho and Swaziland at a spatial resolution of one arc minute of latitude / longitude (~1.7 x 1.7 km) for the 429 700 grid points covering the region. At each of these 429 700 grid points the maximum and minimum temperatures were computed for each day of the 50 year data period from two selected, independent temperature stations and by use of regional and monthly lapse rates (Schulze and Maharaj, 2004). At each grid point the daily values derived from these two stations were then averaged in order to modulate any biases (from lapse rates or station data) emanating from either of the two stations’ generated records (Schulze et al., 2010). Excellent verifications of results from this methodology were achieved (Schulze and Maharaj, 2004).

From the study of Schulze and Maharaj (2004) representative grid points were determined for each of the 5 838 Quinary Catchments covering the study area, using techniques outlined in Schulze et al. (2010). The resulting 50 year series of daily maximum and minimum temperatures for each Quinary Catchment was then used to generate daily estimates of solar radiation and vapour pressure deficit, details of which are described in Schulze et al. (2010). From these, daily values of reference potential evaporation as well as potential crop evapotranspiration could be computed.

**Soils Information**

For multi-soil horizon water budgeting using the QnCBD the following soils variables were input to each Quinary:

- thickness (m) of the topsoil and the subsoil;
- soil water contents (m/m) at
  - saturation (porosity),
  - drained upper limit (also commonly referred to as field capacity), and
  - permanent wilting point (i.e. the lower limit of soil water availability to plants);
- rates of saturated drainage from topsoil horizon into the subsoil, and from the subsoil horizon into the intermediate groundwater zone, and the
- erodibility of the soil (Schulze et al., 2010).

Values of these variables, derived by Schulze and Horan (2008) using the AUTOSOILS decision support tool (Pike and Schulze, 1995 and updates) and applied to the soils database from the Institute for Soil, Climate and Water, were then determined for each Quinary using methods described in Schulze et al. (2010).

**Baseline Land Cover Information**

In order to assess impacts of climate change on hydrological responses, a baseline land cover is required as a reference against which to evaluate the impacts. For the RSA, Lesotho and Swaziland the 70 Veld Types delineated by Acocks (1988) are currently the recognised baseline (i.e. reference) land cover. Based on a set of working rules, month-by-month hydrological attributes, determined by Schulze (2004), were assigned to each of the 70 Acocks Veld Types and were incorporated into the Quinary Catchments Database. These attributes are the water use coefficient, interception loss per rainday, fraction of roots in the topsoil, root colonisation in the subsoil, a coefficient of infiltrability dependent on rainfall intensity estimates, and soil surface cover by litter, an index of suppression of soil water evaporation by a litter / mulch layer. For each of the 5 838 Quinaries in the database the
spatially most dominant Veld Type was then selected as the representative baseline land cover (Schulze et al., 2010).

Further Reading

Climate Databases: Present and Future Climate Scenarios Based on Global Climate Models (GCMs)

Weather and climate forecasts and projections of globally warmed climates into the longer term future are made with GCMs, i.e. Global Climate Models, sometimes also termed General Circulation Models.

The ‘Generic’ Dilemma of Projecting Future Climates with GCMs [Further Reading: Schulze et al., 2014]

Interactions between the many processes that govern the Earth’s climate are very complex and extensive, so that quantitative predictions of the impacts of increasing concentrations of greenhouse gases (GHGs) on climate cannot be made with any certainty through simple intuitive reasoning. The result is that the GCMs that have been developed, and which are mathematical representations of the Earth’s system in which physical and biogeochemical processes are described numerically to simulate the climate system as realistically as possible, are founded on assumptions of the evolution of drivers of climate change (e.g. the distributions of aerosols and GHGs), and their respective concentrations in the atmosphere all contain high levels of uncertainty. The GHG concentrations, for example, depend directly upon natural and human derived (anthropogenic) emissions, which can only be estimated through emission scenarios, developed using so-called “storylines” or “representative concentration pathways” which describe possible developments in global population growth and other aspects of the socio-economic system. These uncertain emission scenarios are then used to drive atmospheric chemistry and carbon cycle models that simulate changes in the concentration of GHGs and aerosols. The resulting concentration scenarios are then input into GCMs, which generate climate scenarios into the future that we, in turn, use to drive models of the impacts on human systems (e.g. of heat waves, or human discomfort) and on natural systems (e.g. yields of crops).

Uncertainties Inherent in GCMs [Further Reading: Schulze et al., 2014]
The uncertainties which are inherent in GCMs have been well documented, and these uncertainties result in certain limitations, with GCMs less capable of simulating second order atmospheric processes such as rainfall, compared to those related to first order atmospheric processes, such as
temperature. We have to appreciate these limitations of GCMs, and in regard to the agriculture sector they include:

- Failure to simulate individual convective (thunderstorm) rainfall events, owing to the coarse spatial resolutions of the GCMs, and the smaller spatial and temporal nature of convective rainfall, which poses problems over most of southern Africa summer rainfall region, where convective rainfall is a dominant form of rainfall and crucial to agricultural production;
- Difficulty in simulating the intensity, frequency and distribution of extreme rainfall events and hence the damage they could do to the farming sector, including flooding;
- Tending to simulate too many light rainfall events (< 2 mm/day) which affect plant diseases and do not enhance soil water content, and generally too few heavy rainfall events (> 10 mm/day) which produce soil moisture for the plant, whilst maintaining a fairly realistic longer term averages of rainfall; and
- Poorly representing major drivers of year-to-year climate variability, such as the El Niño phenomenon, which can severely impact on seasonal crop yields.

**Addressing Shortcomings of GCMs for Applications in this Handbook**

These factors tend to reduce the accuracy of rainfall output from GCMs. Therefore, there remain limits surrounding the usability of direct GCM output in detailed agricultural and hydrological studies, where precipitation, temperature and potential evaporation at the local scale are primary inputs into hydrological models.

To try and overcome these shortcomings, the ratio approach has often been adopted in this Handbook, by determining the *ratio of change* between (say) crop yields from future climate scenarios to present climate scenarios from GCMs on the assumption that some inherent errors in the GCMs will be at least partially self-cancelling.

Even so, outputs from GCMs remain the basis for climate change impact assessments. However, as has already been alluded to, a significant discontinuity exists between the output from GCMs (generated around a grid point every 100 km, i.e. with spatial resolutions generally around 10 000 km²) and the resolution at which local decisions are sought and local adaptation options need to be considered (generally every 3 to 10 km, i.e. with a spatial resolution of 10-100 km²). It is due to this discrepancy that GCM output needs to be translated from the coarse to more local scales by the process of regional climate downscaling which, in the case of GCMs used in this Handbook, includes correcting both temperature and rainfall values for local topographic influences, as described in detail in Schulze *et al.* (2014).

Additionally, since individual GCMs do not give identical values of temperature and rainfall, neither for their present climate scenarios nor for their projected future climates, outputs from a suite of GCMs are used. Averages of the GCM results are then mapped, assuming that an average is likely to give a fairer representation than any individual GCM. Using a suite of models also allows the differences among the GCMs to be quantified, thereby allowing an assessment of the confidence of outputs to be made.

**Further Reading**


**Climate Change Scenarios Used in this Study**

**Introduction**

Outputs from a range of sets of GCMs were used in various sections of this Handbook, and on many of the maps the multiple GCMs used are listed. All the GCMs used were accredited by the South African Long Term Adaptation Scenarios initiative of the Department of Environmental Affairs.

