Thematic Booklet 10

Horticultural Crops and Climate Change in South Africa: 3 Selected Sub-Tropical Fruits

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, E3, E4, K1 and Appendices
DISCLAIMER

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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
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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 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)

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: IPCC, 2007; www.NOAA, 2015)

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:
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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 environment 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\textsubscript{2}, methane CH\textsubscript{4} and nitrous oxide N\textsubscript{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.

**Figure A1.3** Increases in GHG emissions in the recent past (left), with more detail on recent global monthly mean CO\textsubscript{2} concentrations in the atmosphere (Sources: IPCC, 2007; www.NOAA, 2015)

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.

![Figure A1.4](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** 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).

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

**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;
- 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, as has been shown in various more technical reports (for example, Schulze, 2012), 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.

![Provinces, Countries, Major Roads and Towns](image)

**Figure A1.7** Provinces, countries, major roads and towns

**Table A1.1** shows the Northern Cape to be the largest of the nine provinces at 363 389 km$^2$, while Gauteng is 19 times smaller at only 18 760 km$^2$. The total study area is 1 223 201 km$^2$, 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 (km$^2$)</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><strong>1 270 163</strong></td>
<td><strong>100.0</strong></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.
SECTION E  HORTICULTURAL CROPS IN SOUTH AFRICA AND CLIMATE CHANGE

CHAPTER E3  BANANA PRODUCTION IN SOUTH AFRICA AND CLIMATE CHANGE

R.E. Schulze and S. Schütte

Background, Uses and Description

Banana Production in South Africa

Setting the Scene
Production Areas
Production

Employment
Marketing

Climatic Requirements of Bananas

Temperature Criteria

Table E3.1  Key temperature parameters for banana growth (Calberto et al., 2015)

Climatic Zones Suitable for Banana Production

Irrigation

Choice of Cultivar

Climate Related Constraints to Banana Production

Drought and Water Stress
Diseases: Fungi, Viruses and Bacteria
A Final Note on Pests and Diseases

General Impacts of Climate Change on Bananas

Impacts of Climate Change on Banana Production Areas in South Africa

How Were the Impacts of Climate Change on Banana Production Assessed?

Potential Dryland Banana Growth Areas and Yields Based on Historical Climatic Conditions

Figure E3.2  Potential mean annual dryland banana yields for a plant crop (upper right) and for ratoon crops (lower left), based on historical climatic conditions and using the Smith’s (2006) dryland banana yield model

Figure E3.3  Potential annual irrigated banana yields for a plant crop (left) and for ratoon crops (right), based on historical climatic conditions

Projected Changes in Dryland Banana Growth Areas and Yields into the Future

Figure E3.4  Projected changes in dryland banana yields in t/ha annum from the present (1971-1990) into the intermediate future (2046-2065) for a plant crop (top left) and for ratoon crops (top right), and the changes expressed as percentages (bottom maps), based on the Smith (2006) dryland banana yield model with climate outputs from multiple GCMs

Projected Changes in Irrigated Banana Growth Areas and Yields into the Future

Figure E3.5  Projected changes in irrigated banana yields in t/ha annum from the present (1971-1990) into the intermediate future (2046-2065) for a plant crop (top left) and for ratoon crops (top right), and the changes expressed as percentages (bottom maps), based on the Smith (2006) irrigated banana yield model with climate outputs from multiple GCMs

Adaptation to Climate Change
Opportunities / Positive Effects for Sub-tropical Bananas
More Specific Adaptation Strategies

Further Reading

Please cite as follows:
Bananas, of the *Musa* species, said to be native to tropical south and southeast Asia and likely to have been first domesticated in Papua New Guinea, are grown throughout the tropics and subtropics. They are the most popular fruit and globally the fourth most widely consumed crop by humans, after rice, wheat and maize. In sub-Saharan Africa, especially in East Africa, millions of people depend on different types of banana as a staple food and a source of livelihood and well-being, with people in Uganda, Rwanda and Burundi consuming 3-11 bananas per day, and in certain areas average per capita consumption exceeding 100 kg/year. The word banana is thought to be of West African origin, possibly from the Wolof word *banaana*, and passed into English via Spanish or Portuguese.

The banana plant is the largest herbaceous flowering plant. Plants are normally tall and fairly sturdy. Bananas grow in a wide variety of soils, as long as the soil is at least 0.60 m deep, has good drainage and is not compacted. Cultivated banana plants vary in height depending on the variety and growing conditions. Most are around 5 m tall, with a range from 'Dwarf Cavendish' plants at around 3 m to 'Gros Michel' at 7 m. Leaves are spirally arranged and may grow 2.7 m long and 0.60 m wide. They are easily torn by the wind, resulting in the familiar frond look.

Unlike many other crops, which have crop cycles of 3-5 months, banana is a semi-perennial crop with a crop cycle nearly a year long under optimum conditions and even longer with lower temperatures or more erratic water supply. The vulnerability of the crop to climate change is an important consideration, demanding specific tools suited to banana growth habit and crop cycle.

The group comprising bananas, unlike many of the other top crops, is made up of a diverse set of cultivar groups, each with a different genetic make-up, not just varieties of a single species. This diversity adds an additional dimension to any analyses of this crop. Nearly half of global production is the Cavendish group, which is the most important banana in world trade, followed by cooking bananas of diverse types, other dessert bananas and finally plantains.

**Setting the Scene**

Bananas are the most important commercial sub-tropical fruit grown in South Africa, contributing 55-60% to the value all sub-tropical fruits grown in the country. They are planted for sale in local markets or self-consumption, with only a fraction of all bananas being sold on the world markets. The production technologies used for small scale and commercial operations are so different that they are usually separated into two distinct economic activities. On the one hand, small scale production for consumption in the household or sale in local markets makes a limited use of external inputs and is labour intensive. On the other hand, production for commercial operations uses external inputs intensively and is technologically sophisticated.

**Production Areas**

Bananas are produced mainly in Mpumalanga (Onderberg and Kiepersol), Limpopo (Levubu and Letaba) and both the North and South Coasts of KwaZulu-Natal. The total hectares under banana trees is estimated at ~ 11 400 ha, with the Onderberg area near Melalane in Mpumalanga Province being the highest contributor with 36% (4 100 ha) of the total land under banana cultivation. Second is Kiepersol in Mpumalanga province with 22% (2 500 ha)
of the total land under banana cultivation, making Mpumalanga the major producer of bananas in South Africa at ~ 58% of the total land under bananas. The Levubu and Letaba areas in Limpopo accounted for 12% (1400 ha) and 8% (860 ha) respectively, while KwaZulu-Natal’s North and South Coasts each produce 15% (1 700 ha) of total area planted to bananas.

