ASSESSMENT OF AGRO-ECOSYSTEM SUSTAINABILITY ACROSS VARYING SCALES IN SOUTH AFRICA

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DECLARATION

The research described in this thesis was carried out within the School of Bioresources Engineering and Environmental Hydrology, University of KwaZulu-Natal, Pietermaritzburg, under the supervision of Professor R.E. Schulze (School of Bioresources Engineering and Environmental Hydrology, University of KwaZulu-Natal).

I hereby certify that the research results in this thesis are my own original investigation except where acknowledged.

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ABSTRACT

Maize production plays an important socio-economic role in rural communities of the Highveld region of South Africa, yet it is becoming increasingly difficult to produce maize economically with current agricultural policy conditions and existing management systems. This has direct socio-economic impacts for both commercial farmer and small-scale farmer. Sustainable commercial maize production is not only a question of yields, but also of protection of the environmental resource base, social welfare, and the livelihoods of farmers *per se* as well as the surrounding rural and urban communities. Sustainability for the small-scale farmer, on the other hand raises questions of equity, economic viability and household food security. Therefore, information is required to ascertain whether an existing agro-ecosystem can be identified as sustainable, and what facets of that system make it sustainable or unsustainable. To begin to answer these key questions it is important to state, and to some extent attempt to standardise, the definitions of agricultural sustainability.

Agro-ecosystem sustainability with regard to maize production was assessed at the regional scale of the Highveld of South Africa as well as at, the Quaternary Catchment scale and the smallholder farm scale. Von Wiren-Lehr's (2001) goal orientated system was considered an appropriate and practical system by which agro-ecosystem sustainability across a range of scales could be investigated.

At the regional scale, optimum management strategies for each of the 497 Quaternary Catchments in the Highveld region were devised, based on present climatic conditions and using an index which was based on mean yields and yield variability. Economic returns and their impact on sustainability were then also assessed under plausible future climate scenarios.

At the Quaternary Catchment scales optimum management strategies were ascertained by using a sustainability index. These strategies were then modelled under present and plausible future climate scenarios. The results from the sustainability modelling showed that a maize crop will benefit, especially with respect to mean grain yields, from an effective doubling of atmospheric CO_2 concentrations. However, this benefit can be counteracted when there is a concurrent increase in temperature, particularly of 2°C or more.

At the smallholder scale, a range of management options was assessed. These options included several types of tillage practices in combination with applications of either inorganic fertiliser or manure. The management strategies were modelled under present climate conditions and under plausible climate change scenarios for southern Africa. The conventional tillage type (disc) was ranked highest under most of the climatic conditions modelled, including present climate conditions. This was in contrast to actual yields from smallholder farmers (~1 ha field size) in the Potshini area, near Bergville in the KwaZulu-Natal province of South Africa, who have experienced an increase in yield when conservation tillage practices have been used on their land (Smith *et al.*, 2004).

The sustainability of agro-ecosystems depends on the maintenance of the economic, biophysical and social components that make up the system (Belcher *et al.,* 2004). The modelling performed for the Highveld region built on previous work and for the first time incorporated daily temperatures and ISCW soil information into CERES-Maize. The intention was to incorporate other agro-ecosystem functions, as well as yield, into the sustainability assessment. Only limited research has previously been carried out in South Africa with respect to modelling smallholder agro-ecosystems and sustainability. This research sought to model the smallholder system along with the impacts that climate change would have on sustainability and associated food security.

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LIST OF ABBREVIATIONS

ACRU = Agricultural Catchments Research Unit
APSIM = Agricultural Production Systems Simulator
ARC = Agricultural Research Council
BEEH = Bioresources Engineering and Environmental Hydrology
CERES = Crop Environment Resource Synthesis
CO_2 = Carbon dioxide
CV = Coefficient of Variation
DSSAT = Decision Support System for Agrotechnology Transfer
DWAF = Department of Water Affairs and Forestry
ESI = Environmental Sustainability Index
FAO = Food and Agriculture Organisation of the United Nations
GAPS = General-purpose Atmosphere Plant Soil Simulator
GCM = General Circulation Model
GIS = Geographic Information System
IBSNAT = International Benchmark Sites Network for Agrotechnology Transfer
ICASA = International Consortium for Agricultural Systems Applications
ICT = Information and Communication Technology
ISCW = Institute for Soil, Climate and Water
MAP = Mean Annual Precipitation
PC = Personal Computer
QC = Quaternary Catchment
QCDB = Quaternary Catchments Database
RMSE = Root Mean Square Error
SCS = Soil Conservation Service
UK = United Kingdom
UKZN = University of KwaZulu-Natal
UN = United Nations
UNCED = United Nations Conference on Environment and Development (1992)
UNDP = United Nations Development Programme

USA = United Sates of America
USDA = United States Department of Agriculture
WCED = World Commission on Environment and Development
WRC = Water Research Commission

1 INTRODUCTION AND OBJECTIVES

'God has lent us the earth for our life; it is a great entail. It belongs as much to those who are to come after us, and whose names are already written in the book of creation, as to us; and we have no right, by anything we do or neglect, to involve them in unnecessary penalties, or deprive them of benefits which it is our power to bequeath' (Ruskin, 1925; pp. 337-338).

The underlying concepts of Ruskin's statement have re-emerged in the past thirty years or so with growing concern about global environmental problems, issues surrounding development and also food security. The basic concept of sustainability is not new, but now has wider recognition as a goal worth achieving.

The term sustainability is used in phrases such as sustainable planet, sustainable development and sustainable agriculture, and numerous definitions of these phrases have been offered, with wide ranging perspectives. The meaning of sustainability, therefore, 'is strongly dependent on the context in which it is applied and on whether its use is based on a social, economic, or ecological perspective. Sustainability may be defined broadly or narrowly, but a useful definition must specify explicitly the context as well as the temporal and spatial scales being considered' (Brown *et al.*, 1987; p. 713).

A literal definition of sustainability would be 'the capacity to continue into the future indefinitely' (Ekins, 1995; p.186). However, sustainability has been defined using ideas from many sources including physics, ecology, anthropology, philosophy, economics and psychology. These ideas can be synthesised into a rational, interdisciplinary analysis of the potential for sustaining industrial civilisation (Pezzey, 1992).

The term sustainability has been used to refer to both sustainable development and sustainable resource use and is generally accepted as an objective that is desirable to attain. Even with problems of ambiguity in defining sustainability, O'Riordan (1993) remarks that sustainable development has become as an enduring a political concept as democracy, justice and liberty. Maser (1997; p.16) warns against a half-hearted approach to implementing sustainability and maintains that 'sustainability is an absolute. A system is either sustainable in a given state or it is not; there are no degrees of sustainability'.

In 1987 the report on the World Commission on Environment and Development (WCED), commonly referred to as the Brundtland Report, defined sustainable development 'as development that meets the needs of the present without compromising the ability of future generations to meet their own needs. Sustainable development requires meeting the basic needs of all and extending to all the opportunity to satisfy their aspirations for a better life' (WCED, 1987; p.43).

The aim of sustainable development is to improve quality of life, not merely to raise the standard of living, and it is based on a broad definition including social, environmental and economic factors. It views these factors as inter-linked. It considers the needs of future generations as well as those of people today, and seeks to avoid problems in the future by acting today. This type of development also takes into consideration the views of all the people who are stakeholders in any proposed project. Clearly all stakeholders will be part of the current generation, but by applying long term views to projects, future generations can be considered. This is discussed further in Section 2.7. A proposed project is, therefore, planned by co-operation between organisations and the general public so that the plans and proposals will meet peoples' needs. It also balances the importance of the individual with the rights of collective responsibility.

The concept of sustainability needs to be applied to agriculture. Agro-ecosystems are ecological systems modified by human beings to produce food, fibre or other agricultural products (Conway, 1987). In order to be able to predict with any degree of certainty what is sustainable over the long-term, and in turn to design sustainable agro-ecosystems, specific questions about agro-ecosystem functions need to be answered. It is, therefore, necessary to determine what sustainability encompasses and what the key functions of that agro-ecosystem are, as well as determining the degree to which these functions must be maintained. A working definition for this thesis is given in Section 2.7. By undertaking this process, indicators of sustainability can be identified along with those conditions which are necessary for specific agro-ecosystem sustainability (Gliessman, 2001).

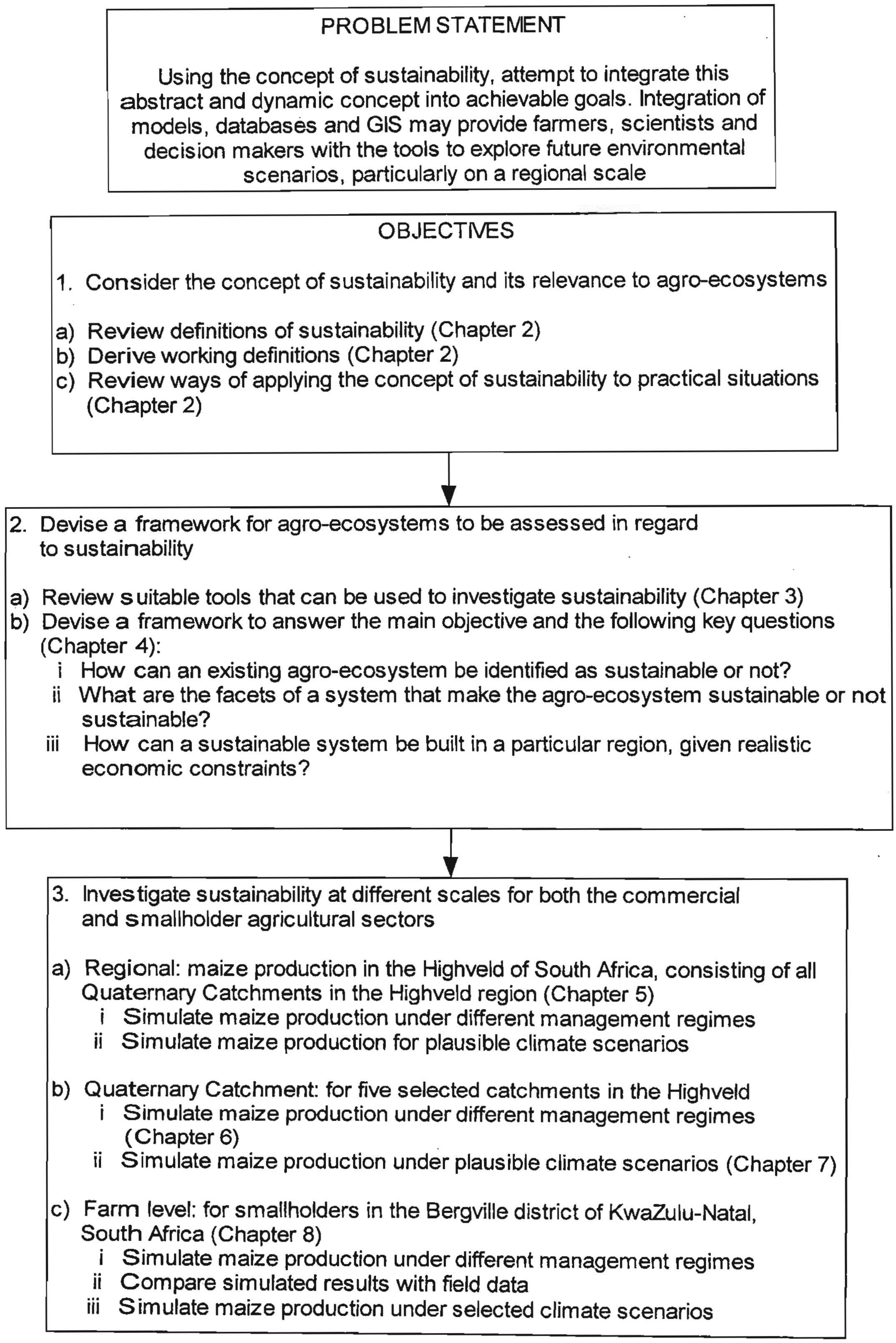
The question of whether an agro-ecosystem is sustainable or not encompasses a wide range of topics which include climate variability and change, management practices, government policy, equity, food security, livelihoods and biodiversity. There is a lack of knowledge in how to maintain the ecological integrity of an agro-ecosystem should a major perturbation occur (O'Riordan, 2002).

For example, a change in the mean climate, or an increase in climatic variability, will have complex impacts on the agro-ecosystem. Climate comprises of complex relationships between variables such as temperature, precipitation, evaporation, wind, and cloud. Such relationships are generally independent of atmospheric carbon dioxide (CO_2), but CO_2 and other greenhouse gases contribute largely through their effect on the radiation balance of the atmosphere. An increased level of CO_2 in the atmosphere has a positive influence on plant photosynthesis (Sombroek and Gommes, 1996).

The risk and uncertainty associated with agriculture affects all decisions made by the farmer. As a direct consequence, uncertainty can cause inefficiencies to occur in the agricultural sector along with concerns over food supply. Chen and Kates (1996) define a food-secure nation as one that provides security at all levels of human organisation from the individual household members, and their differing nutritional requirement, through to regional and national level. Agricultural sustainability is linked to the food security of a nation. The need for food security at different human organisational levels is of crucial importance, particularly in a developing nation such as South Africa which has a high variation in inter-seasonal rainfall. Agro-ecosystems are required to produce the food and fibre for the nation and consequently, sustainability is relevant to the issue of food security. Therefore, it is useful to consider agricultural sustainability at the same scales as food security.