**The GCMs Used**

The first suite of climate change scenarios used were those downscaled / distributed by the

- Climate Systems Analysis Group (CSAG) of the University of Cape Town and derived from global scenarios produced by five IPCC AR4 approved GCMs, all statistically downscaled to over 2 000 climate stations in South Africa and then further bias corrected for the 5 838 Quinaries covering
South Africa by techniques described in Schulze et al. (2010), all for the A2 “business as usual”
future scenarios, and all of which were applied in the IPCC’s Fourth Assessment Report, viz.
- CGCM3.1(T47)
- CNRM-CM3
- ECHAM/MPI-OM
- GISS-ER and
- IPSL-CM4
in each case with daily values of rainfall, maximum and minimum temperatures provided (from
which were computed daily values of solar radiation, maximum and minimum relative humidity
and reference potential evaporation by methods given in Schulze, 2008) for three 20 year time
periods, viz. for
- the present (1971-1990)
- the intermediate future (2046-2065) and
- the more distant future (2081-2100).

A second suite of climate change scenarios came from the
• CSIR, from whom 6 dynamically downscaled GCMs were obtained (Engelbrecht, 2012; pers
com), each with daily values of rainfall and maximum / minimum temperatures from 1961-2100,
generated by IPCC AR4 coupled climate models for the A2 “business as usual” emissions
scenario, and bias corrected for local temperature and rainfall patterns by techniques described in
Schulze et al. (2014) viz.
- CCAM-CSIROmk3.5 Commonwealth Scientific & Industrial Research Organisation Mk3
- CCAM-GFDLcm2.0 Geophysical Fluid Dynamics Lab Coupled Model Version 2.0
- CCAM-GFDLcm2.1 Geophysical Fluid Dynamics Lab Coupled Model Version 2.1
- CCAM-MIROG Model for Interdisciplinary Research on Climate Medium Res
- CCAM-ECHAM5 Max Planck Institute for Meteorology Ocean Coupled Model Ver 5
- CCAM-UKHADcm3 UK Meteorological Office Coupled Model Version 3.

The third suite of climate change scenarios were again provided by the
• Climate Systems Analysis Group (CSAG) of the University of Cape Town, again for the three 20
year periods of the present, the intermediate future and the more distant future, but in this
instance for 10 GCMs in each case for both the B1 (more benign) as well as for the A2 (business
as usual) emissions scenarios and, in addition to daily rainfall and temperatures, also GCM
values of daily solar radiation, all downscaled for solar radiation and temperature (as well as
temperature derived variables) directly to the centroids of the 5 838 Quinaries covering South
Africa, but with rainfall only to the middle Quinary of Quaternary catchments, viz.
- CCMA_CGCM3_1
- CNRM_CM3
- CSIRO_MK_3_5
- GFDL_CM2_0
- GFDL_CM2_1
- GISS_MODEL_E_R
- IPSL_CM4
- MIUB_ECHO_G
- MPI_ECHAM5
- MRI_CGCM2_3_2

The fourth suite of climate scenarios used were from the
• World Climate Research Programme sponsored Coordinated Regional Climate Downscaling
Experiment CORDEX, in each case with daily rainfall and maximum / minimum temperature (with
derived daily values of solar radiation, relative humidity and potential evaporation as described in
various chapters in Schulze, 2008) for the 30 year periods 1976-2005 (with historical climate) and
for 2016-2045 (assuming the business as usual Representative Concentration Pathway 8.5),
downscaled to the 5 838 Quinaries and then bias corrected for local topography by methods
described in Schulze et al. (2014), viz.
- CCCma-CanESM2_historical_RCA5_1976
- CCCma-CanESM2_rcp85_RCA5_2016
- CNRM-CERFACS-CNRM-CM5_historical_RCA5_1976
- CNRM-CERFACS-CNRM-CM5_rcp85_RCA5_2016
- ICHEC-EC-EARTH_historical_RCA5_1976
- ICHEC-EC-EARTH_rcp85_RCA5_2016
Further Reading

Simulation Models: Crop Yield Models

What are Crop Yield Models?
In order to mimic potential impacts of climate change on crop yields, simulation models need to be employed. Crop simulation models are computer programs that describe plant-environment interactions in quantitative terms. Computer models in general are a mathematical representation of a real-world system. Thus, a crop simulation model attempts to simulate the way in which a crop responds to its environment. In reality, it is impossible to include all the interactions in the environment in a computer model. In most cases a computer model is a simplification of a real-world system and may include many assumptions.

In this Handbook both simple and more complex crop yield models were used.

On Issues of Model Complexity in Crop Yield Models and the Approaches Adopted in this Study
Different levels of complexity of crop yield models exist, ranging from relatively simple climate and soils threshold based unidirectional response models, to daily time step soil water budget and phenology driven yield functions of intermediate complexity, to the more complex daily time step physiology and genetics derived growth and yield models (Table A5.1).

Table A5.1 Attributes of biomass/crop yield models of different complexity (After Schulze et al., 1995)

<table>
<thead>
<tr>
<th>LEVELS OF COMPLEXITY OF CROP YIELD MODELS</th>
<th>SIMPLE</th>
<th>INTERMEDIATE</th>
<th>COMPLEX</th>
</tr>
</thead>
<tbody>
<tr>
<td>MODEL STRUCTURE</td>
<td>Experience and rate based climatic threshold yield functions</td>
<td>Phenology driven soil water deficit yield functions</td>
<td>Genetics, physiology, phenology and management based growth, development and yield functions</td>
</tr>
<tr>
<td>MODEL TIME STEP</td>
<td>Monthly / annual</td>
<td>Daily</td>
<td>Daily</td>
</tr>
<tr>
<td>CLIMATE VARIABLES</td>
<td>Rainfall</td>
<td>Rainfall</td>
<td>Rainfall</td>
</tr>
<tr>
<td></td>
<td>Temperature - maximum</td>
<td>Temperature - maximum</td>
<td>Temperature - maximum</td>
</tr>
<tr>
<td></td>
<td>- minimum</td>
<td>- minimum</td>
<td>- minimum</td>
</tr>
<tr>
<td></td>
<td>Heat units</td>
<td>Reference potential evaporation</td>
<td>Solar radiation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CO₂ transpiration feedback</td>
<td>Reference potential evaporation</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>CO₂ transpiration feedback</td>
</tr>
<tr>
<td>SOIL VARIABLES</td>
<td>Single horizon Thickness</td>
<td>1 - 2 horizons Horizon thicknesses Retention constants Drainage/ permeability</td>
<td>Multiple horizons Horizon thick- nesses Retention constants Drainage / permeability Soil physics Soil chemistry - pH, C, N Previous crop residue - O, C:N, root, depth</td>
</tr>
<tr>
<td></td>
<td>Texture class Normative weighting (Deep → shallow) (Clay → sand)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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In both past and current studies in South Africa on agricultural responses to climate change, and in this Handbook, all three levels of model have been, and are being, used, depending on
• the level at which modellers of respective crops have conceptualised climate change effects into their models, on
• data availability, and on
• the process uncertainties which still exist, especially in regard to the CO₂ “fertilization” feed-forward in photosynthesis and the transpiration feed-back resulting from an increase in stomatal control under enhanced CO₂ conditions.

The Smith Rule Based Suite of Models: Application of a Simple Crop Yield Model
Smith (2006 and previous versions) developed a suite of rule based models to estimate yields over South Africa for a range of crops according to
• climatic criteria, using climate variables with limits for each specific crop, optionally adjusted first for
• different levels of management and, secondly, for
• soils characteristics.

The climatic criteria in the Smith models consist of the product of
• the growing season accumulated rainfall,
• an effective rainfall fraction for the growing season, which depends on classes of rainfall amounts within crop specified limits, and
• a dry matter yield index for that crop, which is a function of classes of growing season heat units between crop related upper and lower limits.

The Smith models have in the past been used in sensitivity analyses of climate change. More recently the Smith suite of rule based models has been used with the South African Quinary Catchments Database for climate change impact studies (Schulze, 2010). By way of example, the algorithm developed of the Smith model for dryland winter wheat yield is given in Box A5.1.