**Production**
There has been little growth on banana production over the past decade (Figure E3.1), with the little growth in production volumes being the result mainly because area suitable for banana production is limited in South Africa. Total production is around 400 000 t/annum (Figure E3.1).

![Figure E3.1 Total production and market sales of bananas in South Africa (DAFF, 2013)](image)

**Employment**
Full-time labourers employed on banana farms are primarily employed for a number of specialist tasks such as the control of pests and diseases, harvesting, pack house operations and irrigation management, while seasonal (contract) labour is employed mainly for harvesting or fruit packing. In recent years direct employment within the banana industry was ~ 27 000 people with ~ 108 000 dependents. The banana industry in South Africa thus makes an important contribution to both direct and indirect employment.

**Marketing**
Approximately all bananas produced in South Africa are destined for local fresh consumption via markets (~ 60%) and for processing (~40%), with < 1% exported, this mainly due to South Africa’s location and its subtropical climate, which makes it difficult to compete against equatorial banana producing countries on world markets.

**Climatic Requirements of Bananas** [Further Reading: Lagerwall, undated; Calberto *et al.*, 2015]

Bananas are tropical plants that are grown under sub-optimal, subtropical conditions in South Africa. Production is therefore severely limited by climate, as ideal conditions do not exist in many places in the country.

**Temperature Criteria**
Although bananas are a fairly adaptable crop, where water and nutrients are not limiting in the sub-tropics, the rate of banana growth and development is determined by temperature.
The optimum mean temperature range for leaf development and bunch initiation and growth is between 22°C and 31°C. Growth ceases at a mean daily temperature of 13°C and leaf chlorophyll destruction takes place at an actual temperature of 6°C, with leaf die back at 0°C (Table E3.1). These and other thresholds form a basis of estimating production potential and establishing limiting factors to banana production in South Africa. Given these temperature thresholds, the warm coastal strip from Durban northwards and particularly north of Mtubatuba / St. Lucia is regarded climatically as the area with the best production potential in South Africa.

Table E3.1  Key temperature parameters for banana growth (Calberto et al., 2015)

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Effect of temperature on banana growth</th>
</tr>
</thead>
<tbody>
<tr>
<td>47</td>
<td>Thermal danger point, leaves die</td>
</tr>
<tr>
<td>38</td>
<td>Growth stops</td>
</tr>
<tr>
<td>34</td>
<td>Physiological heat stress starts</td>
</tr>
<tr>
<td>27</td>
<td>Optimum mean temperature for productivity</td>
</tr>
<tr>
<td>13</td>
<td>Minimum mean temperature for growth, field chilling</td>
</tr>
<tr>
<td>6</td>
<td>Leaf chlorophyll destruction</td>
</tr>
<tr>
<td>0</td>
<td>Frost damage, leaves die</td>
</tr>
</tbody>
</table>

The limitations of planting without adequate irrigation, particularly on sandy soils, should be borne in mind. A further limitation in high-lying areas, or areas subject to temperature inversion, are low winter temperatures that result in a virtual shut-down of growth and consequent choke-throat of winter-emerging bunches (so-called “November dump” bunches). These bunches are initiated (at ground level) during the cold winter period and are often deformed as a result of excessive cold during their initiation.

**Climatic Zones Suitable for Banana Production**

From the international literature, the climatic zones suitable for banana production are as follows:

- Areas not suitable for banana production are defined as areas having three or more months with mean temperatures below 13°C.
- Sub-tropical areas are considered those which have a difference between the warmest and coolest months of greater than 8°C, as well as with fewer than three months below 13°C.
- A month is considered dry if it has less than 60 mm precipitation.
- Three categories of average annual temperature were identified: 13-18°C, 18-24°C and > 24°C. While banana will survive in the 13-18°C range, leaf emission is very slow and a stem may take over two years to flower. Assuming no water limitations, in the 18-24°C range, planting to harvest will generally take between 12 months and 24 months, while in the > 24°C range, a stem will produce a bunch in less than one year.
- Bananas do not tolerate long dry seasons. Two categories for length of dry season are used:
  - three months or fewer with less than 60 mm of monthly rainfall (i.e. “dry”) and
  - more than three dry months.
- The combination of total annual rainfall and length of dry season provides an indication both of viability for banana growth without irrigation and of the conditions for leaf diseases. With fewer than three dry months and greater than 150 mm/month of rainfall, banana grows well year-round without irrigation. Such conditions are, however, also more favourable for leaf diseases.

**Irrigation**

Ideally, an evenly distributed rainfall of 100 mm per month is the minimum requirement for bananas. Most production areas in South Africa would fall short of this requirement in at least 7 months of the year and it is therefore not surprising that irrigated bananas in South
Africa outyield dryland plantations by some 50%. It is therefore important to plan for irrigation if the water and financial resources are available.

**Choice of Cultivar** [Further Reading: Lagerwall, undated]

Choice of cultivar depends on the local climatic conditions. In the cool subtropics of South Africa such as Eshowe (Köppen climate zone Cfa), the recommended cultivar is "Williams". Short cultivars such as the traditionally grown "Dwarf Cavendish" should not be grown in cool areas, due to their susceptibility to choke throat. In the warmer subtropics such as the Nkwaleni valley in KwaZulu-Natal (Köppen zone Aw) "Grand Nain" is a recommended cultivar. Because of the severity of coastal winds, the shorter "Chinese Cavendish", which is less prone to lodging, is also recommended.

**Climate Related Constraints to Banana Production** [Further Reading: AATF. 2003; Wikipedia]

**Drought and Water Stress**
With banana’s water requirement ideally in the range from 900-1800 mm during the growth and production cycle (equivalent of 3.0-6.3 mm/day), the important characteristics of the bananas in respect of plant water requirement are:

- shallow root system compared to other fruit crops,
- poor ability to withdraw water from drying soil, and
- rapid physiological response to soil water deficit in conditions of high evaporative demand.

Most of the production areas in South Africa experience marked dry seasons and yet much of the production in this country is rainfed with water conservation methods hardly practised. Yield losses due to water stress can range between 30-50%. Clearly irrigation is the way to go, and would give a quick win, but has a high capital investment which is prohibitive.

**Diseases: Fungi, Viruses and Bacteria**
Biotic stresses are a huge problem in banana production in South Africa. The major problems include fungal diseases such as black sigatoka disease and nematodes, especially the migratory nematodes. Host plant resistance might overcome most of these constraints. Genetic modification of plants might be a solution to these constraints.