Informed decision making under risk involves the combining of the decision makers' expectations about what is likely to happen in the future and individual preferences. Part of managing risk in agriculture consists of coping with the variability of production between years. At the household level it may be crucial for the farmer to minimise the fluctuations in household income over time, or to maintain or increase a particular wealth level and nutritional status. At the national level, governments have to ensure an adequate food supply to the population of all sectors of society (Thornton and Wilkens, 1998).

The primary objective of this thesis is to investigate sustainability in regard to maize production in South Africa (Figure 1.1). This objective was divided into three main sub-objectives:



PROBLEM STATEMENT

Using the concept of sustainability, attempt to integrate this abstract and dynamic concept into achievable goals. Integration of models, databases and GIS may provide farmers, scientists and decision makers with the tools to explore future environmental scenarios, particularly on a regional scale

OBJECTIVES

1. Consider the concept of sustainability and its relevance to agro-ecosystems

a) Review definitions of sustainability (Chapter 2)
b) Derive working definitions (Chapter 2)
c) Review ways of applying the concept of sustainability to practical situations (Chapter 2)

2. Devise a framework for agro-ecosystems to be assessed in regard to sustainability

a) Review suitable tools that can be used to investigate sustainability (Chapter 3)
b) Devise a framework to answer the main objective and the following key questions (Chapter 4):
   i How can an existing agro-ecosystem be identified as sustainable or not?
   ii What are the facets of a system that make the agro-ecosystem sustainable or not sustainable?
   iii How can a sustainable system be built in a particular region, given realistic economic constraints?

3. Investigate sustainability at different scales for both the commercial and smallholder agricultural sectors

a) Regional: maize production in the Highveld of South Africa, consisting of all Quaternary Catchments in the Highveld region (Chapter 5)
   i Simulate maize production under different management regimes
   ii Simulate maize production for plausible climate scenarios

b) Quaternary Catchment: for five selected catchments in the Highveld
   i Simulate maize production under different management regimes (Chapter 6)
   ii Simulate maize production under plausible climate scenarios (Chapter 7)

c) Farm level: for smallholders in the Bergville district of KwaZulu-Natal, South Africa (Chapter 8)
   i Simulate maize production under different management regimes
   ii Compare simulated results with field data
   iii Simulate maize production under selected climate scenarios

Figure 1.1 Objectives of this study

- First, consider the concept of sustainability and its relevance to agro-ecosystems.

- Secondly, devise a methodology (Figure 1.2) for agro-ecosystems to be assessed in regard to sustainability and one which can answer the following key questions (discussed in Chapter 4):
  - How can an existing agro-ecosystem be identified as being sustainable or not?
  - What are the facets of a system that make it sustainable or not sustainable?
  - How can a sustainable system be built in a particular region, given realistic economic constraints? (Gliessman, 2001; pp 3-4).
  - How will the agro-ecosystem respond to climate change?

- Thirdly, investigate agro-ecosystem sustainability of maize production under present climatic conditions and plausible future climate scenarios at the following scales:
  - Regional (Chapter 5), i.e. for maize production in the Highveld of South Africa, consisting of all the Quaternary Catchments in the Highveld region;
  - Quaternary Catchment (Chapters 6 and 7), i.e. for five selected catchments in the Highveld; and
  - Farm level (Chapter 8), i.e. for smallholders in the Bergville district of KwaZulu-Natal, in South Africa.

A review was carried out in Chapter 2, in which the concept, definition and problems of defining sustainability were explored, along with how to then apply sustainability to the decision making process. The definition of sustainable development and agricultural sustainability are difficult to put into practical terms. Sophocleous (2000) has stated that the challenge is to turn this type of definition into achievable policy goals. For example, how can the concept of sustainability with the multiple definitions and the ambiguity associated with it be put into practical terms and decisions? Working definitions derived from a literature review on sustainability are given in Section 2.7.

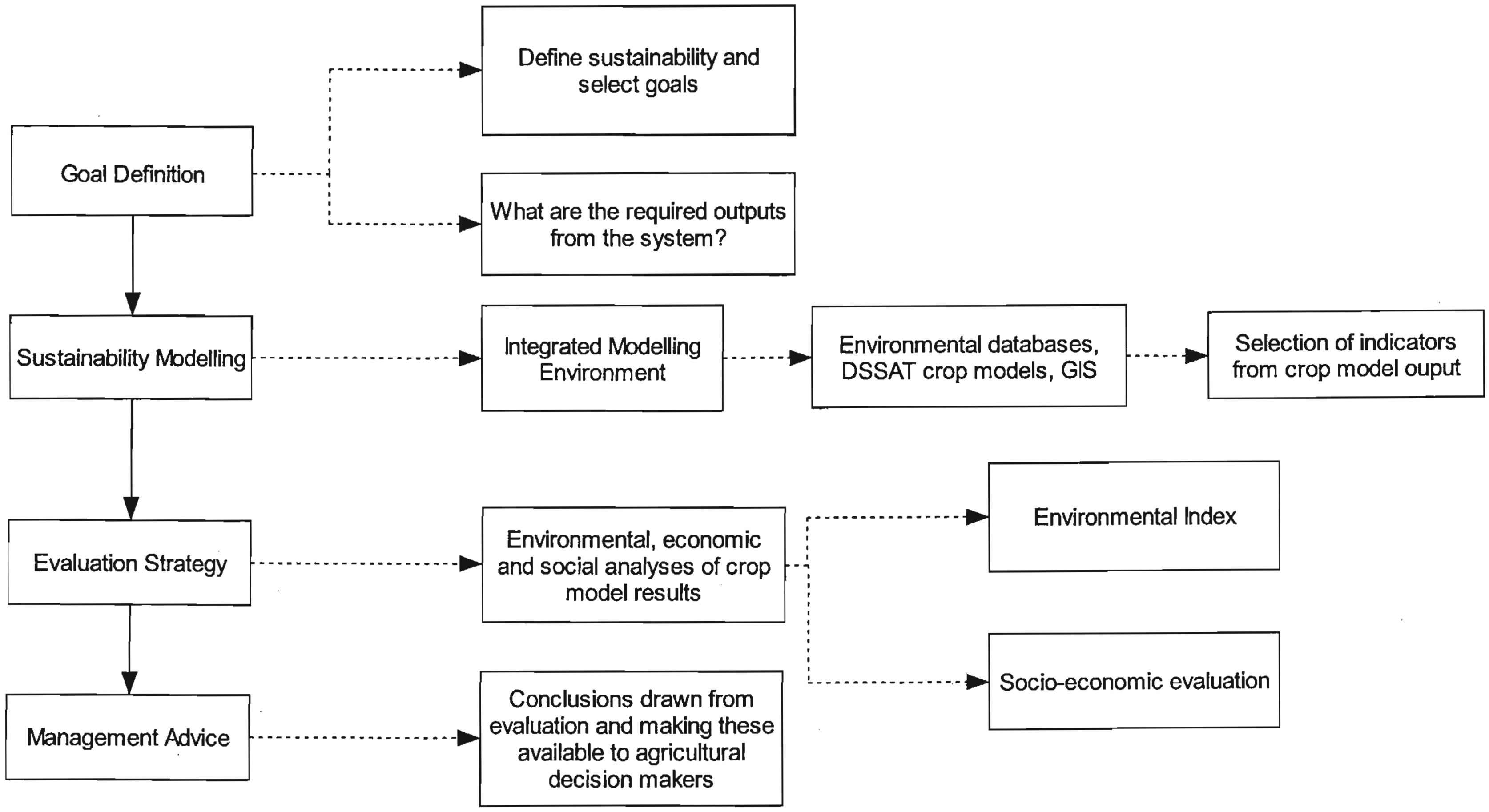


Figure 1.2 Adapted goal-orientated framework to assess agro-ecosystem sustainability (Chapter 4)

One way of implementing sustainable practices into development and agriculture is to adopt a systems approach and devise a framework to investigate sustainability (Chapter 4). Such a framework is required in any attempt to understand the inter-relationships between social, economic and environmental influences that are associated with sustainability. The framework can incorporate a number of tools such as complex crop models, environmental databases and geographic information systems (GIS).

The methodology devised was applied to various case studies which encompassed different scales from regional down to farm level and which considered both the commercial farmer and subsistence smallholder. On a regional scale (Chapter 5) maize production in the Highveld region of South Africa was chosen, as it is the major maize producing region of that country. The effects of climatic change on regional economic returns are assessed as well as the bio-physical and social aspects.

The Highveld region encompasses large tracts of the provinces of North-West, Free State, Gauteng and Mpumalanga (Figure 1.3). In this region, 70 per cent of agricultural land is used to grow cereals, with 90 per cent of South Africa's maize being grown here. As a result, maize production plays an important socio-economic role in the lives of the rural communities in the Highveld region. However, it is becoming increasingly more difficult to produce maize economically with existing management systems and this has a direct socio-economic impact on the already resource-limited inhabitants of the rural areas as well as on large scale commercial growers. Concerns remain about migration to cities, regional unemployment, illiteracy, HIV/AIDS and widespread poverty. Any policies implemented that have an influence on maize production and land use within the Highveld region will consequently influence sustainability and rural development.

According to research carried out by du Toit *et al.* (1999), maize yields decrease with decreasing rainfall in the western areas of the Highveld. The rainfall decreases are, furthermore, associated with increases in rainfall variability. Average maize yields in the drier western half of the Highveld are particular vulnerable to climate variability, with current average yields being between 1 and 3 tonnes per hectare, depending on farming practices and the amount of rainfall during the growing season. This raises food security issues at a regional and national level, as breakeven yields for a commercial farmer in the western Highveld of South Africa are just over 2 tonnes per hectare (du Toit *et al.*, 1999). Whether maize production is sustainable or not, is of huge consequence to the Highveld region. The sustainability of agriculture in the region will be influenced, *inter alia*, by the El Niño phenomenon, climate change and resulting land use changes. The El Niño phenomenon is one of the major factors causing droughts in South Africa. The influence of El Niño on the seasonal rainfall in the Highveld region is a reality for farmers, since it influences directly both the economic security and food security in the short term. Climatic changes such as increases in temperature and increased levels of carbon dioxide in the atmosphere also could also affect food security and agro-ecosystem sustainability in the long run. Irrigation is one possible option to reduce rainfall related risk in agriculture. However, in the western Highveld demand for water resources already exceeds supply so it is difficult to justify irrigation on a large scale. Rainwater harvesting and other water storage methods could play their part in reducing risk, particularly for the farmer that has few resources.

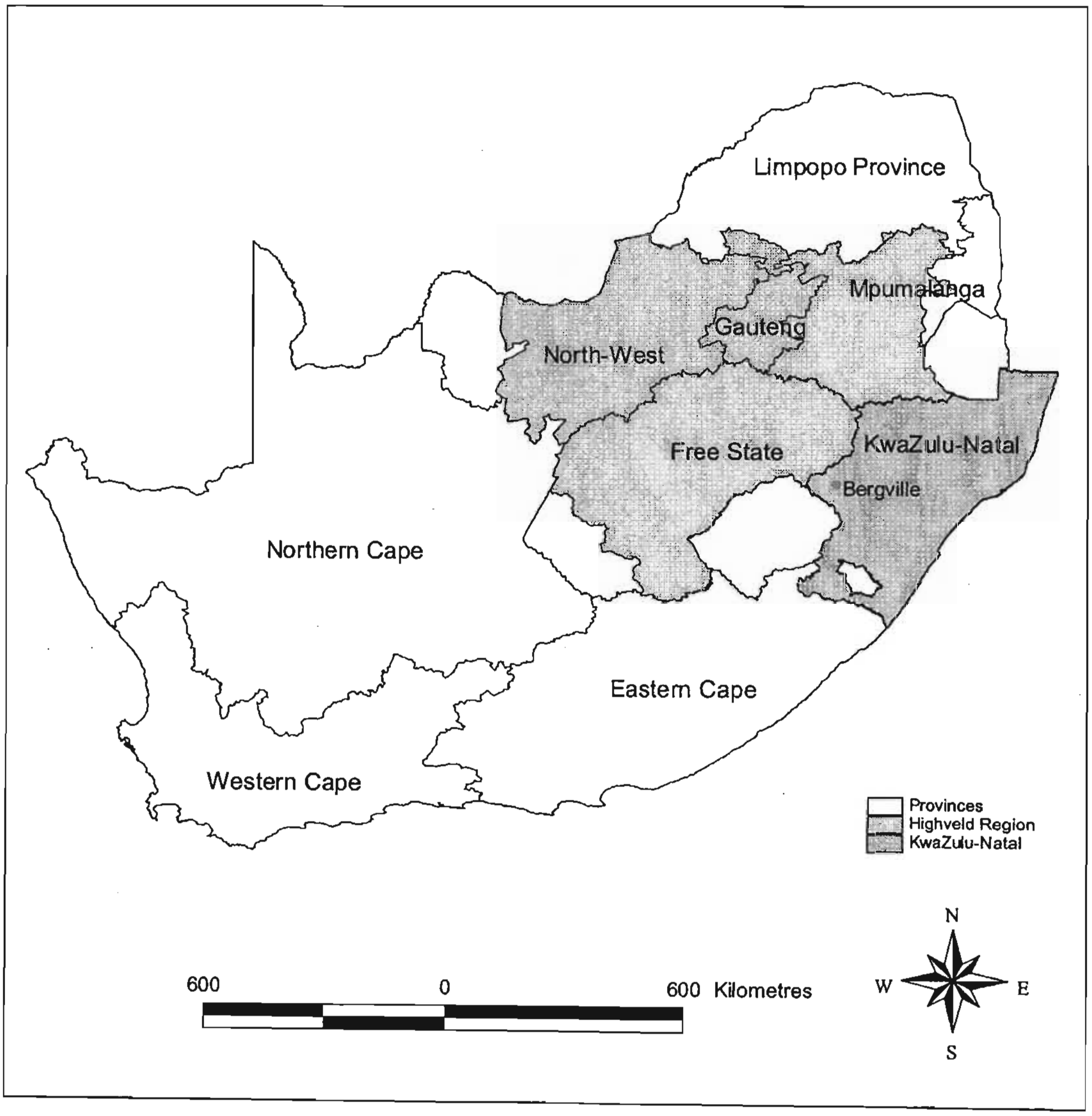


Figure 1.3 Location of the Highveld region in South Africa and the Bergville district in KwaZulu-Natal

For analysis of sustainability using a broader range of biophysical indicators, five Quaternary Catchments, with a range of mean annual precipitation from 432 mm to 903 mm, were chosen from within the Highveld region (Chapter 6). The Primary drainage regions of South Africa have been divided into Secondary, Tertiary and Quaternary catchments. The Quaternary Catchment is the smallest scale that the Department of Water Affairs and Forestry (DWAF) uses for planning purposes. The School of Bioresources Engineering and Environmental Hydrology (BEEH) at the University of KwaZulu-Natal in Pietermaritzburg has developed an environmental database of information at the Quaternary Catchment scale. The South African Quaternary Catchment database comprises of soils information, land cover information, daily maximum temperatures, daily minimum temperature, daily rainfall and reference potential evaporation information for each Quaternary Catchment.