Box A5.1 Estimation of Dryland Winter Wheat Yield, Based on Smith’s Climatic Criteria
Using Smith’s (2006) climatic criteria only, without cognisance of the soil properties or level of management, dryland winter wheat yield with a planting date in May was calculated as

\[ Y_{wd} = 0.0075 \times P_{ems} \times D_{wd} \]

where
\[ Y_{wd} \] = dryland winter wheat yield (t/ha/season)
\[ P_{ems} \] = effective rainfall for May to September
\[ D_{wd} \] = dryland wheat heat unit factor
\[ ASM \] = antecedent soil moisture

with
\[ P_{ms} \] = accumulated rainfall (mm) for May to September (inclusive) for \[ P_{ms} < 850 \text{ mm} \]
while
\[ H_{wi} \] = accumulated heat units (base 4.4 °C) in degree days for the period May to September.

Note that this model does not include a CO₂ fertilization effect.

The DSSAT Crop Systems Model: Application of a Complex Crop Yield Model
DSSAT was originally developed by an international network of scientists, cooperating in the International Benchmark Sites Network for Agrotechnology Transfer project. Updated releases of DSSAT followed (e.g. Hoogenboom et al., 1994; Jones et al., 1998), with Version 4.5 was released in 2011.
In this study the DSSAT v4.5 Crop Systems Model (CSM) was used. Potential dry matter production is calculated as a function of radiation, leaf area index and reduction factors for temperature and moisture stress. Phenological stages are simulated based on growing degree days, and leaf and stem growth are calculated depending on phenological stages. Available photosynthate is initially partitioned to leaves and stems, and later for ear and grain growth. Any remaining photosynthate is allocated to root growth. However, if photosynthate available for root growth is below a minimum threshold, then the grain, leaves and stem allocations are reduced and the minimum level of root growth occurs. Separate routines calculate the water balance, which includes runoff, infiltration, saturated and unsaturated water flow and drainage. Mineral nitrogen dynamics and nitrogen availability for crop uptake are also calculated. The model provides information on above-ground dry matter, on grain dry matter and nitrogen content, as well as providing summaries of the water balance and soil mineral nitrogen. In DSSAT v4.5, the atmospheric CO$_2$ concentration can be specified as a user defined static value or a measured value. The advantages of using the CSM to simulate the effects of climate change are as follows:

• The model structure allows for genetic, physiology, phenology and management based growth development and yield functions, where the growth degree day concept is able to capture the effect of temperature and increased plant growth due to CO$_2$ fertilization.
• The model uses a daily time step which allows for extremes, especially as a result of climate, to terminate growth.
• The climate variables are represented by daily rainfall, minimum and maximum temperature, solar radiation and these are used to calculate reference potential evaporation and the CO$_2$ transpiration feedback. These are the most important input variables that are expected to change under future climate.
• The soil variables such as multiple soil horizons, differences in horizon thicknesses, water holding capacity, drainage and permeability together with previous crop residue and rooting depth dictate, in conjunction with the rainfall from the climate variables, the plant variable water and the potential water stress under present and projected future climates.
• The management options such as planting date, cultivar attributes, planting density, row spacing, nitrogen fertilization and tillage options permit the manipulation of the timing of onset of certain reproductive phases in relation to climatic events. This can be an important factor when adaptation measures to mitigate the effect of climate change.

**APSIM, the Agricultural Production Systems Simulator: Application of a Further Complex Crop Yield Model**

The Agricultural Production Systems Simulator (APSIM) modelling framework was developed by the Agricultural Production Systems Research Unit in Australia (McCown et al., 1995) to simulate biophysical processes in agricultural systems, particularly as it relates to the economic and ecological outcomes of management practices in the face of climate risk. It is structured around plant, soil and management modules including a diverse range of crops, pastures and trees, soil processes including water balance, N and P transformations, soil pH, erosion and a full range of management controls. APSIM resulted from a need for tools that provided accurate predictions of crop production in relation to climate, genotype, soil and management factors while addressing long-term resource management issues. In the APSIM model high order processes such as crop production and the soil water balance are represented as modules which relate to each other only through a central control unit, which is referred to as the program engine. Thermal time is used in the model to drive phenological development and canopy expansion (Keating et al., 1999).

**The AQUACROP Model**

The AQUACROP model was used to estimate the attainable yield of selected biofuel feedstocks, in relation to their seasonal water use. Crop simulations were undertaken for three strategic biofuel feedstocks, viz. soybean, grain sorghum and sugarcane. AQUACROP was developed by the Food and Agricultural Organisation (FAO) and designed to simulate yield response of a range of crops to water availability. The model is particularly suited to conditions where water is a key limiting factor in crop production.

AQUACROP is a water productivity model that simulates biomass production based on the amount of water transpired by the green canopy cover. Canopy cover development (biomass production) is based on thermal time. Temperature governs thermal time as well as pollination success. In addition, low temperatures limit biomass production. Water stress affects the transpiration rate via the crop water productivity parameter, which is a measure of water use efficiency. However, like most crop
models, AQUACROP does not account for the effects of pests and diseases on crop response. The model requires daily rainfall, minimum and maximum temperature as well as reference crop evaporation as climatic input data.

The model is also well suited for the analysis of climate change impacts on crop productivity, water requirements and water consumption. The model allows for the assessment of crop responses under different climate change scenarios in terms of altered water and temperature regimes as well as elevated CO₂ concentration in the atmosphere.

In regard to model calibration, the AQUACROP model (version 4.0) has already been parameterised for a number of crops, of which sugarcane, sugarbeet, grain sorghum, soybean and sunflower are considered suitable feedstocks for biofuel production. Where possible, the model was further calibrated for selected feedstocks to better represent local growing conditions in South Africa. This is discussed further in each Chapter for a specific crop.

The model assesses attainable yield, which refers to the utilisable portion of the biomass that contains sugar (i.e. stem or tuber), starch (i.e. grain) or vegetable oil (i.e. seed). The yield is expressed as mass of dry matter per unit area, i.e. dry kg per hectare or kg/ha.

For national level simulations, the AQUACROP model was linked to the Quinary Catchments database that exists for South Africa, Lesotho and Swaziland. This historical climate database consists of 50 years (1950-1999) of daily climate data (rainfall, maximum and minimum temperature as well as reference crop evaporation) for each of the 5 838 Quinary Catchments. The climate database also contains 20 years of projected climate data for two periods, namely present (1971-1990) and intermediate future (2046-2065). The climate projects were derived from four global climate models (GCMs).

The Quinary Catchments soils database contains soil water retention parameters and soil thickness for two horizons, and the values are deemed to be representative of each entire Quinary. However, AQUACROP also requires saturated hydraulic conductivity which was derived using a pedo-transfer function for each Quinary.

The model was run to determine the attainable yield, water use efficiency and growing season length for a single season. The process was then repeated to obtain simulated data for the following season. The crop yield, water use efficiency and length of growing season for each consecutive season was then analysed to calculate the mean statistic.

This procedure was then repeated for each of the 5 838 Quinary Catchments and again for each selected feedstock. Owing to the large number of model runs, the plug-in version of the AQUACROP model was used. The methodology was fully automated to reduce its computational complexity, thus minimising the time required to complete a national run.