**Black sigatoka**
Black sigatoka is a fungal leaf spot disease first observed in Fiji in the 1960s. Also known as black leaf streak, it has spread to banana plantations throughout the tropics from infected banana leaves that were used as packing material. It affects all main cultivars of bananas, including the Cavendish cultivars, impeding photosynthesis by blackening parts of the leaves, eventually killing the entire leaf. Starved for energy, fruit production falls by 50% or more, and the bananas that do grow ripen prematurely, making them unsuitable for export. The fungus has shown ever-increasing resistance to treatment, with the current treatment very expensive. In addition to the expense, there is the question of how long intensive spraying can be environmentally justified. Several resistant banana cultivars have been developed, but none has received commercial acceptance due to taste and texture issues.

**Fusarium wilt**
Another important fungal disease is Fusarium wilt, also known as Panama disease. It is caused by a fusarium soil fungus (Race 1), which enters the plants through the roots and travels with water into the trunk and leaves, producing gels and gums that cut off the flow of water and nutrients, causing the plant to wilt, and exposing the rest of the plant to lethal amounts of sunlight. According to current sources, a deadly form of Panama disease is infecting Cavendish. All plants are genetically identical, which prevents evolution of disease resistance. Researchers are examining hundreds of wild varieties for resistance. Tropical
Race 4 (TR4) is a reinvigorated strain of Panama disease, first discovered in 1993. This virulent form of fusarium wilt has wiped out Cavendish in several southeast Asian countries. Cavendish is highly susceptible to TR4, and over time, Cavendish is almost certain to be eliminated from commercial production by this disease. The only known defense to TR4 is genetic resistance.

**Banana Bunchy Top Virus**

Banana bunchy top virus (BBTV) jumps from plant to plant using aphids. It stunts leaves, resulting in a "bunched" appearance. Generally, an infected plant does not produce fruit, although mild strains exist which allow some production. These mild strains are often mistaken for malnourishment, or a disease other than BBTV. There is no cure yet, although a breakthrough has been realized in Australia. However, its effect can be minimised by planting only tissue-cultured plants (in vitro propagation), controlling aphids, and immediately removing and destroying infected plants.

**Bacterial wilt**

Banana bacterial wilt (BBW) is a bacterial disease caused by *Xanthomonas campestris* pv. *Musacearum*. After being originally identified on a close relative of bananas in the 1960s, BBW occurred in East African countries since the beginning of this century, affecting all banana cultivars. While a breakthrough for bacterial wilt has been achieved for sugarcane and citrus, a similar strategy when used for bananas uses bovine lysozyme, which brings in issues of bioethics affecting acceptability with a gene coming from an animal. Research on resistance to the pathogen is ongoing.

**A Final Note on Pests and Diseases**

While in no danger of outright extinction, the most common and very popular banana cultivar Cavendish could become unviable for large-scale cultivation in the next 10-20 years as Cavendish lacks genetic diversity, which makes it vulnerable to diseases, threatening both commercial cultivation and small-scale subsistence farming. There is a possibility that those variants which could replace what much of the world considers a "typical banana" are so different that most people would not consider them the same fruit, and blame the decline of the banana on monogenetic cultivation driven by short-term commercial motives.

**General Impacts of Climate Change on Bananas** [Further Reading: Wikipedia; Australian Banana Growers Council; Calberto et al., 2015; Australian Factsheet]

From the literature, some of the possible climate change impacts that could occur in subtropical banana growing regions such as South Africa include the following:

- Production cycles from planting to harvest will be shorter due to an accelerated rate of leaf emission. Certain banana areas which are expected to surpass seasonal temperatures above 30°C may be lost for banana production by 2050.
- Drier, hotter springs could imply water shortages, and with evaporation rates expected to increase, this could result in increased irrigation demands by ~ 10%.
- Higher temperatures will mean losses of fruit due to sunburn, and they will probably also impact fruit size and bunch emergence.
- Plantations are frequently planted with ground covers to retain moisture. However, these could be compromised with prolonged dry conditions and higher temperatures.
- Plantations without irrigation will be more susceptible to soil water stress.
- Increased storm frequencies and intensities could result in banana blowdowns, damage to windbreaks and damage to infrastructure.
- Increased risk of disease is expected due to higher temperatures, extended leaf wetness and soil saturation, with important leaf diseases possibly becoming more aggressive.
- Increased leaf tearing from more frequent and intense storms could result in reduced opportunities for photosynthetic ability.
- Changes in temperature and climate will see changes to pest / predator ratios (e.g. tropical zone pests may move further south.)
• Increased energy costs could impact on farm operations, such as harvesting, storage and transport.
• The genetic diversity of bananas – there are more than 500 varieties around the world – is also a key resource for climate change adaptation that needs to be further studied.

Impacts of Climate Change on Banana Production Areas in South Africa

How Were the Impacts of Climate Change on Banana Production Assessed?
The assessments were made using a rule based banana yield model developed by Smith (2006) which distinguished between yields from a plant crop and those from ratoon crops in subsequent years, as well as distinguishing between banana grown under dryland (i.e. rainfed) conditions and bananas under irrigation.

After eliminating areas according to lower and upper temperature thresholds, frost and a minimum rainfall threshold, the dryland yield model was a function of annual rainfall and a temperature index which considered minimum, maximum and mean temperatures the upper and lower thresholds of which varied between cooler and hotter production areas. All the above critical thresholds differed again between plant and ratoon crops. For estimates of banana yields under irrigation there was no rainfall threshold applied, but rather one of atmospheric demand related to a water use coefficient.

Potential Dryland Banana Growth Areas and Yields Based on Historical Climatic Conditions
As a point of departure before assessing impacts of climate change, potential dryland banana growth areas and yields based on historical climatic conditions are considered first. The term ‘potential’ here refers to yields determined solely on climatic criteria, with no consideration given to impacts of soil properties, nor of management level, both of which modify yields (Smith, 2006). Figure E3.2 shows climatically determined growth areas of dryland bananas to be restricted to the warmer and wetter eastern areas of South Africa, stretching from the northerly coastal areas of the Eastern Cape along the coastal zone of much of KwaZulu-Natal into western Swaziland and into the warm, wet parts of Mpumalanga and Limpopo provinces. Mean annual yields of the dryland plant crop are in the range of 20-40 t/ha/annum, while those from the ratoon crop are somewhat higher at > 40 t/ha/annum.