In Chapter 6, using five selected Quaternary Catchments, management options where explored and these included planting dates, planting strategies involving plant populations and row widths, and nitrogen fertiliser application. Comparisons of different plausible climate scenarios were made in Chapter 7 in the selected Quaternary Catchments using the management options with a high likelihood of sustainability.

Intensification of cropping practices and the increased productivity on small-scale farms are required in order to produce food for an increasing population. However, this should be pursued in a manner which uses sustainable levels of external input in combination with local resources and knowledge (Smith *et al.*, 2004). At the farm level, this implies that many of the decisions made would need to consider the tradeoffs between different biophysical and socio-economic objectives (Kropff *et al.*, 2001). Furthermore, sustainability for the small-scale farmer raises questions of equity, economic viability and household food security. The Bergville district of KwaZulu-Natal, although it falls outside the Highveld region, is such an area which has many smallholder farmers producing maize.

The Institute for Soil, Climate and Water of the Agricultural Research Council (ARC-ISCW) is working with smallholders in the Bergville area in the form a LandCare development project in which appropriate land management technologies are implemented at the field level by participating farmers. Because the ARC-ISCW development project also facilitated comparisons of modelling output with field trial results this area was chosen to explore sustainability at the small-scale farm level (Chapter 8). The Bergville district does not fall within the Highveld region as designated for this thesis

(Figure 1.3), which is the area used for the assessment of sustainability at a regional and Quaternary Catchment scale. The choice of Bergville was nevertheless considered a valid one as upscaling of the findings from the farm level was not an aim of the study.

For small-scale farmers in the Bergville area sustainable maize production is not only a question of yields, but of protection of the environmental resource base, social welfare, and the livelihoods of farmers' as well as rural and urban communities. It is valuable to investigate sustainability at the field scale using both field data and model simulations for an understanding of food security at the household level. In this study a range of management options was assessed under both present climate conditions and different plausible future climate scenarios.

In summary, agro-ecosystem sustainability at different scales is of major importance to national, regional and household food security in South Africa. Figure 1.1 shows the three objectives that this study addresses and Figure 1.2 illustrates the methods employed to accomplish this. Chapter 2 considers Objective 1, as shown in Figure 1.1, which is to review the concept of sustainability, its use in terms such as sustainable development and its relevance to agro-ecosystems. The process of turning a dynamic and abstract concept such as sustainability into practical terms is also discussed in Chapter 2.

2 LITERATURE REVIEW OF THE CONCEPT OF SUSTAINABILITY AND ITS APPLICATION TO AGRO-ECOSYSTEMS

'So far man has been so busy "conquering" nature that he has yet given little thought or effort towards reconciling the conflicts in his dual role, that of manipulator of and inhabitant in ecosystems' (Odum, 1971; p. 23)

The concept of sustainability has emerged from concern over environmental and socio-economic problems caused by the manipulation or destruction of ecosystems in pursuit of development and profit. A review of the concept of sustainability and its many definitions is thus deemed important, as sustainability is an evolving concept and has a broad usage. It is important to state, and to some extent attempt to standardise, the definitions of sustainability, so that sustainable systems can then be identified and the facets that make the system sustainable determined (Gliessman, 2001).

In regard to producing a working definition of sustainability, this author believes that two approaches are possible. One, is to propose a definition from experience and compare it to definitions in existing literature, the second is to review the literature and on the basis of that to synthesise a working definition. In this thesis the second approach is taken.

The concept of sustainability is reviewed in Section 2.1. The main components of sustainability and their inter-linkage are discussed in Section 2.2, with particular attention given to sustainable development and sustainable livelihoods in Sections 2.3 and 2.4. Understanding and establishing sustainable agro-ecosystems is of major importance to national, regional and household food security. The application of sustainability to agriculture and appropriate ways to assess agro-ecosystem sustainability are evaluated in Sections 2.5. To understand the inter-linkages between the components of sustainability a systems approach has been deemed vital (Hansen and Jones, 1996). Therefore, the use of a systems approach to assess agro-ecosystem sustainability is discussed in Section 2.6. A working definition and framework for use in the research carried out in the thesis is proposed in Section 2.7.

2.1 The Concept of Sustainability

The sustainability ideal has been recognised by Park and Seaton (1996) as the driving force behind a philosophy in which there is an awareness today of the needs of future generations. Gold (1999) is in agreement with Park and Seaton (1996) and adds that there is an increasing acceptance of the aspiration to achieve a sustainable planet which will meet the basic needs of the present inhabitants while preserving resources for future generations to flourish.

A literal definition of sustainability would be 'the capacity to continue into the future indefinitely' (Ekins, 1995; p. 186). Alternatively Pezzey (1992; p. 321) gives a wide-ranging definition as 'maintaining the utility, that is average human well-being, over the very long term future encompassing ideas from physics, ecology, evolutionary biology, anthropology, history, philosophy, economics and psychology, into a coherent, interdisciplinary analysis of the potential for sustaining industrial civilisation.'

Sustainability has been defined by researchers from a range of perspectives. This renders the meaning of sustainability dependent on the context in which it is applied, i.e. whether it be from a social, economic or ecological perspective. Brown (1987), comments that a useful definition of sustainability must include the context as well as the temporal and spatial scales.

For example, Costanza *et al.* (1991; pp 8-9), writing from an ecological standpoint state that 'sustainability is a relationship between dynamic human economic systems and larger dynamic, but normally slower-changing ecological systems, in which 1) human life can continue indefinitely, 2) human individuals can flourish, and 3) human cultures can develop; but in which effects of human activities remain within bounds, so as not to destroy the diversity, complexity, and function of the ecological life support system.'

Chambers (1997; p. 11) states that 'sustainability means that long-term perspectives should apply to all policies and actions, with sustainable well-being and sustainable livelihoods as objectives for present and future generations'. Chambers (1997; p. 9) maintains that a change in precedence has taken place for the concept of sustainability to be considered by decision makers. A move has taken place away from 'things and infrastructure to people and capabilities.'

Equity and livelihood security are usually considered as components of the concept of sustainability (WCED, 1987; Lal and Ragland, 1993; Gold, 1999). However, Chambers (1997) regards them as separate. This is illustrated in Figure 2.1.1. Although equity, livelihood security and sustainability are considered separately, they are intrinsically linked. In this web, responsible well-being, or a good quality of life, is seen as the goal.

The capabilities of people and secure livelihood are the means of achieving responsible well-being and sustainability and equity as the foundational principles.

Chambers (1997) argues further that sustainability and equity are not sacrificed to achieve responsible well-being, and that the quality of life is enhanced when sustainability and equity contribute to well-being.

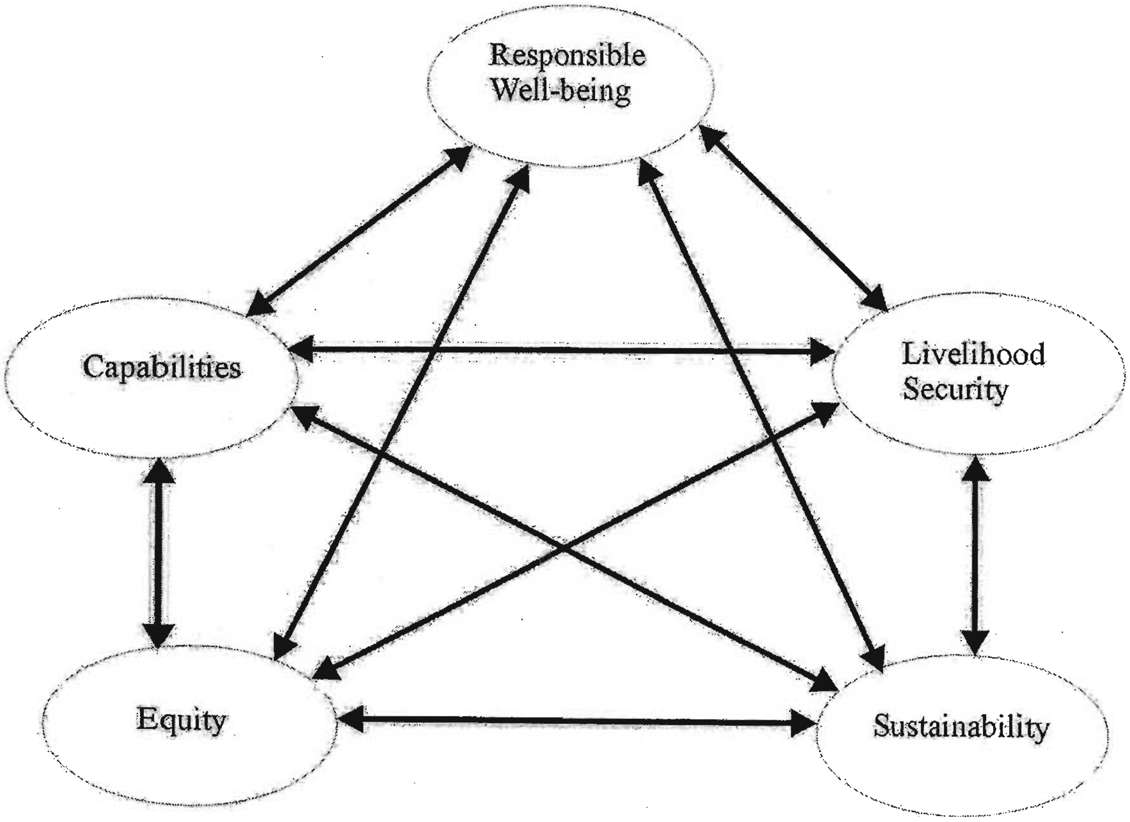


Figure 2.1.1 Web of responsible well-being (after Chambers, 1997)

2.2 The Components of Sustainability

From the plethora of definitions of sustainability some common themes emerge. Hurni (2000) refers to these themes as the five major pillars of sustainability. The following have to occur for something to be sustainable:

- Protection of ecology
- Acceptability to society

- Economically viable
- Economically productive and
- Effective in reducing risk.

Coupled with these five pillars of sustainability is the recognition of the needs of future generations and to not reduce the ability of future generations to meet these needs by the decisions that are made now. However, in the context of South African Highveld conditions and the goal of intensifying production in agro-ecosystems, the following components are imperative to achieving sustainability:

- Resilience of agro-ecosystems
- Social concerns and reducing risk
- Economic viability and production and
- Political constraints.

2.2.1 Agro-Ecosystem Resilience

'Agriculture is an ecological enterprise that depends on ecosystem processes and functions such as soil formation, nutrient cycling, the maintenance of hydrological cycles, the pollination of crops, etc. that are all driven by interactions between the elements of biodiversity' (Williams, 2001; p. 23). Conway (1987) describes agro-ecosystems as 'ecological systems modified by human beings to produce food, fibre or other agricultural products.'

The term resilience has been described as the ability of the system to return to the original state after a disturbance (Scheffer *et al.,* 2002). Agro-ecosystem resilience is, therefore, the magnitude of disturbance that can be absorbed before the system changes structure by changing the variables and processes that control its behaviour (Holling and Gunderson, 2002). This definition of agro-ecosystem focuses on persistence, adaptiveness, variability and unpredictability, which are attributes considered by Holling and Gunderson (2002) to be at the heart of understanding sustainability.