Further Reading

2 http://www.fao.org/nr/water/docs/AquaCropPlugInV40.doc
Simulation Models: The ACRU Agro-Hydrological Model [Further Reading: Schulze, 1995]

Background 1: The Use of Models to Evaluate Agro-Hydrological Responses
Long term observations of hydrological responses such as stormflow or baseflow or sediment yield, as well as of transpiration from plants or evaporative losses from the soil surface, at the scales of homogeneous response areas cannot be made for all feasible combinations of climate, soils, land uses and their different management regimes for reasons of logistics, time and cost. In order to mimic such responses, an appropriately structured and conceptualised agro-hydrological simulation model has to be used. Such a model is thus viewed as a tool for transferring knowledge (i.e. observation > analysis > information > prediction) from a selected study area where observations are made (e.g. a research plot or catchment) to other unmonitored areas (e.g. farm or Quinary Catchment) where the information is required and agro-hydrological decisions may have to be made. The model does this by simplifying a complex terrestrial system by way of a sequence of equations and pathways which describe the atmosphere-soil-plant-water continuum on the landscape component of the area (or catchment) and the flows and storages in the channel component of the catchment.

Background 2: From Model Input to Model Output
Such an agro-hydrological model requires input of known, or measurable, or derivable factors made up of data and information on, inter alia,

- climate (e.g. daily rainfall, maximum and minimum temperature, potential evaporation),
- physiography (e.g. altitude, its range within a catchment, slope gradients),
- soils (e.g. thicknesses of the various soil horizons, as well as soil water retention at critical soil water contents and saturated drainage rates from the respective horizons, and/or the inherent erodibility of the soil),
- land uses (e.g. natural vegetation and crop types, levels of management, planting dates, growth rates, above- as well as surface and below-ground vegetation attributes at different growth stages during the year and for different management strategies / scenarios),
- soil water budgeting threshold and rates (e.g. onset of plant stress, degrees of stress, capillary movement),
- runoff producing mechanisms (e.g. stormflow generation, recharge and resultant baseflow rates, as well as flows from impervious areas),
- irrigation practices (e.g. crop type, above-and-below-ground attributes at different growth stages, modes of scheduling and their controls, source of water, application efficiencies) and, where relevant, information on
- dams (e.g. inflows, full supply capacities, surface areas, evaporation rates, releases, abstractions and inter-basin transfers), or
- other abstractions (e.g. domestic, livestock by amount, season and source of water).

This information is transformed in the model by considering

- the climate, soil, vegetative, hydrological and management subsystems
- how they interact with one another
- what thresholds are required for responses to take place
- how the various responses are lagged at different rates and
- whether there are feedforwards and feedbacks which allow the system to respond in a positive or reverse direction.

The model then produces output of the unmeasured variable to be assessed, such as

- streamflow (i.e. the so-called “blue water” flows), from different pervious and impervious parts of the catchment, including stormflows and baseflows being modelled explicitly and on a daily basis, and hence high and low flows,
- evaporation (i.e. the so-called “green water” flows) from different parts of the catchment, and made up of productive transpiration through the plant plus the non-productive evaporation from the soil surface,
- crop yield (e.g. per season, annum or growth cycle; dryland or irrigated; and where relevant, with
economic analysis),
- irrigation water requirements (gross or net requirements; associated crop yields; deep percolation and stormflow from irrigated areas; water use efficiencies under different modes of scheduling water for irrigation; analysis of incremental benefit of applying irrigation vs dryland farming),
- peak discharge, and
- sediment yield from different parts of the catchment and computed on an event-by-event basis for the pertinent hydrological, soil, slope, plant cover and management conditions,

with all of the above output available as a
- risk analysis (month-by-month / annual statistics for median / mean conditions and for, say, driest / wettest years in 10 or 20 years; flow variability or extreme value analysis).

The ACRU agro-hydrological modelling system (Schulze, 1995 and continual updates includes the facilities to simulate the agro-hydrological responses described above and was selected as a suitable model for this Handbook.

**Concepts of the ACRU Model**

ACRU is a daily time step, physical-conceptual and multi-purpose model (Figure A5.4).

<table>
<thead>
<tr>
<th>INPUTS</th>
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<tbody>
<tr>
<td>LOCATIONAL</td>
</tr>
<tr>
<td>CATCHMENT</td>
</tr>
<tr>
<td>CLIMATIC</td>
</tr>
<tr>
<td>HYDROLOGICAL</td>
</tr>
<tr>
<td>LAND CHANGE</td>
</tr>
<tr>
<td>AGRONOMIC</td>
</tr>
</tbody>
</table>

| SOILS |
| RESERVOIR |
| LAND USE |
| IRRIGATION SUPPLY |
| IRRIGATION DEMAND |

<table>
<thead>
<tr>
<th>OPERATIONAL MODES</th>
</tr>
</thead>
<tbody>
<tr>
<td>SOIL WATER BUDGETING/ TOTAL EVAPORATION MODELLING</td>
</tr>
<tr>
<td>POINT or LUMPED or DISTRIBUTED MODES or G.I.S. LINKED</td>
</tr>
</tbody>
</table>

| DYNAMIC TIME or ANNUAL CYCLIC CHANGE |

<table>
<thead>
<tr>
<th>SIMULATION OPTIONS / COMBINATIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>RUNOFF COMPONENTS</td>
</tr>
<tr>
<td>RESERVOIR STATUS</td>
</tr>
<tr>
<td>SEDIMENT YIELD</td>
</tr>
<tr>
<td>IRRIGATION DEMAND</td>
</tr>
<tr>
<td>IRRIGATION SUPPLY</td>
</tr>
<tr>
<td>LAND USE IMPACTS</td>
</tr>
<tr>
<td>CLIMATE CHANGE</td>
</tr>
<tr>
<td>CROP YIELD</td>
</tr>
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</table>

<table>
<thead>
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<tbody>
<tr>
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<tr>
<td>Monthly</td>
</tr>
<tr>
<td>Annual</td>
</tr>
<tr>
<td>Risk Analyses</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>SPECIFIC OBJECTIVES / COMPONENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stormflow B.ation, Peak Discharge</td>
</tr>
<tr>
<td>Hydrograph (generating routing - EV analyses)</td>
</tr>
<tr>
<td>Outflows of normal flow depression abstraction, infiltration, transfers off-channel storage</td>
</tr>
<tr>
<td>Sediment from dams, Reservoir - situation</td>
</tr>
<tr>
<td>Crop Demand - on demand - fixed cycle - fixed amount - deficit</td>
</tr>
<tr>
<td>From reservoir, river and reservoir off-channel storage Return flows</td>
</tr>
<tr>
<td>Gradual change, Abrupt change Total evaporation Tillage practices Wetlands</td>
</tr>
<tr>
<td>CO2, C, E, S, P</td>
</tr>
<tr>
<td>Maize, Sugar cane Primary productivity dryland irrigated profit / loss</td>
</tr>
</tbody>
</table>

Figure A5.4  ACRU: Concepts of the modelling system (Schulze, 1995)

It contains options to output, inter alia, daily values of stormflows, baseflows, total streamflow, transpiration, soil water evaporation, peak discharge, sediment yields, recharge to groundwater, reservoir status, irrigation water supply and demand as well as seasonal crop yields at a specific location / catchment. The model revolves around multi-layer soil water budgeting (Figure A5.5) and is structured to be sensitive to changes in land uses and management. Individual processes and equations are not given here, but can be read up in Schulze (1995)

**Further Reading**

Figure A5.5   *ACRU*: Model structure (Schulze, 1995)
Appendix 2: On Clarification of Terms and Concepts Used Frequently in this Handbook

R.E. Schulze

Weather and Climate Related

Weather
Hazard
Climate
Climate System
Climate Variability
Forecasts
Extreme Weather Events
El Niño-Southern Oscillation (ENSO)

Climate Change Related

Anthropogenic Emissions
Greenhouse Gases (GHGs)
Greenhouse Effect
Climate Change
Emission / Climate Scenarios
Simple Incremental Scenarios
Climate Projections
Business as Usual (BAU) Projections
Climate Predictions
GCMs
Downscaling
Uncertainty
Ensemble of Models / Multiple Models
Confidence

Vulnerability, Impacts and Adaptation Related

Risk
Risk Mitigation
Vulnerability
Exposure
Climate Change Impacts
Sensitivity
Tipping Point
Resilience
Coping
Coping Capacity
Adaptation
Adaptation Assessment
Adaptive Capacity
Adaptation Constraint
Adaptation Deficit
Adaptation Limit
Adaptive Management
Adaptation Opportunity
Adaptation Options
Adaptive Policy
Community-Based Adaptation
Co-Benefits
Mainstreaming Climate Change
No Regret Principle
Precautionary Principle
Mitigation
Many relatively specialised terms are used in the field of climate change studies, and different user communities often interpret terms and concepts related to climate change differently. This Chapter therefore serves to clarify some key terms in the context that they are used in this Handbook. Where possible the terms have been simplified from their formal definitions and sometimes explanatory notes have been added. The reader will find that the terms are often partially overlapping and not entirely independent of one another. The terms have been gleaned from multiple sources, notably from IPCC (Intergovernmental Panel on Climate Change) documentation.