Potential irrigated banana yields under historical climatic conditions are markedly higher than those grown dryland (Figure E3.3), with yields in some areas nearly doubling, and again with the ratoon crop yields shown to outperform those of the plant crop. Additionally, because rainfall is no longer considered to be a constraining factor, the area where bananas can be grown under irrigation expands when compared to that of dryland production. Note that in the maps excessive temperature impacts have not yet been incorporated.
Projected Changes in Dryland Banana Growth Areas and Yields into the Future

With warmer conditions together with the increases in rainfall projected from the present (1971-1990) into the intermediate future (2046-2065) by the GCMs used in this study,
Dryland banana yields are modelled to increase by anything from 10-30 t/ha/annum for plant, and somewhat more for ratoon crops (Figure E3.4 top maps), this being equivalent to percentage increases in the range of 20-50% for plant, and 20-40% for ratoon crops (Figure E3.4 bottom maps). Additionally, the dryland banana belt shifts inland to cover the northeastern parts of the Eastern Cape, virtually all of KwaZulu-Natal and Swaziland and expanded parts of Mpumalanga.

**Figure E3.4** Projected changes in dryland banana yields in t/ha annum from the present (1971-1990) into the intermediate future (2046-2065) for a plant crop (top left) and for ratoon crops (top right), and the changes expressed as percentages (bottom maps), based on the Smith (2006) dryland banana yield model with climate outputs from multiple GCMs.

**Projected Changes in Irrigated Banana Growth Areas and Yields into the Future**

Irrigated banana yields are modelled to increase by somewhat less than dryland yields, generally being in the range of 10-20 t/ha/annum, or equivalent to increases of 20-30% (Figure E3.5). Note that in the maps excessive temperature effects have not yet been incorporated.

**Adaptation to Climate Change** [Further Reading: Calberto et al., 2015; Australia Factsheet]

Planning early to adapt to the risks of climate change and being aware of the opportunities that climate change may also have to offer will help minimize the impacts on banana farm productivity and protect farm businesses. 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.
Opportunities / Positive Effects for Sub-tropical Bananas

- Projections for South Africa show an increase in areas climatically suited to bananas in future due to increased temperatures and reduced incidence of frosts in certain locations.
- The potential expansion inland of the banana belt should be evaluated in greater detail, taking cognizance also of soil, water availability as well as economic issues.
- Specific cultivar groups presently grown in cooler areas such as the East African highlands merit special studies, because these are the cultivars that may expand to higher elevations. However, growers in warmer and / or lower elevation areas may need to substitute other cultivars as temperatures increase.
- Production cycles from planting to harvest will be shorter due to an accelerated growth rates, and farmers need to take advantage of this, being mindful, however, that water demands, whether for dryland or irrigated bananas, are projected to increase by 10-15% over the next four or so decades.

More Specific Adaptation Strategies
To Potentially Increased Storm Frequency and Intensity

- Cultivate and prepare ground for planting only during drier months to avoid erosion during heavy rainfall periods.
- Use irrigation to establish groundcover immediately after cultivation and place temporary controls (e.g. hay bales, hessian sausages) in erosion prone areas.
- Ensure that drainage lines are well grassed and rocked to withstand high water velocities.
- Establish windbreaks in current and new plantings, keeping in mind the following:
  - careful species selection to avoid brittle trees,
  - potential competition for light, water, nutrients with the bananas,
  - effect of spray drift,
  - good air drainage to prevent cold air gathering in pockets, and
  - use of artificial structures.

To Increased Pest and Disease Incidence

- Conduct more frequent monitoring for pests and diseases.
- Ensure disease prevention strategies such as de-leafing are carried out frequently.
- Manage soil borne pests, e.g. plantations with high nematode infestations have weaker root systems and are more prone to blowdowns during storms.
- Participate in grower networks providing information on new pest incursions and outbreaks.

General

- Make use of shade cloths to cope with high temperatures and wind speeds.
- Plant cover crops between rows to prevent erosion.
- Undertake an energy audit of farm operations to identify where savings can be made.
- Explore options for on-farm energy generation, e.g. solar or wind turbines.
- Use lighter coloured and reflective bunch covers to reduce bunch temperatures during summer months and coat the bags with pesticides.
- Reduce post-harvest losses.

Potential Seasonal Water Shortages

- On-farm water storages may be required for new plantations, with a volume of 2000 to 3000 mm equivalent per ha of bananas considered for dry years.
- If water supply is inadequate for full irrigation, design irrigation to supply peak water demand periods on a portion of the plantation, which is better than under-irrigating everywhere.
- Consider increasing the capacity of existing on-farm storages, with deeper storages preferred to reduce evaporation losses.

Further Reading

Calberto, G., Staver, C. and Siles, P. 2015. An assessment of global banana production and suitability under climate change scenarios, In Elbehri, A. (Editor): Climate Change and Food Systems: Global Assessments and Implications for Food Security and Trade. Food and Agriculture Organization of the United Nations (FAO), Rome, Italy
Lagerwall, G. (Undated). Bananas in KwaZulu-Natal. KZN Department of Agriculture and Environmental Affairs, Pietermaritzburg, RSA.
SECTION E  HORTICULTURAL CROPS IN SOUTH AFRICA AND CLIMATE CHANGE

CHAPTER E4  CITRUS FRUIT PRODUCTION IN SOUTH AFRICA AND CLIMATE CHANGE

R.E. Schulze and S. Schütte

Introduction

Citrus Growing Areas in South Africa and Broad Climatic Suitability for Certain Cultivars

*Citrus Growing Areas by Climatic Zones*
*Climatic Suitability of Cultivars by Climate Zone*

Soil Requirements

Yields

More Specific Climate Requirements of Cultivars

*Navel Oranges*
*Valencia Oranges*
*Grapefruit*
*Lemons*

Mapping Optimum Growing Areas of Citrus Cultivars in South Africa and Impacts of Projected Climate Change on Growing Areas

*Navel Oranges*
**Figure E4.1** Temperature based criteria met out of 7 for Navel oranges under historical climatic conditions (1950-1999; right) and under projected intermediate future climate conditions (2046-2065; right), based on outputs from multiple GCMs

*Valencia Oranges*
**Figure E4.2** Temperature based criteria met out of 12 for Valencia oranges under historical climatic conditions (1950-1999; left) and under projected intermediate future climate conditions (2046-2065; right), based on outputs from multiple GCMs

*Grapefruit*
**Figure E4.3** Temperature based criteria met out of 6, plus frost frequency criteria, for grapefruit under historical climatic conditions (1950-1999; left) and under projected intermediate future climate conditions (2046-2065; right), based on outputs from multiple GCMs