In agro-ecosystems where there is a complex interaction between nature and people, flexibility is required to maintain resilience. Attempting to stabilise these systems to a perpetual optimal state, particularly in regard to production, reduces resilience and often results in the system being close to a critical threshold, i.e. where the nature and extent of feedbacks within the system change to such an extent that the result is a change of direction for the system itself. The reduced resilience of the agro-ecosystem permits critical thresholds to be crossed more easily (Walker and Meyers, 2004)

Walker *et al.* (2004) suggest there are four fundamental aspects concerning the resilience of an agro-system at a particular organisational scale:

- Latitude: This is the maximum amount of change a system can experience before losing its ability to recover, i.e. before crossing a threshold which, if breached, makes recovery difficult or impossible.
- Resistance: This relates to the ease or difficulty of changing the system i.e. - how resistant it is to being changed.
- Precariousness: This questions how close the system currently is to a limit or threshold.
- Panarchy: Because of cross-scale interactions, the resilience of a system at a particular focal scale will depend on the influences from states and dynamics at scales above and below it. For example, external oppressive politics, invasions, market shifts or global climate change can trigger changes in local agro-ecosystems.

Extreme change to both natural and social systems is part of humanity's history. The remarkable resilience of natural ecosystems, in particular, can be found in examining the scales at which processes operate to control the system. In many terrestrial systems, it is the geophysical controls that dictate at scales larger than tens of kilometres. At smaller scales than this, interacting biotic processes can control structure and variability. These are also the scale ranges at which human activities interact with the landscape (Holling *et al.,* 2002; p. 15).

The controls established by each biotic structuring process within terrestrial ecosystems are generally robust to the stresses placed upon them, and the resulting behaviour is resilient. That robustness comes from functional diversity and spatial heterogeneity in the species and physical variables which control the key processes that structure and organise patterns in ecosystems and landscapes (Holling *et al.,* 2002; p. 15).

Ecosystem integrity refers to the system being whole and unimpaired. The integrity of an agro-ecosystem implies the integrity of both system structure and function, maintenance of system components and the ensuing dynamics of the system (Regier, 1993). Agro-ecosystems with high integrity are ones that are relatively resistant to environmental change and stresses and can recover their original conditions after a perturbation

(Andreasen *et al.*, 2001). Sustainability, therefore, can be considered a fundamental part of agro-ecosystem integrity. Ecosystem integrity can be characterised into compositional, structural and functional components and measurable indicators can be selected that correspond to these components (Noss, 2000). For example, the different components of ecosystem integrity can be measured in the following way:

- Compositionally, i.e. by functional groups of organisms or mapped plant communities
- Structurally, i.e. by landscape patterns and
- Functionally, i.e. ecological processes.

Noss (2000) suggests that more attention should be given to structural and functional components of ecosystems. The notion of integrity must recognise a human perspective, such as the ability of an agro-ecosystem to continue to provide the goods and services that humans expect (De Leo and Levin, 1997). Examples of ecosystem services which are particularly important for agro-ecosystems are: continuation of the genetic diversity essential for successful crop and animal breeding; recycling of nutrients; biological control of pests and diseases; erosion control and sediment retention; and regulation of local hydrological processes. At a global scale other services become important, such as the regulation of the gaseous composition of the atmosphere (Swift *et al.*, 2004).

Ecosystem functions can be divided into four primary categories (De Groot *et al.*, 2002):

- Regulation functions, i.e. the capacity of natural and semi-natural ecosystems to regulate essential ecological processes and life support systems through bio-geochemical cycles and other biospheric processes, where the regulation functions are also able to provide clean air and water, as well as biological controls;
- Habitat functions, i.e. where natural ecosystems provide refuge and reproduction habitat to wild plants and animals;
- Production functions, i.e. photosynthesis and nutrient uptake by autotrophs which convert energy, carbon dioxide, water and nutrients into a wide variety of carbohydrate structures which are then used by secondary producers to create an even larger variety of living biomass; and
- Information functions, e.g. recreation and aesthetic experience (De Groot *et al.*, 2002).

In regard to achieving sustainability of agro-ecosystems there needs to be an emphasis on conserving biodiversity at multiple scales within a landscape, along with the ecological processes within it and by doing so, preserve biodiversity and ensure sustainability (Jewitt, 2002).

2.2.2 Social concerns and reducing risk

For a complete analysis of sustainability, any investigation must not only consider the protection of the environmental resource base, but must include social welfare, as well as the livelihoods of farmers and rural and urban communities.

Both Stinner *et al.* (1997) and Giampietro (1997) have stressed the importance of indigenous knowledge and experience when looking to implement sustainable farming practices, understanding the conservation of local resources and diversity of agro-ecosystems.

If sustainability is the desired goal then any development projects should include community participation. Development projects such as irrigation schemes have frequently failed because of neither involving local people in the decision making process nor using local knowledge. Doughty and Hall (1995), highlight that considerable negative consequences have occurred owing to a lack of understanding of the people and society, even when the aim was to help them. In considering environmental issues, Doughty and Hall (1995) continue by recommending that communities should not only be consulted, but also be actively involved. In observing small-scale farming and soil conservation projects in Africa, Critchley (1991) found that success occurred when farmers were treated as part of the solution and not part of the problem.

The concept of sustainability is concerned with the welfare of the individual and the community. A problem for many communities is the migration of people to the cities for employment and better social care. To prevent this, there is a need for employment opportunities in rural areas, improved education, health care and cultural activities. Another issue in southern Africa is one of land tenure. The ownership and the right to work the land in traditional rural areas are a major political concern and, as Mkhabela (2002; p. 143) concludes, 'land tenure remains a complex and precarious issue in rural

South Africa' and security of tenure is not assured under the system of land being vested in the local tribal chiefs.

For a farming system to be sustainable it not only needs to be profitable and environmentally sound, but also needs to enhance community and rural life (Gold, 1999). The management practices on the farm also affect the local community. Potential health hazards to farm workers and consumers are tied to sub-therapeutic use of antibiotics in animal production, and pesticide and nitrate contamination of water and food. For example, farm workers have been poisoned in fields, and toxic residues have been found on foods, and certain human and animal diseases have developed resistance to currently used antibiotics (Gold, 1999).

2.2.3 Economic viability and production

Using agriculture as an example, economic viability and production need to be considered from the farm level through to national level, in particular with concerns over food security. If a farm is not profitable then it is not sustainable, as 'unprofitable agricultural systems will not continue' (Edwards-Jones and Howells, 2001; p. 32). Chambers (1997) writes of the need of agriculture to be able to sustain livelihoods of farmers and their families. On a regional scale it is also important that individual farms are profitable, as the resulting production creates business opportunities for both rural and urban communities. Farmers should be encouraged to diversify and have less dependency on one particular crop. The farmer would then be less susceptible to a change in a crop's price (Gold, 1999).

A major challenge to agriculture in southern Africa is to meet production requirements for food demand, as the population is expected to double in the next thirty years (du Toit *et al.,* 2002a). A food-secure nation should provide security at all levels of human organisation, from the individual household members and their differing nutritional requirement, through to regional and national level. At the national level food security is associated with the sufficiency of the national food balance (Chen and Kates, 1995). Depending on the level of human organisation, the definition of food security is viewed in different ways.

A concern with the need to increase food production is whether the food will be produced in what may be regarded as a sustainable manner. When considering a food security scenario, or system, Rothman and Coppock (1995) point out that the inter-linkages of components in a system must be considered in regard to sustainability and that inter-regional linkages in the food system must also be contemplated.

2.2.4 Political constraints to sustainability

For sustainability to be possible there has to be the political will to drive it. However, this has its difficulties, for as Stroup and Shaw (1992; p. 267) point out, 'when environmental goals and controls are politically determined, they are subject to a process that is often driven by groundless accusations, supported by public fear, and legislated with special interests in mind.' In developed countries 'too often the quest for growth, jobs and industrialisation has caused a cycle of unsustainable reactions and almost invariably lead to ecological breakdown and environmental deterioration' (Roberts, 1995; p. 18).

A political issue that is stressed by the concept of sustainability is that of equity in the distribution of income and resources. In developing countries equity is often a key goal of development for governments. Taylor (2002) writes that often a significant part of government policy is to redistribute income in order to reduce poverty. Failure to do so could have a variety of impacts which include social unrest and a slower economic growth.

The destruction of ecosystems has occurred because of failure by economic and political institutions to provide appropriate incentives. Farber (1991) highlights five major causes of this as:

- short-term perspectives
- failure in property rights
- concentration of economic and political power
- immeasurability and
- institutional and scientific uncertainty.

A short-term perspective with regard to policies can be the result of fear of imminent political change, the need for foreign currency or population growth (Farber, 1991). Failure to have adequate property rights in place will mean that farmers will be unable to gain loans for land improvement, also making it economically difficult for potential farmers to enter commercially into agriculture (Gold, 1999). Therefore, the possibility of sustainability can be increased by an enhanced definition of land tenure and property rights (Farber, 1991). When economic power is concentrated both between and within countries, there is the potential for ecosystems to be destroyed and benefits of the economic enterprise to be taken out of the country, for example, by mining firms exploiting one area and moving to another. The benefits of sustainability to the developer are minimal, but the environmental and social costs to the area are high as the developer may have shorter-term perspectives than local rural and urban communities (Farber, 1991).

The United Nations (1992) has identified that there is a general lack of capacity for the collection and assessment of environmental and ecological data, particularly in developing countries. This, in turn, hinders the dissemination of useful information to decision makers. Therefore, the need for simplicity in policy-making could promote economic growth over the ecosystem protection simply because of problems with environmental data collection and dissemination (Farber, 1991). It has been suggested by Farber (1991) that lack of available environmental and ecological information about biophysical interactions will hinder sustainability policies, especially if the policies directly affect industry.

2.3 Sustainable Development

Development has been described as economic growth, or a raise in living standards (Clark, 1991; p. 23). The US Department of Commerce (2002) defines economic development as 'enhancing the factors of productive capacity - land, labour, capital, and technology - of a national, state or local economy.' Brown (1998) considers this traditional view of development as inappropriate, as its environmental impacts are often negative, as illustrated in Figure 2.3.1.

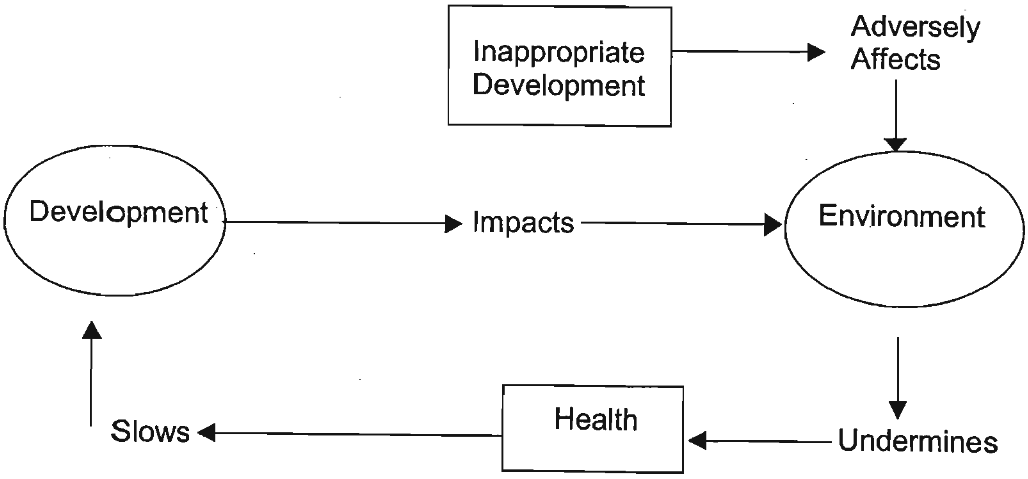


Figure 2.3.1 Inappropriate development (after Brown, 1998)

'Decades of experience have shown that economic growth does not by itself lead to improved living standards for the majority' (Clark, 1991; p. 24). An alternative to the traditional form of development is one that is termed sustainable.

In 1987 the report of The World Commission on Environment and Development (WCED), commonly referred to as the Brundtland Report, defined sustainable development as 'development that meets the needs of the present without comprising the ability of future generations to meet their own needs. Sustainable development requires meeting the basic needs of all and extending to all the opportunity to satisfy their aspirations for a better life' (WCED, 1987; p. 43).

Braat (1991; p. 61) states that the WCED concept of sustainability 'combines two basic notions: economic development and ecological sustainability. Ecologically sustainable economic development can be thought of as the process of related changes of structure, organization and activity of an economic-ecological system, directed towards maximum welfare, which can be sustained by the resources to which that system has access.'

Sustainable development is described by Liverman *et al.* (1998; p. 133) as the 'indefinite survival of the human species (with a quality of life beyond mere biological survival) through the maintenance of basic life support systems (air, water, land, biota) and the existence of infrastructures and institutions which distribute and protect the components of these systems.'

The WCED definition of sustainable development is concerned with meeting the needs of people in the present and in the future. Park and Seaton (1996; p. 87) point out that 'there are clearly dangers in predicting the future and then planning for it,' as the understanding of what is sustainable may change and that what is seen 'as sustainable today may be undesirable a decade into the future.' A prediction on future generations' needs has to be made if this definition is used, but predicting what people will require fifty years hence is, at best, an estimate.

Reid (1995) asks whether we should be concerned with future generations' needs at all when little is done about intra-generational equity. Member governments of the United Nations often call for an end to poverty and the continuance of human deprivation on massive scales, but then allow numbers of the homeless, malnourished and the unemployed to increase in their own countries. A large proportion of the world's population do not have access to basic needs such as clean water, housing and education; therefore, should not the main consideration be of meeting peoples' needs now?