**Weather and Climate Related**

**Weather**
*Weather* is the sum total of prevailing atmospheric variables (e.g. temperature, humidity, wind) at a given place and at any instant (now) or brief period of time (this morning). Weather is an everyday experience – one talks of “today’s weather”.

**Hazard**
*A hazard* is the potential occurrence of a natural or human-induced physical event (e.g. a flood producing rainfall) or trend, or a physical impact, that may cause damage and loss to property, infrastructure (e.g. farm roads), livelihoods (loss of jobs), service provision and environmental resources, and at times even loss of life, injury or other health impacts (e.g. from heat waves), as well as. In this Handbook, the term hazard usually refers to weather or climate-related physical events or trends or their physical impacts. A hazard has a magnitude (how much rainfall in total), an intensity (how many mm/hour), a duration (e.g. falling over 2 days), has a probability of occurrence (on average once every 5 years) and takes place within a specified location.

**Climate**
*Climate*, in a narrow sense, is usually defined as the “average weather”, or more rigorously in a wider sense, as the state of the climate system including the statistical description in terms of the mean (e.g. what is the average rainfall) and variability of relevant quantities (e.g. in mm) over a period of time ranging from months to years to decades and centuries. These quantities are most often surface variables such as temperature, precipitation, relative humidity and wind. The conventional period to define climate is 30 years.

**Climate System**
The *climate system* is the highly complex system consisting of the following major components, viz: the atmosphere, the hydrosphere (water), the lithosphere (geology and soils) and the biosphere (vegetation), and the interactions among them. The climate system evolves in time under the influence of its own internal dynamics and because of external forcings such as volcanic eruptions, solar variations, and anthropogenic (i.e. human) forcings such as the changing composition of the atmosphere and land use change.

**Climate Variability**
*Climate variability* (CV) refers to any variations (deviation) from the long-term expected value (the mean) and other statistics (such as the occurrence of extremes) of the climate on all time and spatial scales beyond that of individual weather events. Variability may be due to natural internal processes within the climate system, i.e. internal variability, or to variations in natural or human-induced
(anthropogenic) external forcing, i.e. external variability. Internal variability is an entirely natural phenomenon, is reversible and non-permanent. An example would be the droughts in southern Africa associated with the El Niño. CV has time scales from
- diurnal (within the course of a day, e.g. time of occurrence of convective thunderstorms), to
- daily (i.e. variations from one day to the next), to
- intra-seasonal (e.g. monthly CVs), to
- inter-annual (e.g. year-to-year variability), and
- decadal (e.g. consecutive wet years or dry years).

**Forecasts**

Forecasts focus on individual events (e.g. a cold front is being forecast) where the physical processes (i.e. what causes the front) or statistical inter-linkages are relatively well understood to the extent that, depending on the nature of the event being forecast, it is possible to provide information about its timing (when will the front arrive), location (where) and magnitude (how much rain is forecast). Forecasts facilitate short term planning to the farmer and are thus able to reduce sources of uncertainty and hence diminish risk.

**Extreme Weather Events**

An extreme weather event is an event that is rare at a particular place and time of year. Definitions of rare vary, but an extreme weather event would normally be as rare as, or rarer than, the 10th percentile (i.e. statistically the lowest in 10 years) or the 90th percentile (e.g. the statistically highest in 10 years) of a probability density function (i.e. a statistic used to calculate extremes) estimated from observations. By definition, the characteristics of what is called extreme weather may vary from place to place in an absolute sense (i.e. what is rare in the semi-arid Karoo may not be rare along the coast of KwaZulu-Natal). When a pattern of extreme weather persists for some time, such as a season, it may be classed as an extreme climate event, especially if it yields an average or total that is itself extreme (e.g. drought or heavy rainfall over a season).

**El Niño–Southern Oscillation (ENSO)**

El Niño, in its original sense, is a warm water current that periodically (approximately every 2-7 years) flows along the coast of Ecuador and Peru, disrupting the local fishery. This oceanic event is associated with a fluctuation of the surface pressure pattern within the tropics and circulation in the Indian and Pacific Oceans, and is called the Southern Oscillation. This coupled atmosphere-ocean phenomenon is collectively known as El Niño–Southern Oscillation. During an El Niño event, the prevailing trade winds weaken and the equatorial countercurrent strengthens, causing warm surface waters in the Indonesian area to flow eastward to overlie the cold waters of the Peru ocean current. This event has great impact on the wind, sea surface temperature and precipitation patterns in the tropical Pacific. It has climatic effects throughout the Pacific region and, through what are known as teleconnections, in many other parts of the world, including southern Africa, where it is associated with drought conditions. The opposite of an El Niño event is called La Niña, associated in southern Africa with periods of above average rainfall.

**Climate Change Related**

**Anthropogenic Emissions**

Anthropogenic emissions are those of greenhouse gases (GHGs) and aerosols resulting from human activities. These activities include the burning of fossil fuels, deforestation, land use changes, livestock production, fertilization, waste management and industrial processes.

**Greenhouse Gases (GHGs)**

Greenhouse gases are those gaseous constituents of the atmosphere, both natural and anthropogenic, that absorb and emit radiation at specific wavelengths within the spectrum of terrestrial radiation emitted by the Earth's surface, the atmosphere itself and clouds. This property causes the greenhouse effect. Water vapor (H₂O), carbon dioxide (CO₂), nitrous oxide (N₂O), methane (CH₄), and ozone (O₃) are the primary greenhouse gases in the Earth’s atmosphere. Moreover, there are a number of entirely human-made greenhouse gases in the atmosphere, such as the halocarbons and other chlorine- and bromine-containing substances.
**Greenhouse Effect**

The *Greenhouse effect* is the infrared radiative effect of all infrared-absorbing constituents in the atmosphere. Greenhouse gases, clouds, and (to a small extent) aerosols absorb terrestrial radiation (i.e. the longwave radiation) emitted by the Earth’s surface and elsewhere in the atmosphere. These substances emit infrared radiation in all directions, but, everything else being equal, the net amount emitted to space is normally less than would have been emitted in the absence of these absorbers because of the decline of temperature with altitude in the troposphere and the consequent weakening of emission. An increase in the concentration of greenhouse gases increases the magnitude of this effect; the difference is sometimes called the enhanced greenhouse effect. The change in a greenhouse gas concentration because of anthropogenic emissions contributes to an instantaneous radiative forcing. Surface temperature and troposphere warm in response to this forcing, gradually restoring the radiative balance at the top of the atmosphere.