*Lemons*
**Figure E4.4** Temperature based criteria met out of 5, plus frost frequency criteria, for lemons under historical climatic conditions (1950-1999; left) and under projected intermediate future climate conditions (2046-2065; right), based on outputs from multiple GCMs

An Overall Word of Caution

Other Impacts of Climate Change

*Rind Colour*
*Winter Dormancy*
*Water Requirements*

Other Climate-Related Sensitivities in Citrus Production

*Increased CO₂ Concentrations*

*Additional Storage and Transport Costs Due to Higher Outside Temperatures*
Other South African Findings

Adapting South Africa's Citrus Industry to Projected Climate Change
Aligning Citrus Cultivars to Projected Climatic Conditions
Shade Nets
Other Adaptation Strategies for Citrus

Further Reading

Please cite as follows:
**E4 CITRUS FRUIT PRODUCTION IN SOUTH AFRICA AND CLIMATE CHANGE**

**Introduction** [From Citrus Fruits, 2015]

Citrus fruits are a subtropical fruit, but can tolerate light frost. Cultivars vary in climatic requirements and each type should be looked at individually. Highest production is obtained in areas with a well-defined cold-induced dormancy period or a moisture stress period.

The citrus industry in South Africa is older than 300 years, with currently more than 20 million citrus trees planted on 58 000 ha. With approximately 1 300 producers growing for export and 2 200 smaller producers, over 100 000 workers are employed in the sector. Production is split as follows:

- 70 % oranges,
- 16 % grapefruit,
- 7 % naartjies and
- 7 % lemons.

Each of the above types of citrus fruit has a range of different cultivars that mature from early to late and/or have unique characteristics, such as red pigmentation. There are approximately 210 commercial varieties being planted in South Africa.

Citrus is grown in three different climatic regions and on a significant scale in five of South Africa’s provinces, with production as follows:

- Limpopo 31%
- Eastern Cape 23%
- Mpumalanga 21%
- Western Cape 17%
- KwaZulu-Natal 7%
- Other Provinces 1%

The sector is operated through the Citrus Growers Association of Southern Africa, CGA, with main mandates to
- ensure that the industry retains a competitive edge in the global marketplace
- support the endeavours of its members to operate profitably in a highly demanding and challenging environment
- enable the South African citrus producers to stand proudly when evaluated against the socio-economical and socio-political challenges posed by our unique and diverse regions and communities

The CGA further aims to maximise the long-term profitability of its members by
- providing the industry with access to, and retention within, global markets,
- optimising cost effective production of, and setting standards for, quality fruit,
- continual commitment to funding research, development and stakeholder communication
- caring for the environment and the community within which members operate.

The growers are organised into regions as follows: Western Cape, KwaZulu-Natal Midlands, Onderberg-Nelspruit, Letsitele-Limpopo, N Cape-Senwes Transvaal, Swaziland, Zimbabwe, Boland, Sundays River Valley, Patensie, Eastern Cape-Midlands, Hoedspruit, Nkwalini and Pongola.

**Citrus Growing Areas in South Africa and Broad Climatic Suitability for Certain Cultivars** [From Citrus Fruits, 2015]

**Citrus Growing Areas by Climatic Zones**
Areas where citrus can be grown in South Africa include
the cool coastal areas of the Eastern and Western Cape, the semi-tropical areas of Limpopo, Mpumalanga and KwaZulu-Natal, and the more tropical areas of the likes of Nelspruit and Letaba.

This variation of climate helps bring to the industry the advantage of having a variety of different cultivars available at different times.

In South Africa suitable areas for citrus are grouped together in four climatic zones, which are:

<table>
<thead>
<tr>
<th>Cold Areas</th>
<th>Cool, Inland Areas</th>
<th>Intermediate Areas</th>
<th>Hot Areas with Low and High Humidity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>High Humidity- Malelane, Komatipoort, Swaziland Lowveld, Pongola, Nkwalini</td>
</tr>
</tbody>
</table>

Climatic Suitability of Cultivars by Climate Zone
Citrus fruits in South Africa are divided into cultivar groups because of their origin, characteristics and ripening times. Each cultivar group has a unique climatic requirement that is dependent on temperature, heat units, day length and light and humidity. The cultivar groups are as follows:
- Mandarins and hybrids
- Lemons and limes
- Grapefruit
- Navel oranges
- Midseason varieties
- Valencia oranges
- Pumelo types and
- Kumquats

These cultivars dominate differently in the different climatic zones shown above.
- Cold Areas: Mandarins, lemons, navel oranges, certain Valencia oranges
- Cool Inland Areas: Valencia oranges, lemons, navel oranges, certain mandarins, mid-seasons
- Intermediate Areas: Valencia oranges, midseasons, lemons, certain navel oranges and grapefruit (marginal)
- Hot Areas: Valencia oranges, grapefruit, lemons, navel oranges (marginal) and mandarins (marginal)

Soil Requirements
The best soils can loosely be grouped as well drained sandy soil, sand loam, clay loam and clay soils, ideally with 15-25% clay (above 30% is marginal), a pH 6.5 and 7.5, no salts in the
top 0.50 m, a soil depth of 0.50 m to 1 m and no stratified alluvium in top 0.5 m. Soil preparation is essential to optimize citrus production.

**Yields**

Within an orchard yield varies greatly from tree to tree, while for a single tree yield varies from year to year. Sometimes a two-year fruit bearing cycle occurs. Good yields of citrus are:
- orange - between 400 and 550 fruits per tree per year corresponding to 25 to 40 tons per ha per year;
- grapefruit - 300 to 400 fruits per tree per year and 40 to 60 tons per ha;
- lemons - 30 to 45 tons per ha per year; mandarin - 20 to 30 tons per ha per year.

The water utilization efficiency for harvested yield for citrus fruits is about 2 to 5 kg/m$^3$ with a moisture content of the fruits of about 85%, except for lime which contains about 70% moisture.

**More Specific Climate Requirements of Cultivars**

While specific climatic requirements for the various citrus cultivars vary slightly from reference to reference, the criteria used in this study for mapping impacts of projected climate change on shifts in optimum and sub-optimum areas, and listed below, were those by Smith (2006), with values in [ ] from the F&NPK (2006) document.

**Navel Oranges**

This is an early variety, thriving best under cool to cold winter conditions, with warm summers and low humidity. If conditions are too warm, small fruit is produced and maturation is too early, resulting in a decline in juice acid content. High temperatures cause ‘November drop’. A maximum temperature of > 40°C for one day in spring will reduce yields by up to 6%.