Attfield (1983; pp. 90-91) answers this question by stating that 'the same reasoning which suggests that we have obligations, wherever we can to prevent suffering or misery to contemporary strangers, however distant in space, suggests that we have similar obligations to future strangers, however distant in time: for distance in time is just as irrelevant as distance in space.'

To ensure that sustainable development is possible in all countries in the future the United Nations (1992) suggests that two areas need to be addressed.

- First, the environmental and ecological data gap which exists between developed and developing countries needs to be bridged
- Secondly, the availability of information needs to be improved.

The gap in the availability, quality, coherence, standardisation and accessibility of environmental data between the developed and the developing world has been increasingly and seriously impairing the capacities of countries to make informed decisions concerning the environment and development. There is a general lack of capacity, particularly in developing countries, and in many areas at the international level, for the collection and assessment of data, for their transformation into useful information and for their dissemination.

The objectives of sustainable development need to be expounded to provide solid bases for decision-making at all levels and to contribute to a self-regulating sustainability of integrated environment and development systems. Such a model of sustainable development is illustrated in Figure 2.3.2, and should be contrasted with the model of inappropriate development which was shown in Figure 2.3.1.

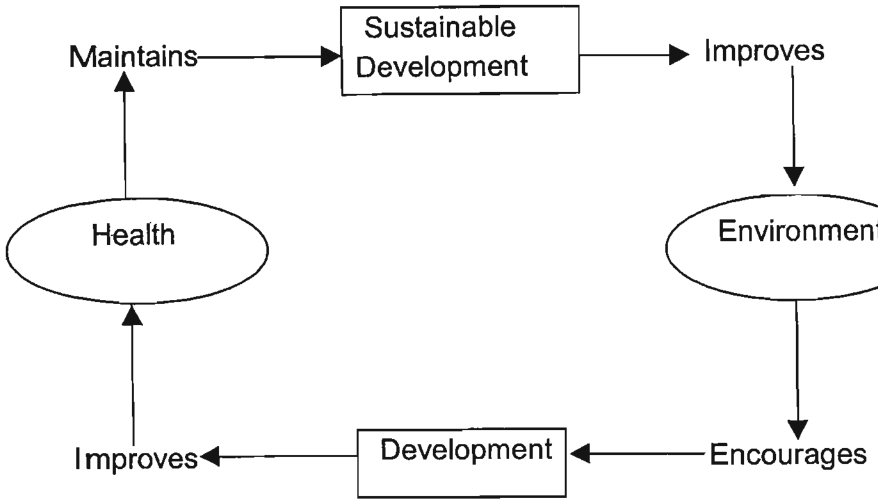


Figure 2.3.2 A model of sustainable development (after Brown, 1998)

In sustainable development, everyone is simultaneously a user and provider of information in the broadest sense. The need for information arises at all levels, from that of senior decisions at national and international levels through to decisions made by the individual.

The idea of mixing the technical considerations on whether an activity is sustainable, with moral considerations, is a view that Beckermann (1995) considers flawed. The main reason for this is that definitions that include ethical instruction generally fail to state why the ethical route suggested is any better than alternative routes.

The WCED definition of sustainable development, with the inclusion of the idea of peoples' needs is difficult to convert into economic terms. Pearce *et al.* (1989) have developed an approach that focuses on natural capital assets and they suggest that the capital assets should not decline over time.

Pearce (1993) categorises the types of sustainable development into four broad bands, with the categories defined from an economic point of view. Figure 2.3.3 shows the range of views which can exist under the banner of sustainable development.

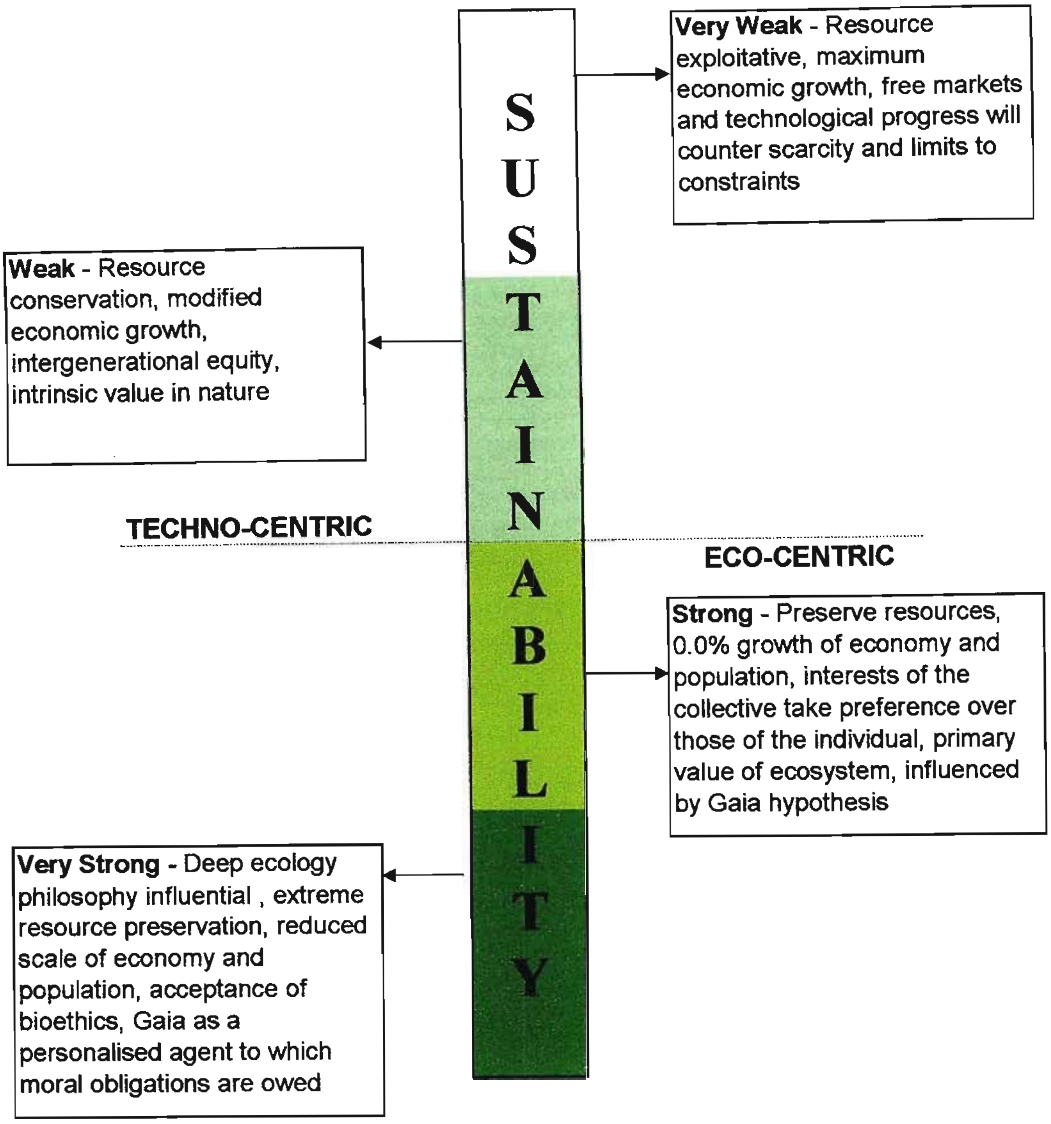


Figure 2.3.3 Types of sustainability based on Pearce's (1993) concepts

The techno-centric views are the principles that a vast majority of the world's countries are following in terms of government policies and 'this mode values the natural world as a resource rather than for its intrinsic value. Its approach to problems of environment and development is based on a faith in human abilities to use technologies to control natural processes' (Reid, 1995; p. 130).

The classification of sustainability by Pearce (1993; pp. 18-19) is in terms of how a 'stock of capital' is transferred between generations. The stock of capital can either be natural resources or man-made capital, including knowledge. How this transfer of capital is perceived, and consequently achieved, will determine which sustainable development option the decision-makers fall into.

The very weak and weak sustainability options do not place much importance on how the stock of capital is passed on. Termed 'techno-centric' options, they argue that any reduction in natural resources would need to be compensated by increased infrastructure. Fewer infrastructures would have to be offset by increased natural habitats. Any environmental issues that occur would be dealt with through legislation, for example 'the polluter pays' principle. The weaker versions of sustainability have a common theme in that a deterioration of the environment and reduction in the resource base is acceptable, as long other forms of capital replace them (Turner, 1993).

Proponents of the stronger versions of sustainable development are termed eco-centric by Pearce (1993). Eco-centrics believe that markets cannot solve the environmental problems, but that direct regulation and planning are required and that the range of economic activity should be scaled down.

Eco-centric views are influenced to a greater or lesser extent by Jim Lovelock's Gaia hypothesis (Lovelock, 1987). Gaia seems to be much more than stewardship on behalf on the planet, i.e. humans should be hands-off and let the living organism of planet earth regulate and steward itself, stipulating that humans should take a peripheral role.

It could be argued that the picture of 'very strong' sustainability could, in fact present strong threats to sustainability given the negative environmental impacts of poverty. This is a view that the author of thesis agrees with. There seems to be a conflict between strong sustainability and poverty alleviation. In Africa, only 60% of people have access to safe water supplies and the number of undernourished exceeds 200 million (Wright *et al.*, 2002). In the author's view development must take place along relatively weak sustainability pathway. Economic development must occur in such a way as to provide people with access to safe drinking and adequate sanitation. The very strong sustainable pathways hints at letting the 'organism of the earth' steward itself and regulate human population levels. This is a concerning viewpoint as it takes no account of people in dire circumstances, and is void of any human compassion. It is the author's view that western philosophers/scientists associated with Gaia philosophy have replaced the Judeo-Christian God with one their own, namely 'Mother Earth', particularly as a key to 'very strong' sustainability is embracing Gaia as a personalised agent to which moral obligations are owed.

The very weak sustainability and very strong sustainability options have, however, similarities in certain respects. Both suggest that the earth is able to adjust and counter any environment problem that may occur. However, it is in the response to this idea where the differences occur. The very weak sustainability response is that the earth can deal with any environmental problems and the ones it cannot, technology will solve. Therefore, we are free to exploit the earth resources to make profit and meet our needs. Very strong sustainability treats the earth with reverence and states that it is our moral duty to make sure that the earth resources are heavily protected.

Reid (1995) explains that the main obstacles to a move by decision-makers to eco-centric thinking are political. A shift by governments away from a pursuit of economic growth to one that endorses the protection of resources would result in strong opposition from businesses, unions and individuals worried about job losses.

2.4 Sustainable Livelihoods

The term 'sustainable livelihoods' emerged in the early 1990s through its use by the World Commission on Environment and Development. The concept of sustainable livelihoods started as a methodology to improve resource productivity and encompass issues such as ownership and access to assets, jobs and resources in order to meet basic needs. Singh and Gilman (2000) report that the need for such a concept evolved out of the realisation that food security was not merely an issue connected with agricultural productivity, but involved all the elements associated with poverty in general. The concept has since developed through its use at the 1992 United Nations Conference on Environment and Development (UNCED) and at the Copenhagen World Summit for Social Development in 1995, as well as at the Fourth World Conference on Women (FWCW) in Beijing in 2003. These conferences have moved the concept to one of action and have emphasised the relationships between sustainability, employment, social integration, gender and poverty eradication for policy and development programming.

The United Nations Development Programme (UNDP, 1999) has defined livelihoods as the assets, activities and entitlements which people use to make a living. Sustainable livelihoods are those that are able to cope with, and recover from, shocks and stresses such as drought and policy failure and are also economically efficient, ecologically sound, and socially equitable. The definition of sustainable livelihoods presented here is similar to the definition of agro-ecosystem resilience presented in Section 2.2.1, implying that sustainable livelihoods that are based on agro-ecosystems are dependent on agro-ecosystems resilience.

In defining sustainable livelihoods a clear distinction is made between livelihoods and jobs. Jobs are characterised as carrying out a particular activity for payment. A livelihood is identified as a number of activities that do not necessarily have a formal agreement and are not restricted to one type of activity. A job, therefore, can form part of a livelihood (UNDP, 1999). Livelihood systems include a complex and multi-faceted sets of physical economic and social strategies. A sustainable livelihood is one that encompasses the major themes of general sustainability definitions such as equity, conservation and access to resources and economic productivity. Singh and Gilman (2000) stress that sustainable livelihoods are also about the manner in which people, particularly those living in poverty perceive their own reality, and how this appreciation of reality interacts with what happens in the rest of society. To turn sustainable livelihood theory into practice, the UNDP, along with other international agencies, have a developed a framework for implementation at a country level. This framework is summarised in Figure 2.4.1.