**Climate Change**

*Climate change*, broadly speaking, refers to any change in climate over time, whether due to natural variability or as a result of human activity. A more comprehensive definition is that climate change is a statistically significant change of climate which is attributed directly or indirectly to human activities that have altered the composition of the global atmosphere, and which is in addition to natural climate variability observed over comparable time periods. Human activities include the burning of fossil fuels (oil, coal, natural gas), unsustainable land use systems and clearing of forests, resulting in increasing the concentration of the greenhouse gases (GHGs such as CO$_2$, CH$_4$, N$_2$O, water vapour and chlorofluorocarbons, CFCs) in the atmosphere. These gases act to trap the energy from the sun resulting in global warming. Note that

- Climate change is considered to be irreversible and permanent, where a trend over time (either positive or negative) of means and deviations from the mean as well as other higher order statistics (e.g. changes in extremes) is superimposed over naturally occurring variability; that
- The time scale of climate change is decades to centuries, and that
- The trend is more likely to occur in steps than linearly over time.

**Emission / Climate Scenarios**

An *emission scenario* is a plausible representation of the future development of emissions of (mainly) greenhouse gases over decades, based on a coherent and internally consistent set of “what if” assumptions about driving forces into the future – driving forces such as population growth, increased energy demand, socio-economic development, politics, land use and technological change, and their key interactions and relationships. Concentration scenarios, derived from emission scenarios, are used as input to climate models, or GCMs, to compute climate projections. In this Handbook many of the scenarios are from the so-called SRES scenarios of the “Special Report on Emission Scenarios” from the year 2000; others are from the new emission scenarios for climate change, termed the four Representative Concentration Pathways or RCPs, which were developed for, but independently of, the present 2013 IPCC assessment. Note that scenarios are neither predictions nor forecasts, but are useful to provide a view of the implications of developments and actions.

**Simple Incremental Scenarios**

Another type of scenarios can take the form of *simple incremental scenarios*, which in effect are a type of sensitivity analyses of plausible changes in climate such as

- increases in temperature by +1°C, or +2°C, or +3°C, or
- changes in precipitation by -10%, or -20%, or +10%, or +20%, or
- enhancements of atmospheric CO$_2$ concentrations to 1.5 times pre-industrial revolution values, or to an effective doubling of CO$_2$, or to specific concentrations (in ppmv),
- with changes made by small, but realistic (i.e. plausible), increments from a baseline, and
- changes made initially to single variables and later to multiple variables, and with the usefulness of such sensitivity analysis being that one can
- *gauge* likely impacts,
- determine *critical thresholds* of change (when does the system “flip”?),
- determine *when* change becomes significant,
- determine *where* change is significant, and
- determine *which* driver is more significant than others, thereby determining the *sensitivity* of the “exposure unit” (e.g. of rainfall).
**Climate Projections**

*Climate projections* are simulated projections of the responses of the climate system to emission or concentration scenarios of greenhouse gases and aerosols, or radiative forcing scenarios, which are based on assumptions concerning, for example, future socio-economic and technological developments that may or may not be realised, and are therefore subject to substantial uncertainty.

- Climate projections are usually based on simulations by Global Climate Models, also known as General Circulation Models (GCMs).
- Projections are not predictions in the sense that the quality of a projection, and therefore the likelihood that it will occur, cannot be firmly determined.

**Business as Usual (BAU) Projections**

‘Business as usual projections’ are based on the assumption that operating practices and policies remain as they are at present. Although baseline scenarios could incorporate some specific features of BAU scenarios (e.g. a ban on a specific technology), BAU scenarios imply that no practices or policies other than the current ones are in place.

**Climate Predictions**

A *climate prediction* or *climate forecast* is the result of an attempt to produce (starting from a particular state of the climate system) an estimate of the actual evolution of the climate in the future, for example, at seasonal, inter-annual, or decadal time scales. Since the future evolution of the climate system may be highly sensitive to initial conditions, such predictions are usually probabilistic in nature. The predictability of a phenomenon can be defined as the degree to which its evolution can be deduced from the known initial conditions and the known evolution of factors that affect the phenomenon. It thus depends significantly upon the spatial and temporal scales of the phenomenon. Predictions are based on statistical theory, which uses the historical records to estimate the probability of occurrence of events. Predictions are therefore based on average probabilities and give no indication of when a particular event may occur.

**GCMs**

The climate system can be represented by models of varying complexity; that is, for any one component or combination of components a spectrum or hierarchy of models can be identified, differing in such aspects as the number of spatial dimensions, the extent to which physical, chemical, or biological processes are explicitly represented, or the level at which empirical parameterizations are involved. These models are termed GCMs, i.e. General Circulation Models or Global Climate Models. They are numerical (i.e. quantitative) representations of the climate system based on the physical, chemical and biological properties of its components, their interactions and feedback processes. These complex mathematical models represent 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 climate and the climatological seasonal cycle over broad continental scales for most variables of interest for climate change. There is an evolution towards more complex models with interactive chemistry and biology. Climate models are applied as a research tool to study and simulate the climate, and for operational purposes, including monthly, seasonal, and inter-annual climate predictions. According to the Intergovernmental Panel on Climate Change (IPCC) there is considerable confidence that climate models can provide credible quantitative estimates of future climate change, particularly at larger spatial scales.

**Downscaling**

*Downscaling* is a method that derives local- to regional-scale (10 to 100 km) information from larger-scale models such as GCMs. Two main methods of downscaling exist: dynamical downscaling and empirical / statistical downscaling. The dynamical method uses the output of regional climate models, of global models with variable spatial resolution, or high-resolution global models. The empirical / statistical methods develop statistical relationships that link the large-scale atmospheric variables with local / regional climate variables. In all cases, the quality of the driving model remains an important limitation on the quality of the downscaled information. In this Handbook examples of both statistical and dynamic downscaling are used.
**Uncertainty**

Uncertainty is a state of incomplete knowledge that can result from a lack of information or from disagreement about what is known or even knowable. It may have many types of sources, from imprecision in the data to ambiguously defined concepts or terminology, or uncertain projections of human behavior. Uncertainty can therefore be represented by quantitative measures (e.g., a probability density function) or by qualitative statements (e.g., reflecting the judgment of a team of experts).

In regard to climate scenarios, it is largely the uncertainty surrounding the assumptions made in emissions scenarios which determines the range of uncertainties from outputs of GCMs. These are based on one of several emissions scenarios or representative concentration pathways (see also the section on GCMs), bearing in mind that

- uncertainties exist within each of the scenarios, with each having their own explicit assumptions on greenhouse gas emissions dependent on technology, politics, economics and type of development, and associated probabilities, that
- no one scenario is "a more likely future", or a "best guess", that
- uncertainties occur due to differences between GCMs, each of which represents certain processes differently and not perfectly, with no GCM being the "best", and
- "best" in agriculture (or any other sector) not necessarily being the "best" in terms of (say) hydrology, and that
- uncertainties associated with changes in precipitation (the main "driver" of agricultural potential) are greater than uncertainties in temperature, that
- uncertainty is greater in regard to the magnitudes of change (i.e. how big the change will be) than the direction of change (e.g. whether rainfall will increase or decrease), and
- they are greater for changes in variability and extremes than for means, while
- uncertainties associated with downscaling from global to agriculturally relevant local scales, be it by empirical/statistical techniques or by dynamic methods, remain a source of concern.
- It is because of the above uncertainties 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.

**Ensemble of Models / Multiple Models**

An ensemble is a collection of model simulations characterizing a climate prediction or projection. Differences in initial conditions and model formulation result in different evolutions of the modelled system and may give information on uncertainty associated with model error and error in initial conditions in the case of climate forecasts and on uncertainty associated with model error and with internally generated climate variability in the case of climate projections. In this Handbook the averages of GCM derived results which have been mapped have been termed "Outputs from Multiple Models".