Temperatures for optimal yields and quality are:

<table>
<thead>
<tr>
<th>Temp</th>
<th>Winter (Nov-Dec)</th>
<th>Summer (Jun-Aug)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{\text{max}}$</td>
<td>26.0-30.0°C</td>
<td>22.5-24.5°C</td>
</tr>
<tr>
<td>$T_{\text{min}}$</td>
<td>&gt; 14.5°C</td>
<td>&lt; 17.9°C</td>
</tr>
<tr>
<td>$T_{\text{ave}}$</td>
<td>&lt; 13.0°C</td>
<td>&gt; 2.0°C</td>
</tr>
</tbody>
</table>

Heat units, annual (Base 10°C) 2 000 – 3 000

[Base 13°C: 1600-1900]

**Valencia Oranges**

This variety is the last to mature (July-October), and is adaptable to many areas. It will tolerate a wide range of winter conditions from cold to hot. It requires warmer and more humid conditions than navels.

Temperatures for optimal yields and quality:

<table>
<thead>
<tr>
<th>Temp</th>
<th>Winter (Dec-Feb)</th>
<th>Winter (Nov)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{\text{max}}$</td>
<td>28.0-35.0°C</td>
<td>20.0-30.0°C</td>
</tr>
<tr>
<td>$T_{\text{min}}$</td>
<td>&lt; 27.2°C</td>
<td>&lt; 15.0°C</td>
</tr>
<tr>
<td>$T_{\text{ave}}$</td>
<td>&gt; 12.0°C</td>
<td>&gt; 6.0°C</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Temp</th>
<th>Summer (Jul)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{\text{max}}$</td>
<td>12.0-16.0°C</td>
</tr>
<tr>
<td>$T_{\text{min}}$</td>
<td>6.0-11.5°C</td>
</tr>
<tr>
<td>$T_{\text{ave}}$</td>
<td>12.0-16.0°C</td>
</tr>
</tbody>
</table>
Heat units (Base 10°C) 2 000 to 4 000 (wide tolerance)  
[Base 13°C: 1 200 to 3 500 (wide tolerance)]

**Grapefruit**
Grapefruit have a short fruit developmental cycle. Unlike navel oranges, grapefruit require a warm, humid climate with a relatively short, warm winter. They are a high acid fruit which require heat for acid to decline to an acceptable level.

Temperatures for optimal yields and quality:
- \( T_{\text{max}} \) (Jan) 30.0-35.0°C
- \( T_{\text{max}} \) (Jul) 22.5-24.5°C
- \( T_{\text{min}} \) (Jan) 19.0-21.5°C
- \( T_{\text{max}} \) (Jul) > 8.0°C
- \( T_{\text{ave}} \) (Jul) 15.5-17.5°C
- Absolute \( T_{\text{min}} \) 0.0- 1.0°C

Heat units (Base 10°C) 3 000 to 4 550 (wide tolerance)

**Lemons**
Lemons are adapted to a wide range of climatic conditions. In hotter areas trees produce one large main crop from February to March with a large fruit size. In cooler areas, the main crop is produced from May to July with a smaller fruit size. Trees also produce two to three crops at other times of the year.

Temperatures for optimal yields and quality:
- \( T_{\text{max}} \) (Jan) 26.0-35.0°C
- \( T_{\text{max}} \) (Jul) <25.0°C
- \( T_{\text{min}} \) (Jan) <21.0°C
- \( T_{\text{min}} \) (Jul) > 8.0°C
- \( T_{\text{ave}} \) (Jul) <17.0°C
- Absolute \( T_{\text{min}} \) (Jul) – 3.0°C

Mapping Optimum Growing Areas of Citrus Cultivars in South Africa and Impacts of Projected Climate Change on Growing Areas

**Navel Oranges**
Maps of the number of temperature related criteria met out of 7 for Navel oranges (see Section above) under historical climatic conditions and for projected intermediate future conditions are shown in Figure E4.1. Areas where most criteria are met under historical (1950 – 1999) conditions are concentrated in the south and west of the Western Cape, and parts of the KwaZulu-Natal interior, Mpumalanga and North-West Province. These are not necessarily the areas of most current production. Note, however, that no consideration has been given in the map of rainfall, humidity criteria, nor of suitable soils.

Projecting into the intermediate future (Figure E4.1 right), there appears a distinct concentration of high numbers of temperature criteria met simultaneously in the Karroo, the eastern and central Free State, Gauteng and parts of the Eastern Cape and Mpumalanga – which may imply future shifts in production areas of Navel oranges.

According to the 12 temperature based criteria identified by Smith (2006) for Valencia oranges, ideal production areas under current climatic conditions occur in an arc from the KwaZulu-Natal coastal hinterland through the middleveld of Swaziland, Mpumalanga, much of Limpopo and into North West (Figure E4.2 left). Into the intermediate future (2046-2065) this arc extends westwards and into the Northern Cape, and intensifies in places (Figure E4.2 right). These projected shifts are not as drastic as were those for Navels.
Figure E4.2  Temperature based criteria met out of 12 for Valencia oranges under historical climatic conditions (1950-1999; left) and under projected intermediate future climate conditions (2046-2065; right), based on outputs from multiple GCMs

**Grapefruit**

Under current climatic conditions near-ideal production areas for grapefruit, according to the temperature criteria of Smith’s (2006), are the frost-free zone along the eastern border of South Africa extending from the northern coastal zone of KwaZulu-Natal through the lowveld of Swaziland, into the eastern parts of Mpumalanga and Limpopo and extending westwards along the northern border of the country (Figure E4.3 left).

This pattern alters significantly into the intermediate future (Figure E4.3 right), with the perimeter of much of South Africa being moderately suitable for grapefruit production (3 to 4 temperature criteria met out of 6), and where 5 criteria are met in the Northern Cape and North West, protection against frost would have to become an important adaptation mechanism.

**Lemons**

According to Smith (2006), 5 temperature criteria have to be met for areas to be climatically optimum for lemon production, in addition to considering frost occurrence. Four and 5 of these criteria are met under historical (1950-1999) climatic conditions in arc around South
Africa’s western, southern and eastern coastal areas and their hinterlands and including most of Swaziland, the eastern parts of Mpumalanga and much of Limpopo (Figure E4.4 left).

**Figure E4.3** Temperature based criteria met out of 6, plus frost frequency criteria, for grapefruit under historical climatic conditions (1950-1999; left) and under projected intermediate future climate conditions (2046-2065; right), based on outputs from multiple GCMs.