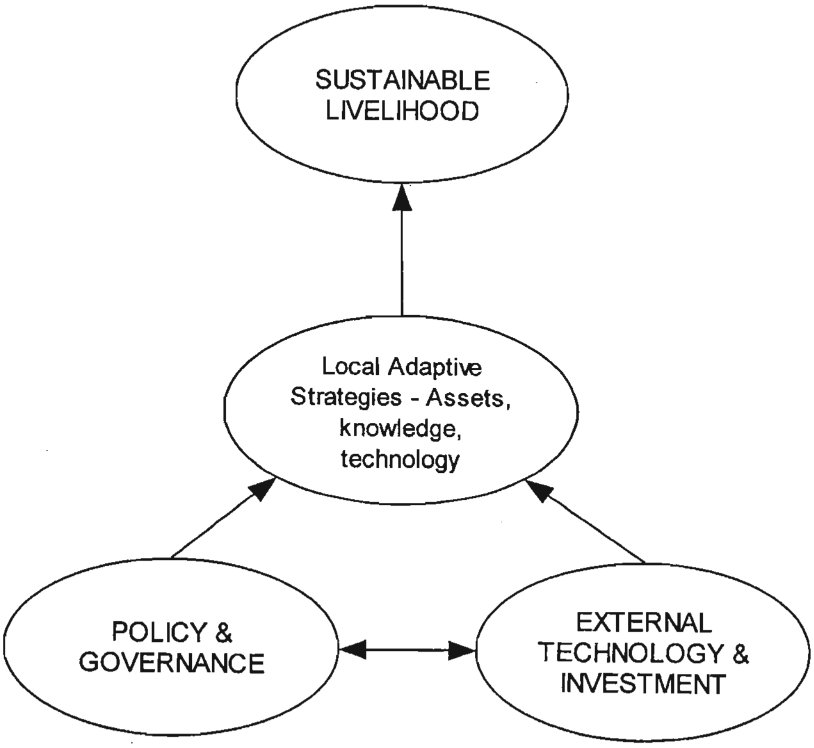


Figure 2.4.1 A framework for promoting sustainable livelihood (after Singh and Gilman, 2000)

The beginning of the process is a participatory assessment of attributes such as assets, risks, entitlements and the indigenous knowledge base found in a particular community. This is followed by an analysis of the macro-, micro and district policies, along with governance procedures. Some of the questions raised by the analysis of policy will include the following:

- What are the livelihood priorities of people living in poverty?
- How do policies impact peoples' livelihood strategies? and
- How do people participate in the policy making process? (Pasteur, 2001)

Also required is an evaluation of the possible use of contemporary technology that would complement indigenous knowledge systems in order to improve livelihoods. The final stage is to identify a macro-micro investment strategy so that the two levels of finance complement each other. For a successful implementation the stages of the framework should be integrated (Singh and Gilman, 2000). An alternative framework is presented by the UK government's Department for International Development, DFID (Figure 2.4.2). This particular sustainable livelihoods framework highlights five interacting elements: contexts; resources; institutions; strategies; and outcomes (Solesbury, 2003). Hinshelwood (2003) argues that when used flexibly the DFID framework can be an effective tool for organising and analysing ideas in regard to sustainable livelihoods.

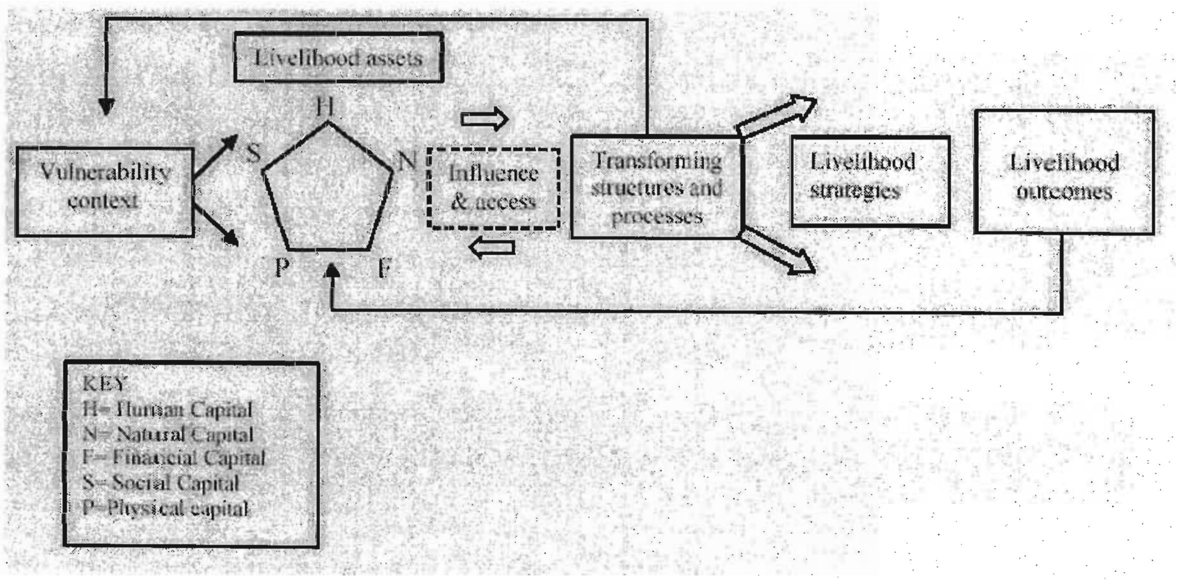


Figure 2.4.2 DFID sustainable livelihoods framework (Carney, 1998)

Campbell *et al.* (2001) identify five categories they consider to be fundamental in a sustainable livelihoods framework. The categories are physical, financial, social, natural and human capital. These categories also constitute the core of the DFID framework (Figure 2.4.2). Using sustainable livelihoods frameworks (Campbell *et al.*, 2001; Solesbury, 2003) can assist in integrating across disciplines, scales, stakeholders and components (Sayers and Campbell, 2001).

2.5 Sustainability in Agriculture

Commercial agriculture has undergone significant transformation, particularly since World War II. New technologies, mechanisation, increased use of chemicals, government policies and new types of cultivars and hybrids have all contributed to an increase in farm productivity and have led to a marked decrease in relative farm labour costs. However, these advances and management practices have created environmental problems such as soil erosion, groundwater contamination and social changes such as a decline in family-owned farms, poor conditions for farm labourers, rural to urban migration and increasing the costs of production (Feenstra, 1997). With this in mind Maser (1997; p. 13) asks 'Will the ecosystems of the future, which we are today shaping, continue to function in such a way that the quality of human life we have come to expect continue?'

Gliessman (2001; pp. 3-4) raises the following three questions:

- 'How do we identify an existing agro-ecosystem as sustainable or not?
- What are the facets of a system that make it sustainable or unsustainable?
- How can we build a sustainable system in a particular region, given realistic economic constraints?'

To begin to answer these key questions it is important to state, and to some extent attempt to standardise, the definitions of agricultural sustainability.

2.5.1 Definitions of sustainability in agriculture

'The principle objective of agricultural sustainability is to meet human needs by improving standards of living, alleviating drudgery and human suffering, and providing a respectable way of life for a majority of the population' (Lal and Ragland, 1993; pp. 1-2). Conway (1987; p. 101) considers sustainability in agriculture to be 'the ability of the agro-ecosystem to maintain productivity when subject to a major disturbing force.' O'Connell (1992) describes sustainability in agriculture as a combination of practices such as crop rotation and integrated pest management. In contrast to this, Feenstra (1997) explains that sustainable agriculture is not about using a set of practices, but rather that it challenges producers to think about the long-term effects of management decisions and how these impact the dynamics of agricultural systems. From a plethora of definitions and contributing philosophies, three common goals of sustainable agriculture appear,

- those of environmental health,
- economic profitability and
- socio-economic equity.

Rigby and Caceres (2001; p. 23) found that it was extremely difficult to determine whether certain agriculture practices were sustainable or not. It is only in retrospect that sustainable techniques could truly be identified.

A definition of agricultural sustainability that is widely used is one by the American Society of Agronomy (1989). This states that 'a sustainable agriculture is one which, over the long term, enhances environmental quality and the resource base on which agriculture depends; provides for basic human food and fibre needs; is economically viable; and enhances the quality of life for farmers and society as a whole' (quoted in Hansen, 1996; p. 118).

The United States Farm Bill that was passed 1990 built on the principles of the definition by the American Society of Agronomy. It states that the term sustainable agriculture means an integrated system of plant and animal production practices having a site-specific application that will, over the long term:

- Satisfy human food and fibre needs
- Enhance environmental quality and the natural resource base upon which the agricultural economy depends
- Make the most efficient use of non-renewable resources and on-farm resources and integrate, where appropriate, natural biological cycles and controls, and
- Sustain the economic viability of farm operations and enhance the quality of life for farmers and society as a whole (Gold, 1999).

Pretty (1995) describes agricultural sustainability as a system which engages in:

- Incorporating natural processes such as nutrient cycling into the production processes
- Reducing non-renewable inputs that damage the environment and harm the farmers health and minimising variable costs
- Progressing towards a more socially-just from of agriculture
- Making increasing the use of biological and genetic potential of plant and animal species
- Increasing the use of local knowledge and practices
- Allowing farmers and rural communities to become more self-reliant
- Matching crop patterns with production potential and environmental constraints of climate and landscape
- Facilitating profitable and efficient production using integrated farm management
- Conserving soil, water, energy and biological resources.

For sustainability in agriculture to occur, Pretty (1995) suggests that certain conditions need to transpire, as summarised in Figure 2.5.1.

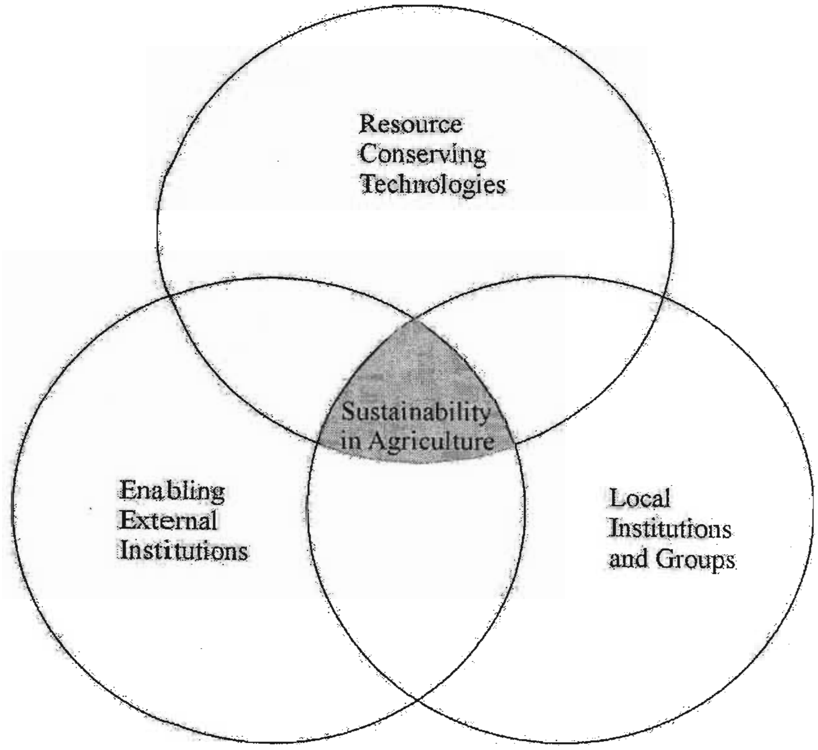


Figure 2.5.1 The conditions required for sustainability in agriculture (after Pretty, 1995)

Local institutions and groups need to use resource-conserving practices such as soil and water conservation and be supported by external research, extension and development institutions. To prevent sustainability in agriculture from being limited to a specific locality, the local, regional and national governments must have policies in place that facilitate the expansion of sustainability.

2.5.2 Conserving resources

Agricultural sustainability involves, *inter alia*, the protection of the water and soil resources, reduction in the reliance on finite fuels, reduction in air pollutants, environmentally safe livestock production and the support of rural communities.

According to Gregorich (1995), the question as to whether agricultural practices are sustainable or not depends on the amount of degradation of the soils. If the soil is not protected to some extent then resources such as time, money and chemicals will be required in increasing quantities to maintain agricultural production. If degradation is prevented, or reversed, in areas where degradation has already occurred, then agricultural sustainability can be realised. Methods of protecting and enhancing the productivity of the soil suggested by Feenstra (1997) include using cover crops, compost and/or manure, reducing tillage, avoiding traffic on wet soils and maintaining soil cover with plants and/or mulches.

If the cost of the conservation measures is perceived to be more than the expected benefits then farmers will be unwilling to introduce resource-conserving measures. Farmers may not conserve soil and water if the future is uncertain in regard to political instability, imminent conflict or if land tenure is uncertain (Pretty, 1995). Other factors of concern include those about the risks involved, fear of innovation and insecurity about the change in practice (Roberts, 1995).

2.5.3 Sustainability in small-scale agriculture

Sustainability for the small-scale farmer raises questions of equity, economic viability and household food security. The term 'small-scale farmer' in the context of this study is used to refer to subsistence and emerging commercial farmers and those farmers who work communal plots.

2.5.3.1 Gender issues in agriculture

A large number of farmers in Africa are females. It has been suggested that 60-80% of the agricultural labour force is female (Williams, 1994), implying that women are responsible for ~70% of the total agriculture in Africa. The role of the female is, therefore, of significant importance in African agriculture.

In southern Africa, because of the traditional migratory system where men seek work in urban areas, the majority of women live and earn livelihoods for themselves and their families in rural areas (Tshatsinde, 1990). They are involved in many activities involving the agricultural processes, in the raising of animals and in commercial activities.

The farmers who are situated in the rural areas tend to be full-time as they are often too far from the urban centres to find work there. Additionally, in rural South Africa the current (2004) employment situation is particularly depressed. In terms of employment, 90 per cent of women in rural areas are employed in the rural sector. Tshatsinde (1990) has suggested that the contribution of women in agricultural production is not easy to quantify in statistical terms, as most of the work is unpaid and is, therefore, unseen. Rural women contribute more than 20% to the average family income and sometimes their routines involving agriculture and household activities take more than 18 hours a day (Tshatsinde, 1990).