**Confidence**

Confidence, in the context of climate change studies, is the validity of a finding based on the type, amount, quality, and consistency of evidence (e.g. mechanistic understanding, theory, data, models, expert judgment) and on the degree of agreement. Confidence is usually expressed qualitatively.

**Vulnerability, Impacts and Adaptation Related**

**Risk**

Risk is the potential for consequences where something of human value (e.g. food supply; but including humans themselves) is at stake and where the outcome is uncertain. Risk is often represented as the probability of occurrence of hazardous events (e.g. a devastating drought) or trends (e.g. global warming over time) multiplied by the consequences (e.g. economic; food famine) if these events occur. This Handbook assesses climate-related risks.

**Risk Mitigation**

Risk mitigation considers setting up alternative measures to reduce the impacts of a hazard by minimising its destructive and disruptive effects, thereby lessening the scale of the disaster. It attempts to find practical and workable strategies and solutions for minimising risk at scales ranging from international, to national to local.
**Vulnerability** [Note that broad definitions only are given here as the entire Chapter A2 is devoted to this theme]

Vulnerability to climate change is the degree to which geophysical systems (e.g. the hydrological cycle; the landscape), biological systems (e.g. the crop) and socio-economic systems (e.g. the farming community) are susceptible to, and unable to cope with, adverse impacts of climate change, including climate variability and extremes. It is a measure of a system’s (e.g. that of agriculture) susceptibility to the type (e.g. less rainfall), the magnitude (e.g. by how much) and the rate (how quickly will it set in) of climate change, and it therefore depends on what the system (e.g. again, the agriculture sector) is exposed to (e.g. soil water stress), what it is sensitive to (e.g. too many consecutive days of stress), and whether it has the capacity to adapt to climate change (e.g. by conservation tillage). In a simpler definition, vulnerability is the characteristic of a person, or group, or component, of a natural system in terms of its capacity to resist and/or recover from and/or anticipate and/or cope with, the impacts of an adverse event.

**Exposure**

Exposure is the extent (i.e. the nature and degree) to which a climate-sensitive sector (e.g. farming) is in contact with/ exposed to significant climatic variations (e.g. of rainfall).

**Climate Change Impacts**

Climate change impacts are the consequences of climate change on any natural and human system and, depending on the consideration of adaptation, one can distinguish between potential impacts and residual impacts, where

- **Potential Impacts** imply all impacts that may occur given a projected change in climate, without considering adaptation, while
- **Residual Impacts** are the impacts of climate change that would occur after adaptation.

**Sensitivity**

Sensitivity is the degree to which a system (e.g. agricultural) or species (e.g. *Zea mays*, or maize) is affected, either adversely or beneficially, by climate-related stimuli. Climate-related stimuli encompass all the elements of climate change, including mean climate variability, and the frequency and magnitude of extremes. Effectively it is the magnitude of change in a response (e.g. crop yield) to a change in the driver of that response (e.g. rainfall). The effect may be

- **direct** (e.g. a change in rainfall implies a change in yield), or
- **indirect,**

and the response to an event or exposure can be

- **positive** (e.g. as rainfall increases, so does crop yield), or
- **negative**, i.e. inverse (e.g. as the drought increases, so the crop yield will decrease).

**Tipping Point**

A tipping point is the level of change in system properties beyond which a system reorganizes, often abruptly, and does not return to the initial state even if the drivers of the change are abated.

**Resilience**

Resilience is the capacity of a social-ecological system to cope with a hazardous event or disturbance, responding or re-organizing in ways that maintain its essential function, identity, and structure, while also maintaining the capacity for adaptation, learning, and transformation. A resilient system is synonymous with a region that is ecologically, economically and socially sustainable and has the ability of a social or ecological system to absorb disturbances (e.g. a drought) and recover from them while retaining the same basic structure and ways of functioning. Because the word “resilience” has been used in different ways, we need to be clear about its meaning.

- One interpretation has to do with the rate of return of a system to some equilibrium state after a small disturbance. This is what we term “engineering resilience”, or in ordinary English, the “bounce-back-ability”.
- In another definition resilience is the magnitude of disturbance that can be experienced before a system moves into a different state and different set of controls. This is termed “ecosystem resilience”.

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Based on this interpretation resilience, when applied to ecosystems, or to integrated systems of people and natural resources (such as farming), has three defining characteristics:

- The amount of change the system can undergo and still retain the same controls on function and structure (still be in the same state - within the same domain of attraction); resilience therefore implying that there are thresholds which, when exceeded, result in a system being vulnerable;
- The degree to which the system is capable of self-organisation; and
- The ability to build and increase the capacity for learning and adaptation, including the capacity to adapt to stress and change.

**Coping**

Coping is the use of available skills, resources and opportunities to address, manage, and overcome adverse conditions, with the aim of achieving basic functioning of people, institutions, organizations, and systems in the short to medium term.

**Coping Capacity**

Coping capacity is the ability of people, institutions, organizations, and systems, using available skills, values, beliefs, resources, and opportunities, to address, manage, and overcome adverse conditions in the short to medium term.

**Adaptation** [Note that broad explanations and definitions only are given here as the entire Chapter A3 is devoted to this theme. There is a degree of repetition, however]

*Adaptation* to climate change refers to the actions of making adjustments / alterations of current human practices and capital to natural (e.g. agricultural) or human systems, or changes in decision environments, in response to actual or expected climatic stimuli (e.g. to increases in temperature) or their effects (i.e. impacts on crop yields), which could moderate (i.e. reduce) harm and which might therefore ultimately enhance resilience or reduce vulnerability to observed or expected changes in climate, or even exploit beneficial opportunities. In natural systems such as the agriculture sector, adaptation implies human interventions which may facilitate adjustment to expected climate and its effects. One can either

- adapt incrementally, i.e. step by step, or
- adapt transformationally, in which fundamental attributes of a system (e.g. farming with sugarcane) are changed in response to climate and its effects.

Various types of adaptation can be distinguished.

- **Anticipatory Adaptation**, i.e. adaptation that takes place before impacts of climate change are observed. It is also referred to as proactive adaptation.
- **Autonomous Adaptation**: Here adaptation does not constitute a conscious response to climatic stimuli, but is triggered by ecological changes in natural systems and by market or welfare changes in human systems. It is also referred to as spontaneous adaptation.
- **Planned Adaptation**: This is adaptation that is the result of a deliberate policy decision, based on an awareness that conditions have changed or are about to change and that action is required to return to, maintain, or achieve a desired state.
- **Private Adaptation**: In this type, adaptation is initiated and implemented by individuals, households or private companies. Private adaptation is usually in the actor’s (e.g. the individual farmer’s) rational self-interest.
- **Public Adaptation** is adaptation that is initiated and implemented by governments at all levels. Public adaptation is usually directed at overall / collective needs.
- **Reactive Adaptation**: This is adaptation that takes place after impacts of climate change have been observed.

Adaptation includes responses in the decision environment, such as changes in social and institutional structures or altered technical options that can affect the potential or capacity for these actions to be realized.

From an agricultural perspective adaptation to climate change therefore refers to the adoption of appropriate coping strategies to minimise any negative effects of climate change. This includes a range of management related activities and practices such as timing of agricultural activities (e.g. of planting dates), annual cultivar choice assumptions and other farm-level choices, such as crop selection and breeding, animal selection and rainfall use efficiency.
The majority of climate change impact studies imply only changes to climate, but no change in agricultural technologies. Technology is, of course, a most important driver to adaptation, but one has to concede that relationships determining technology development remain unclear and will require further research focus.

More detail on the various types and levels of adaptation as well as on differences between adaptive management and adaptive governance are given in Chapter A3.