Into the intermediate future (2046-2065) optimum production areas shift somewhat to a circle around the perimeter of South Africa, essentially eliminating only areas that are too hot in the east and north and areas that are too cold and frost prone in the central parts (Figure E4.4 right).

**Figure E4.4** Temperature based criteria met out of 5, plus frost frequency criteria, for lemons under historical climatic conditions (1950-1999; left) and under projected intermediate future climate conditions (2046-2065; right), based on outputs from multiple GCMs.

*An Overall Word of Caution*
It should be emphasised that in the above assessments only broad temperature, and no other climatic factors such as humidity (important re. pests and diseases) or hail or daily threshold temperatures (for sunburn and other damage), have been considered in this analysis, and that the assumption is that any of the citrus cultivars would be irrigated and that water availability would not be an issue. Additionally, in this analysis soil attributes have not been factored in.

**Other Impacts of Climate Change** [From: SmartAgri, 2016; WRC Project 1882, 2016]

Although only few studies have been conducted in South Africa directly on the impacts of climate change on citrus production, some of the other local studies have relevance for understanding the climatic requirements of successful production.

**Rind Colour**
Rind colour of citrus fruit, which develops after the so-called ‘colour break’, is largely determined by prevailing weather conditions during fruit maturation and is linked to the passing of ‘cold fronts’ in the southwestern Cape and possibly to cold shocks. The most favourable temperature combination leading to a bright orange citrus rind is mild days, cold night air temperatures and cool soil temperatures. Large day-night temperature fluctuations are particularly beneficial for excellent fruit colour. A day/night temperature of 20°C/5°C appears to be optimal, whereas a day/night temperature of 30°C/10°C produces less well-coloured fruit. It is thought that high day temperatures may inhibit colour development even if night temperatures are adequately low.

**Winter Dormancy**
Citrus requires cool winters to induce a degree of dormancy (e.g. soft citrus and Navels) and for the induction of flowering. However, no published studies are available for South African conditions, but it is important of considering location-specific phenophases and their shifts with climate change within given regions, as dissimilar trends may occur within a country. Hot conditions during the period of fruit set are detrimental to set and yield. Local studies are underway to identify the impacts of winter dormancy.

**Water Requirements**
Citrus trees require water all year round, provided by a combination of rainfall and irrigation. Some local research on citrus water relations has been conducted, but no climate change simulations have been attempted. Higher temperatures are likely to increase crop water requirements, with more water being needed per irrigated hectare. Citrus is sensitive to water stress, with flowering and fruit-set periods being the most critical phases, and several studies have reported negative effects of low water availability on growth, yield and fruit quality. It is anticipated that increases in irrigation requirement will be approximately 6-8% and 15-20% for the 2050s and 2080s, respectively.

**Other Climate-Related Sensitivities in Citrus Production**
These include frost, flooding, soil salinity, wind, and air pollution such as ozone. No information is readily available on how these may affect citrus production in South Africa in the future, with the exception of frost, which is expected to become less problematic as minimum temperatures rise.

**Increased CO₂ Concentrations**
A considerable amount of research has been conducted internationally on the effects of rising atmospheric CO₂ concentrations on citrus physiology and production, with biomass and yields expected to increase significantly (in some cases > 50%) through CO₂ fertilization, with the greatest increases projected for warm and dry regions. However, to date no studies have been conducted in South Africa.
**Additional Storage and Transport Costs Due to Higher Outside Temperatures**

Different citrus cultivars have different optimum storage and transport temperatures, and with rising ambient temperatures costs of cooling are expected to increase. Storage temperature criteria are given below.

- **Grapefruit**
  
  The optimum storage and transport temperature of grapefruit varies between 16°C and 8.5°C. The standard procedure is however to constantly maintain the dry air temperature (DAT) at 7.0°C to ensure an average pulp temperature of 8.5°C. Early season fruit still requiring external skin colouring, however, should be stored and shipped at 16°C, while optimum storage temperature of well coloured fruit is 10°C. Cold treatment to control quarantine pests during storing and shipping should be below 0.0°C.

- **Lemons**
  
  Optimum commercial storage temperature of lemons is 7.0°C to 10.0°C with a relative humidity of 95%. The warmer temperature of 10°C is used at the beginning of the season to enhance colour development. The optimum shipping temperature is 7.0°C. Lemons to destination requiring in transit cold treatment must be precooled and shipped below 0.0°C depending on the requirements of the importing country.

- **Limes**
  
  Optimum storage temperature of limes is 11.0°C with a RH of 95%.

- **Oranges**
  
  Oranges store best at a pulp temperature of 4.5°C. Early season oranges can be stored and transported at 11°C to promote external colour development. Prompt cooling soon after harvest should be applied and optimum pulp temperature should be reached within 6 days from harvest.

- **Soft Citrus**
  
  Soft citrus, easy peelers or mandarins are common names for this group of citrus cultivars which are stored optimally at 3.5°C at a RH of 95%. Soft citrus is sometimes kept at 11.0°C for relatively short periods to stimulate colour development should it be required.

**Other South African Findings**

Modelling results show that an increase in average temperatures and seasonal shifts are the biggest threats that the citrus industry in Mpumalanga faces, with the following problems associated with increased temperatures:

- Quality losses in citrus as a result of sunburn
- Reduction in citrus fruit set as a result of sunburn
- Seedless citrus cultivars being less tolerant to increased temperatures than seeded cultivars, however, with the demand being for seedless cultivars; and
- The projected decrease in yield and quality as a result of climate change likely to impact on the food value chain through
  - lower production volumes
  - lower fruit quality and
  - increased prices, and
- a slight decrease in profitability, although farming operations will still be profitable, with farmers with high debt levels ratios likely more financially vulnerable than those with low debt levels.

All-in-all, however, citrus fruit production in cooler core global production regions (such as the USA) may benefit from climate change due to the reduced incidence of very cold weather, and warming combined with increased rainfall. The responses in much of South Africa are likely to be more similar to other production regions where warming and drying are projected, such as Spain, and citrus could well benefit, with new production areas opening up provided that access to sufficient irrigation water is not limiting.

**Adapting South Africa’s Citrus Industry to Projected Climate Change**
Aligning Citrus Cultivars to Projected Climatic Conditions
The section above with maps on optimum production areas of Navel oranges, Valencia oranges, grapefruit and lemons refers, and findings are not repeated here.

Shade Nets [From WRC Project 1822, 2016]
A key adaptation strategy to counter the impact of climate change on financial vulnerability is to install shade nets over citrus production areas to reduce, inter alia, hail damage. The installation of shade nets proves to lessen the impact of climate change on financial vulnerability to a certain extent and seems worthwhile to investigate further, given the high initial capital outlay.