2.5.3.2 Food Security

Agriculture is full of risk and uncertainty, and as a consequence, risk has a weighty influence on decisions made. Production instability at the household level can have serious effects on income and food security (Jones and Thornton, 2002). Chen and Kates (1996) define a food-secure nation as one that provides security at all levels of human organisation, from the individual household members and their differing nutritional requirement, through to regional and national level. At the household level it may be crucial for the farmer to minimise the fluctuations in household income over time, or to maintain or increase a particular wealth level and nutritional status. At the national level, governments have to ensure an adequate food supply to the population for all sectors of society (Thornton and Wilkens ,1998).

Crucial to rural household food security are householder plots and community gardens. A community garden is a communal plot of land usually 1-2 ha in size. Each member of the garden has their own section of land in which to grow crops. Generally this tends to be vegetables as they have a higher cash value than other crops. Each farmer is then able to decide what crops to grow when to do so and when to irrigate.

Many of the community gardens do not grow the amount of produce they have the potential for. Generally, in community gardens which are close to towns the farmers are part-time and they have other ways of generating income as they are close to the areas where there is work (Walker, 1999). Community gardening is unique in the opportunity it can provide the poorest of the poor people to improve their standard of living (de Lange, 1994).

Gellen (1994) reports that there are some vital components to ensuring food security. At the household level it would include securing a family's ability to grow and purchase enough food and address inequality regarding access to resources. Also, support and incentives would need to be channelled to small-scale farmers, targeting in particular women. At a community level, procedures should be established to protect those most vulnerable to climatic extremes. Amalu (2002) comments that people struggling for survival generally will not consider long-term sustainability, even if initially their practices destroy their long-term basis for survival.

Food security at the household level is implicitly linked to land and water quality. Degradation of these resources can affect rural household consumption by:

- reducing subsistence food supplies
- reducing food purchases due to higher food prices
- reducing household incomes
- reducing agricultural employment and
- negative health effects due to reduced water quality or food consumption (Penning de Vries *et al.*, 2002).

2.5.4 Climate change and agricultural productivity

An important element of the regional expression of global change is climate driven, which in turn is driven by a changing atmosphere and land surface. The regional change arising out of global change is much more than only the effect of climate change; it is the interaction of a variety of forcings, the human dimensions of which are of fundamental importance (Tyson *et al.*, 2002).

On a global scale South Africa, and particularly the southern African region, has low carbon emissions (Tyson *et al.*, 2002). Given these apparently low emission figures, it is tempting to minimise the contribution of the region to global change. According to Tyson *et al.* (2002) this would be misleading. The urban and industrial emissions of aerosols and trace gases, along with biomass burning in the tropics have major implications for regional change.

Climate change in the southern African region could have important consequences for the production of cereal crops (Perks, 2001). A particularly negative aspect in Africa is that local production of cereals has not increased at the same rate as the population (Sombroek and Gommes, 1996), this being in contrast to the rest of the world, where food production has increased at a faster rate than human populations. Also, the production of tuber and root crops is rising faster than that of the nutritionally more important cereals (Sombroek and Gommes, 1996). Any change in the climate that may have negative impacts could, therefore, exacerbate the situation where production of food is not increasing with anticipated demand.

Downing *et al.* (1996) describe four ways which climate change is likely to alter the plant environment:

- CO_2 : The direct effects of carbon dioxide enrichment on plants are beneficial.
- Temperatures: It is projected that across southern Africa temperatures will increase (Schulze and Perks, 2000; Schulze *et al.*, 2005). Warmer climates will affect, *inter alia*, the distribution of agro-ecological zones.
- Water: Since thermal suitability is not a major constraint on agriculture in southern Africa, the dominant effect of climate change is likely to be through altered water balances which may alter significantly (Schulze *et al.*, 2005).

- Frequency distributions of temperature, rainfall and other climate elements may change: For example, rainfall that occurs with less regularity would exacerbate water stress.

The productivity of agro-ecosystems could be significantly impacted by the effects of climate change. This could result in highly productive areas to become less so. The direct impacts on marginal areas could either be to make agriculture unsustainable or, conversely, to increase the potential productivity considerably (Reilly, 1996). Agricultural crops grow optimally within ranges of temperature and rainfall specific to each given crop (Schulze, 1997). A consequence of future climate change is that agricultural production belts for different crops may shift. Perks and Schulze (2000) found that sorghum's optimum growth areas in South Africa to be relatively robust to anticipated climate change. The area under maize production however, is likely to shrink mainly along the western margin of the present-day distribution of production.

Reilly (1996) refers to two basic methodologies to assess the impacts of climate change on agricultural productivity:

- Structural modelling of the agronomic response of plant and management decisions of farmers based on controlled experimental evidence; and
- Dependence on the observed response of crops and farmers to varying climate.

The most certain aspects of climate change in southern Africa are local warming and higher atmospheric carbon dioxide concentrations. Their effects on crops suggest faster growth and higher yields per unit of water required. Southern African countries with comparatively wealthy economies, such as Botswana and South Africa, may be able to cope with any adverse impacts through imports and agricultural developments. Sustainable development depends on continued prosperity and investment (Downing *et al.,* 1996). These anticipated changes may mean that areas currently under commercial agriculture and forestry may have to shift geographically, often at considerable cost to the changing environmental conditions. However, not all changes will be negative and new opportunities will be presented for the enterprising to exploit (Tyson *et al.*, 2002).

2.6 Characterising Agricultural Sustainability

Hansen (1996) categorises sustainability characterisation into three approaches:

- Characterisation based on adherence to prescribed approaches and an interpretation of sustainability as an approach to agriculture (O'Connell, 1992);
- Characterisation by multiple qualitative indicators and attempts to integrate such indicators being consistent with interpreting sustainability as an ability to satisfy diverse goals (e.g. Troquebiau, 1992, López-Ridaura *et al.*, 2000); and
- Characterisation by combining varied indicators of sustainability into integrated quantitative measures (e.g. Sands and Podmore, 2000).

Torquebiau (1992) investigated bio-physical and socio-economic conditions of agro-forestry home gardens in order to contribute to an operational understanding of sustainability. This consisted of identifying sustainability descriptors (e.g. soil or external inputs) and devising hypotheses to assess the effects of agro-forestry on these descriptors. Measurable indicators that characterise the system descriptor are then employed to evaluate if a particular production system has a negative or positive effect on the descriptors. If there is a negative effect on a descriptor, then the system is deemed unsustainable.

López-Ridaura *et al.* (2000) suggest that the operationalising of sustainability requires new evaluation methods which are qualitatively distinct and facilitate an integrated assessment of the ecological, social, and economic features of agro-ecosystems, and that this should be achieved through the use of appropriate indicators. López-Ridaura *et al.* (2000) highlight a need to develop indicators to assess the relative degree of sustainability of contrasting production systems, especially those throughout the rural sector of the developing world. The framework is based on sustainability being defined by seven general attributes: productivity, stability, reliability, resilience, adaptability, equity, and self-reliance. Sustainability evaluations would only be valid for a specific management system in a given geographic location.

Sands and Podmore (2000) designed an Environmental Sustainability Index (ESI) for use with agricultural systems (Figure 2.6.1). The calculation of the index involves two steps:

- simulating the crop management system and then

- calculating the index from model output.

The indicators used in the environmental sustainability index were chosen to represent soil properties and groundwater availability. This index takes on an environmental perspective and consists of both on- and off-site effects.

Figure 2.6.1 shows (from left to right) the ESI's computational steps from daily outputs, to annual sub-indices, to sustainability sub-indices, which are then aggregated to produce the ESI. The component sub-indices are based on transformations obtained from simulations of the agricultural system using a daily model. The sustainability sub-indices characterise the status of specific soil and water resources over the simulation period, in response to agricultural management practices.

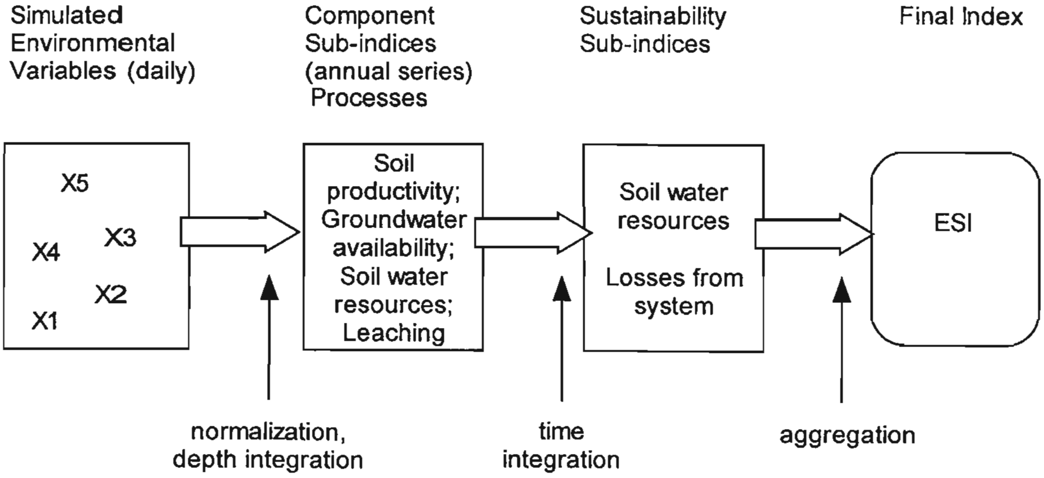


Figure 2.6.1 Flow of information to calculate the environmental sustainability index, ESI (after Sands and Podmore, 2000)

In discussing agricultural sustainability, Hansen (1996) considers it necessary to characterise the concept of sustainability when using it to identify constraints, concentrate research and for policy development. These characteristics are: the definition of sustainability should be literal and in turn system-orientated, quantitative, predictive and stochastic (i.e. treating variability as a determinant of sustainability), as well as diagnostic, in nature (i.e. using an integrated measure of sustainability to identify and prioritise constraints).

2.7 Sustainability: A Working Definition

A working definition of sustainability was derived from the literature review on sustainability (Chapter 2). The derived definition for sustainability will be used as the basis for the framework outlined in Chapter 4 that will be employed to assess agricultural sustainability at various scales in South Africa (Chapters 5, 6, 7, 8).

From the sustainability definitions reviewed and from an examination of the philosophies and schools of thought behind the definitions, this author regards the work of Chambers (1997) as being highly influential and also pertinent to agriculture. Chambers (1997) recognises that humans are at the centre of agricultural systems and that their well-being is a key for the sustainability of agro-ecosystems.

Based on the work of Chambers (1997) the definition of sustainability used by the author in this thesis is:

> '*Sustainability is applying long term perspectives, in regard to human well-being and ecological integrity, to policies and actions.*'

To use Pearce's (1993) terminology, this definition follows a 'weak sustainability' pathway in regard to development and it would be categorised as techno-centric. However, it does recognise intergenerational equity, resource conservation and the value of the goods and services provided by ecosystems. The definition is also essentially void of any influence of the Gaia hypothesis (Section 2.3), as this author believes that it is fundamentally unethical to have a moral obligation to the earth, and this author further believes that the philosophy also entails a reduction in the value of human life.

The sustainability timeframe used in the working definition is worded as 'long term'. How long is long term? In regard to this thesis long term is considered to be two generations, or 40-50 years. This is also the length of the datasets readily available for the agro-ecosystem modelling in southern Africa and it is felt that this length of time frame is useful particularly in looking at possible impacts of climatic changes on agro-ecosystems. This definition does not ignore future generations *per se,* but considers the next one to two generations of being of more significance, as beyond this, timeframe assumptions about humans needs and what society will be like, and what the environmental conditions will be, become considerably more uncertain.

Human well-being is simply the quality of life that a person has. For the purposes of this thesis the 'quality of life' is referring to peoples' physical life, such as whether the person has enough food to eat, access to clean water, basic sanitation etc. and not necessarily the persons emotional or spiritual state.

Ecological integrity refers to the completeness of both agro-ecosystem structure and function, the maintenance of system components and the resulting dynamic of the system. Using a broad term such as integrity allows scope to include the resilience of agro-ecosystems to disturbances. This is particularly important when considering climatic changes or the inter-annual variation of environmental conditions.

This author contends that the working definition of sustainability proposed in this section fulfils Hurni's (2000) five pillars of sustainability (Section 2.2). These pillars are what Hurni (2000) suggests are the fundamentals in the vast majority of sustainability definitions. With human well-being as an essential element of the working definition this author considers four of the pillars (*viz.* acceptable to society, economically viable, economically productive and effective in reducing risk) would be met, although human well-being itself encompasses more than these 'four pillars'. The fifth pillar, that of protection of ecology, would be included as part of maintaining ecological integrity.

According to Brown *et al.* (1987) the working definition of sustainability proposed requires the context to be stated as well as the spatial scales being considered (Chapter 1). Therefore, when applied to agricultural sustainability in South Africa the context and spatial scales need to be stated within the definition. Two definitions of agricultural sustainability which have different spatial scales are given, one for agro-ecosystems in the Highveld region of South Africa and one for smallholder agro-ecosystems in KwaZulu-Natal, South Africa. The working definition of sustainability applied to agriculture in the Highveld of South Africa (Chapters 5, 6, 7) is:

'for the agro-ecosystems in the Highveld region to continue in the long term providing quality well-being for farmers and local communities and to maintain the ecological integrity of the agro-ecosystem.'