**Adaptation Assessment**

An adaptation assessment is the practice of identifying options to adapt to climate change and evaluating the options in terms of criteria such as availability, benefits, costs, effectiveness, efficiency and feasibility.

**Adaptive Capacity** [Note that more detail on adaptive capacity is given in Chapter A3]

Adaptive capacity has been defined as the ability or potential of a system, or institutions, humans and other organisms, to respond successfully (i.e. adjust in both behaviour and in resources and technologies) to climate change (including climate variability and extremes), to moderate (i.e. reduce) potential damages (by changing one's exposure to or sensitivity to the specific element of climate change), to take advantage of opportunities, or to cope with the consequences of impacts (by recovering or maintaining welfare / system function in the face of climatic change) and to profit from new opportunities (assuming climate change affects agents differentially).

**Adaptation Constraint**

Adaptation constraints are the factors that make it more difficult to plan and implement adaptation actions or factors that restrict options.

**Adaptation Deficit**

The adaptation deficit is the gap between the current state of a system and a state that minimizes adverse impacts from existing climate conditions and variability, i.e. the adaptation we should have been doing anyway.

**Adaptation Limit**

The adaptation limit is the point at which one's objectives (or the needs of, say, the agriculture sector) cannot be secured from risks which one cannot tolerate through adaptive actions.

**Adaptive Management**

Adaptive management is a process of iteratively (i.e. step by step) planning, implementing, and modifying strategies for managing resources in the face of uncertainty and change. Adaptive management involves adjusting approaches in response to observations of their effect and changes in the system brought on by resulting feedback effects and other variables.

**Adaptation Opportunity**

Adaptation opportunities are the factors that make it easier to plan and implement adaptation actions, that expand adaptation options, or that provide ancillary co-benefits.

**Adaptation Options**

Adaptive options are the array of strategies and measures that are available and appropriate for addressing adaptation needs. They include a wide range of actions that can be categorized as structural, institutional, or social.

**Adaptive Policy**

This is a kind of adaptation that can be applied by a set of policy actors to affect what kinds of decisions are made about social standards, infrastructure development and management practices, land and ecosystem planning and / or civic goals; and how those decisions are made.

**Community-Based Adaptation**

Community-based adaptation focuses attention on empowering and promoting the adaptive capacity of communities. It is an approach that takes context, culture, knowledge, agency, and preferences of communities as strengths.
**Co-Benefits**

Co-benefits are the positive effects that a policy or measure which is aimed at one objective might have on other objectives, irrespective of the net effect on overall social welfare. Co-benefits are often subject to uncertainty and depend on local circumstances and implementation practices. Co-benefits are also called ancillary benefits.

**Mainstreaming Climate Change**

- **Mainstreaming**, in the climate change context, refers to integration of climate change vulnerabilities or adaptation into some aspect of related government policy such as water management, disaster preparedness and emergency planning or land use planning.

- **Actions** that promote the mainstreaming of climate change adaptation include:
  - integration of climate information into environmental data sets,
  - preparing climate change related vulnerability or hazard assessments,
  - factoring climate change into broad development strategies, as well as into macro policies and / or sector policies,
  - institutional or organisational structures, or
  - development project design and implementation.

- By implementing mainstreaming initiatives, it is argued that adaptation to climate change will become part of, or will be consistent with, other well established programmes, particularly sustainable development planning, but that mainstreaming needs to encompass a broader set of measures to reduce vulnerability than has thus far been the case.

- Mainstreaming initiatives are classified in the development planning literature at various levels:
  - At the international level, mainstreaming of climate change can occur through policy formulation, project approval and country-level implementation of projects funded by international organisations.
  - At the regional level mainstreaming assesses the likely impacts of climate change on key economic sectors such as water, agriculture or human health, while
  - At the community level responses may also be defined.

**No Regret Principle**

No regret measures are those whose benefits equal or exceed their cost to society. They are sometimes known as “measures worth doing anyway”.

**Precautionary Principle**

The precautionary principle recognises that the absence of full scientific certainty shall not be used as a reason to postpone decisions when faced with the threat of serious or irreversible harm.

**Mitigation**

Mitigation is largely concerned with innovative ways of eliminating or reducing the risks and hazards associated with greenhouse gas emissions (mainly of fossil fuel related activities, methane and nitrous oxide) by avoiding, reducing or minimising sources of pollution that can have a deleterious effect on levels of GHGs and hence global warming and climate change.

**Agriculture Related**

**Carbon dioxide (CO₂) Fertilization**

The enhancement of the growth of plants as a result of increased atmospheric carbon dioxide (CO₂) concentration.

**Food System**

A food system includes the suite of activities and actors in the food chain (i.e. producing, processing and packaging, storing and transporting, trading and retailing, and preparing and consuming food); and the outcome of these activities relating to the three components underpinning food security (viz. access to food, utilization of food, and food availability), all of which need to be stable over time. Food security is therefore underpinned by food systems, and is an emergent property of the behavior of the whole food system. Food insecurity arises when any aspect of the food system is stressed.

**Crop Modelling**
Crop models 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. Agronomic models thus 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 past 35 or so years.

**C3 and C4 plants**
The different methods plants use to convert carbon dioxide from air into organic compounds through the process of photosynthesis. All plants use C3 processes; some plants, such as buffel grass and many other warm climate grasses, also use C4 processes. C4 plants have an advantage in a warmer climate due to their higher CO₂ assimilation rates at higher temperatures and higher photosynthetic optima than their C3 counterparts.

**Drought**
A drought is a period of abnormally dry weather long enough to cause a serious agricultural or hydrological imbalance. Drought is a relative term; therefore any discussion in terms of rainfall deficit must refer to the particular Rainfall-related activity that is under discussion. For example, a shortage of rainfall during the growing season impinges on crop production or ecosystem function in general (due to soil moisture drought, also termed agricultural drought), and during the runoff and percolation season primarily affects water supplies (hydrological drought). Storage changes in soil moisture and groundwater are also affected by increases in actual evapotranspiration in addition to reductions in precipitation. A period with an abnormal precipitation deficit is defined as a meteorological drought. A mega-drought is a very lengthy and pervasive drought, lasting much longer than normal, usually a decade or more.

**Terms in General Usage**

**Anthropogenic**
Resulting from, or produced by, human activities.

**Stakeholders**
These include all individuals and / or groups who are affected by, or can affect, a given operation (e.g. a farming operation). Stakeholders can be individuals (the farmer), interest groups (the co-op) or corporate organisations (e.g. the supermarket group which sells the farming products).

**Participation**
The process through which stakeholders influence and share control over development initiatives and decisions and resources affecting them. It can improve the quality, effectiveness and sustainability of projects and strengthen ownership and commitment of government and stakeholders.

**Capacity Building**
*Capacity building* is a co-ordinated process of deliberate interventions by insiders and / or outsiders of a given society leading to skill upgrading, both general and specific, procedural improvements, and organisational strengthening. Capacity building refers to investment in people, institutions, and practices that will, together, enable countries in the region to achieve their development objective. Capacity is effectively built when these activities are sustained and enhanced with decreasing levels of donor-aid dependence accompanied by increasing levels of societal goal achievement.

**Empowerment**
*Empowerment* is the expansion of assets and capabilities of poor people to participate in, negotiate with, influence, control, and hold accountable institutions that affect their lives. In its broadest sense, empowerment is the expansion of freedom of choice and action. It is a participatory process, which places or transfers decision-making responsibility and the resources to act into the hands of those who will benefit. This can include:
- capacity building for stakeholder organisations;
- strengthening legal status of stakeholder organisations;
- stakeholder authority to manage funds, hire and fire workers, supervise work, procure materials;
• stakeholder authority to certify satisfactory completion of project and establish monitoring and evaluation indicators; and
• support for new and spontaneous initiatives by stakeholders.