Furthermore, while water use efficiency (WUE) is a key concept to solve water shortage problems in semi-arid areas, shade net structures in semi-arid and arid environments can be considered as an intermediate solution for increasing WUE and reducing plant water stress. It offers many advantages and environmental benefits, and that is why an increasing area of citrus in South Africa is being grown under shading materials of various types. It was found that the use of the shading net reduces wind speed within the foliage and helped to decrease fruit drop. The shade provided by the net does not affect yield and internal fruit quality (ratio of sugar to acid), but may increase fruit average weight and diameter.

The shade nets over citrus can eliminate many of the threats associated with projected climate change and will have the following advantages:
• Improvement in citrus fruit quality by reduced damage from hail, wind and sun,
• Less stress on the citrus tree, resulting in more consistent yields, and
• More effective use of irrigation water to the citrus tree because of reduced evapotranspiration.

Other Adaptation Strategies for Citrus [From WRC Project 1822, 2016]
The following adaptation strategies were identified by farmers and other role-players who were interviewed in the course of WRC Project 1882 (in no specific sequence):
• Changes in cultivars to align with projected changes in temperature regimes
• Ridging (to improve drainage)
• Assessing the availability of irrigation water into the future, as this is critical to the citrus industry, with projections of flow into and from the supply dams being of paramount importance
• More effective management of irrigation systems, in particular migrating to drip irrigation in order to improve the accuracy to soil moisture control
• Using rootstocks which can cope better with pathogens
• Focusing on cultivar development to increase natural heat resistance
• Use of mulching cover to conserve moisture

The successful application of the above adaptation strategies will largely eliminate the negative effects of climate change on the food value chain of citrus.

Further Reading
SmartAgri, 2015. Chapter 9 Climate change risk and impact, and Chapter 10 Current responses: Adaptation and risk management. A Status Quo Review of Climate Change and the Agriculture Sector of the Western Cape Province. Western Cape Department of
Agriculture and Department of Environmental Affairs and Development Planning, Cape Town, RSA.

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
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 th 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](image)

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

**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](image)

**Figure A5.2** Flowpaths between Quinary and Quaternary Catchments

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-MIROC 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
  - NCC-NorESM1-M_historical_RCA5_1976
  - NCC-NorESM1-M_rcp85_RCA5_2016

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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><strong>MODEL STRUCTURE</strong></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><strong>MODEL TIME STEP</strong></td>
<td>Monthly / annual</td>
<td>Daily</td>
<td>Daily</td>
</tr>
<tr>
<td><strong>CLIMATE VARIABLES</strong></td>
<td>Rainfall, Temperature - maximum - minimum Heat units</td>
<td>Rainfall, Temperature - maximum - minimum Reference potential evaporation CO₂ transpiration feedback</td>
<td>Rainfall, Temperature - maximum - minimum Solar radiation Reference potential evaporation CO₂ transpiration feedback</td>
</tr>
<tr>
<td><strong>SOIL VARIABLES</strong></td>
<td>Single horizon Thickness Texture class Normative weighting (Deep → shallow) (Clay → sand)</td>
<td>1 - 2 horizons Horizon thicknesses Retention constants Drainage/ permeability</td>
<td>Multiple horizons Horizon thicknesses Retention constants Drainage/ permeability Soil physics Soil chemistry - pH, C, N Previous crop residue - O, C:N, root, depth</td>
</tr>
<tr>
<td><strong>MANAGEMENT OPTIONS</strong></td>
<td>Normative Weighting (Excellent → poor)</td>
<td>Plant date Cultivar attributes Tillage options</td>
<td>Plant date Cultivar attributes Plant density/row spacing N-fertilization Tillage options</td>
</tr>
</tbody>
</table>
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,
- 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.

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.

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
- \( P_{ms} \) = accumulated rainfall (mm) for May to September (inclusive) for \( P_{ms} < 850 \) mm

where

\[ ASM + P_{ms} \]

with

\[ H_{wi} = \text{accumulated heat units (base 4.4 °C) in degree days for the period May to September.} \]

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

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 climates.
- 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.
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 CO$_2$ 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


1 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>
<th>LOCATIONAL</th>
<th>CATCHMENT</th>
<th>CLIMATIC</th>
<th>HYDROLOGICAL</th>
<th>LAND CHANGE</th>
<th>AGRONOMIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>SOILS</td>
<td>RESERVOIR</td>
<td>LAND USE</td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

**OPERATIONAL MODES**

<table>
<thead>
<tr>
<th>OPERATIONAL MODES</th>
<th>SOIL WATER BUDGETING/ TOTAL EVAPORATION MODELLING</th>
</tr>
</thead>
<tbody>
<tr>
<td>POINT OF LUMPED or DISTRIBUTED MODES or (L.S. LINKED)</td>
<td></td>
</tr>
<tr>
<td>DYNAMIC TIME or ANNUAL CYCLIC CHANGE</td>
<td></td>
</tr>
</tbody>
</table>

**SIMULATION OPTIONS / COMBINATIONS**

<table>
<thead>
<tr>
<th>EXECUTION 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>
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<tr>
<td>CROP YIELD</td>
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<table>
<thead>
<tr>
<th>OUT</th>
<th>Daily</th>
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<tbody>
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<td>PUT</td>
<td>Monthly</td>
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<td></td>
<td>Annual</td>
</tr>
<tr>
<td></td>
<td>Risk Analyses</td>
</tr>
</tbody>
</table>

**SPECIFIC OBJECTIVES / COMPONENTS**

- Stormflow, baseflow, peak discharge, hydrograph: generation, routing, EV analyses
- Runoff, normal flow, evaporation, infiltration
- Sediment: generation, reservoir, evaporation
- Crop demand: - on demand, fixed cycle, deficit, from reservoir
- Form: - reservoir, river and reservoir, storage, return flows
- Gradual change: - abrupt change, total evaporation, tillage practices, wetlands

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
Agriculture Related
- Carbon dioxide (CO$_2$) Fertilization
- Food System
- Crop Modelling
- C3 and C4 plants
- Drought

Terms in General Usage
- Anthropogenic
- Stakeholders
- Participation
- Capacity Building
- Empowerment

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 CO₂, CH₄, N₂O, 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 CO₂ concentrations to 1.5 times pre-industrial revolution values, or to an effective doubling of CO₂, 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).

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**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”.

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
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 ones 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 CO$_2$ 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.