The working definition of sustainability applied to small-holder agro-ecosystems in the Potshini area, near Bergville KwaZulu-Natal, South Africa (Chapter 8) is:

'for smallholder agro-ecosystems in the Potshini area to continue in the long term, providing quality well-being for farmers and local communities and to the maintain ecological integrity of the agro-ecosystem.'

These working definitions of agricultural sustainability will be used as the goal of the framework to assess sustainability, which is described in Section 4.2.

A range of tools is available to decision makers when utilising a systems approach to explore sustainability. These include crop growth models, water and soil simulation models, regional and national databases of environmental information and GIS. When a range of these tools is employed, the outputs from them can provide an array of information to help the decision making process. These tools are discussed in Chapter 3.

3 LITERATURE REVIEW OF TOOLS FOR THE ASSESSMENT OF AGRO-ECOSYSTEM SUSTAINABILITY

A range of tools is available to assist researchers and decision makers in investigating the issues surrounding sustainability in agriculture. An assessment of agro-ecosystem sustainability involves future events being examined. Therefore, tools that can simulate the relevant processes of an agro-ecosystem, even in a simple representation, help the decision maker in developing strategies to achieve sustainability. Relevant tools would be ones which, *inter alia*, allow the decision-maker to ask 'what if' questions. These tools include certain crop models and spatial databases. In Section 3.1 the use of crop yield and crop growth models are discussed in regard to sustainability. Models from three research teams which form part of the informal network known as the International Consortium for Agricultural Systems Applications (ICASA) are discussed in Section 3.1.2. The CERES suite of crop yield models is reviewed in Section 3.1.3. Section 3.2 first reports on spatial databases in general and then discuss how they can be used in co-operation with crop models.

3.1 Crop Models

A system is a limited part of reality that contains inter-related elements. A model is a simplified representation of a system, and simulation may be defined as the art of building mathematical models and a study of their properties with reference to those systems (de Wit, 1982; p. 3).

In agro-ecosystems the production of crops involves complex relationships between crop genotype, the soil, the environment and management practices. These interactions within the agro-ecosystem can be simulated with computer models using suitable data sources (Hoogenboom *et al.*, 1990). Crop models are developed as tools to aid crop system decision-making and policy analysis (Boote *et al.*, 1996). A valuable property of crop models is their ability to utilise long-term climate data in order to provide long-term yield simulations which can then serve to quantify risk (Hensley *et al.*, 1997).

A definition of a crop model has been given as a 'quantitative scheme for predicting the growth, development and yield of a crop, given a set of genetic coefficients and relevant environmental variables' (Monteith, 1996; p. 695).

There are numerous organisational levels when considering the biology of crops. Usual levels would include crop, plant, organ, tissues, cells, organelles, macromolecules, molecules and atoms. It is important to remember that the response of the system at a certain level is related to the response at lower levels and successful operation at that level is dependent on the lower levels functioning correctly, and not vice-versa (Thornley and Johnson, 1990).

Boote *et al.* (1996) list the uses of crop models as follows:

- Models can assist researchers in their understanding about the interactions of genetics, physiology, and the environment.
- They can assist in pre-season and in-season management decisions on cultural practices, fertilization, irrigation and pesticide use.
- Crop models can assist policy-makers by predicting rates of soil erosion, leaching of agrochemicals, effects of climatic change and large-area yield forecasts.

An application of crop production models is to determine the yield that can be achieved with current varieties in a specific environment and to ascertain opportunities for yield improvement in well managed systems (Kropff *et al.,* 2001). In systems that are low yielding due to factors such as limited access to external inputs, it is not always possible to simulate the optimum yield. Therefore, to simulate yields in such environments alternative approaches are required.

It is conventional to distinguish between mechanistic and empirical models (Monteith, 1996; p. 695). In empirical models the observed data are examined and an equation, or set of equations, is formulated to fit these data. The mechanisms that trigger the responses are not investigated. The model is, therefore, basically a mathematical description of observed data. However, empirical models can provide the decision maker with a robust tool with which to summarise and interpolate data (Thornley and Johnson, 1990).

A mechanistic crop model contains the crop system broken down into components, with the model then assigning processes and properties to these components. Mechanistic modelling follows the reductionism method, i.e. responses at a certain level of the biological system are related to the responses at lower levels. Responses at the whole-plant level are synthesised by combining the set of equation that define the system components (Thornley and Johnson, 1990).

There is a need for both complex and simple models. In some cases, simple model are not appropriate because they are not programmed to address a particular phenomenon. In other cases, complex models are not appropriate because they may require inputs that are not practical to obtain in a field situation (Boote *et al.*, 1996; p. 704).

3.1.1 Crop yield models

The major use of crop yield models is to evaluate how crop production can be increased and how the efficiency of the resources used can be enhanced. Examples of computer models that have the capacity to produce yield estimates include *ACRU* and GAPS.

In the *ACRU*, agrohydrological modelling system (Schulze, 1995) crop-related sub-models have been developed that are not site or climate specific. These sub-models include maize, sugarcane and wheat yield simulation models, as well as one for primary production. These models have been developed and tested widely under southern African conditions (e.g. Schulze et al., 1995a; Lumsden, 2000). The *ACRU* maize yield model has three growth stages for maize:

- Growth stage 1 - emergence to flower initiation
- Growth stage 2 - flowering stage, and
- Growth stage 3 - end of flowing to maturity.

The length of time for each phenological stage is driven by growing degree days. The seasonal maize grain yield is calculated using potential maize grain yield for the season and this model operates when *ACRU* splits crop transpiration from soil water evaporation (Schulze *et al.*, 1995). This daily time step model can also simulate crop yields under 2xCO_2 atmospheric conditions.

GAPS is a model which simulates components of the atmosphere and the soil and plant system. GAPS was initially designed for use in research into environmental biophysics (Rossiter and Rhia, 1999). This model enables the user to compare different means of simulating the same processes and these selections are separate from other modelling choices. Photosynthesis is computed each time step for both the sunlit and diffuse-lit leaf areas and the model is able to simulate photosynthesis in situations where water becomes limiting during mid-afternoon hours, when stomata tend to close. The growth of the maize crop is simulated on a daily time step and included are processes that change the leaf area index as well as accounting for canopy expansion and root expansion (Rossiter and Rhia, 1999).

The GAPS model has been used to estimate crop yields on a regional scale in Illinois, USA (Moen *et al.*, 1994). Melkonian *et al.* (1998) compared different re-orientations of crop responses to elevated carbon dioxide, while Rossiter and Rhia (1999) implemented two routines for use in GAPS to model plant competition.

The GAPS and *ACRU* maize models replicate yield responses in different ways. The GAPS model produces estimations based on the yield responses to climate. However, *ACRU*, which is an agrohydrological model, has a soil water budget as the basis for the model and yield responses are estimated in response to the changing soil water budget.

3.1.2 Crop growth simulation models

Simulation models are an appealing tool to investigate crop improvement, as growth and development can be predicted in regard to the effect of soil and climatic conditions, agronomic practices and cultivar traits (White 1998).

The International Consortium for Agricultural Systems Applications, ICASA, is an informal network which seeks to develop and apply compatible and complementary crop simulation models and other systems analysis tools. In particular, three research groups associated with ICASA have sought to develop crop simulation models that are modular in structure, so as to increase the ease with which new components can be added and maintained (Jones, 2001). These groups are

- the Agricultural Production Systems Research Unit in Australia (APSRU), which developed the APSIM model
- the 'School of de Wit' at the Agricultural University, Wageningen in the Netherlands and
- the erstwhile International Benchmark Sites for Agro-Technological Transfer, IBSNAT. IBSNAT ended in 1991 but the models developed have been adapted to various regions in the world and are widely used by researchers and decision-makers.

Each of the groups was made up of researchers from a range of institutions in different countries.

3.1.2.1 APSIM

The Agricultural Production Systems Simulator, or APSIM, was developed by the APSRU in Australia in response to existing crop system models' not providing all of the following criteria:

- satisfactory sensitivity in regard to extremes of climatic inputs for economic risk assessment of yield variability
- simulation of trends of various management strategies on soil productivity and
- software that allows research teams to continually improve the models in the APSIM shell (McCown *et al.*, 1996).

The significant difference between APSIM and other model systems is that the soil and its response to weather, crops and management is the focus, rather than the crops being the centre point of the model system. The structure of APSIM is shown in Figure 3.1.1. The different processes relate to each other through a central control unit. Several of the models of APSIM that are used to model various processes have been adapted from other systems. For example, the soil nitrogen model has been adapted from the DSSAT-CERES model. McCown *et al.* (1996) comment that the key difference between DSSAT and APSIM is that DSSAT is unable to simulate the cumulative effects of the crop on the soil. However, this is no longer the case, as the DSSAT models have been developed to simulate the effect.

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 (Figure 3.1.1). The crop growth modules can be interchanged, and more than one growth module can be connected concurrently (McCown *et al.,* 1996).

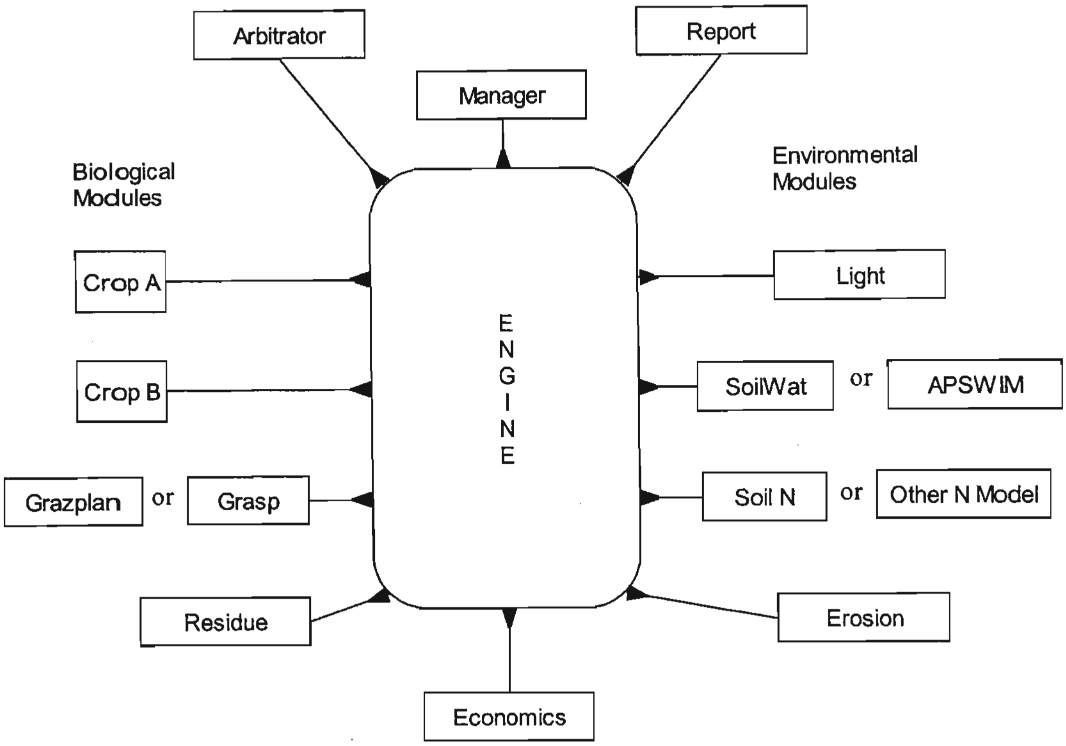


Figure 3.1.1 The structure of the APSIM program (after McCown *et al.*, 1996)

The APSIM wheat and sorghum crop models have been used to characterise major drought periods in Australia. A range of cropping systems at different locations was studied. The results from APSIM were compared with rainfall estimates of drought for the same period and APSIM was deemed a superior measure of drought severity on farm performance. This was due mainly to the agricultural simulator's being able to reflect on the impacts of rainfall timing, intensity and soil water storage (Keating and Meinke, 1998).

Asseng *et al.* (1998) found APSIM to be a useful tool in estimating the yield for wheat as well as for nitrogen leaching from a sandy soil in Australia. The soil was found not to meet potential yield estimates owing to its high drainage and leaching potential. Also in Australia, Muchow and Keating (1998) used APSIM for irrigation scheduling and yield estimates for sugarcane. These results enabled a range a management options for sugarcane production to be investigated.

Keating and McCown (2001) report on the APSIM model's being adapted and used for small-scale agriculture in Africa, particularly in Kenya and Zimbabwe. Research was carried out on soil fertility in areas that experience extremes in climate variability. Different scenarios were investigated regarding processes at work in both the soil and plant. Results emphasise the value of matching investments in fertiliser with early establishment and weed control.

3.1.2.2 School of de Wit crop models

Crop simulation models have been developed at the Agricultural University, Wageningen in the Netherlands by the 'School of de Wit'. In general the models produced by the School have similar characteristics:

- Rates of change are calculated as functions of time.
- The system is divided into hierarchical levels of organisation.
- The system is characterised by a set of state variables.
- The models are explanatory because the calculations involving rate variables are based on knowledge of the variables in the system.
- All plants in the crops are considered to be of the same genotype (Bouman *et al.,* 1996).

Two of the more important models developed by the researchers at Wageningen are MACROS and SUCROS (Bouman *et al.,* 1996). Figure 3.1.2 shows the relationship between state, rate and auxiliary variables and the flow of matter. The diagram is for the SUCROS model, but is considered a standard structure of a crop simulation model from the School (Bouman *et al.,* 1996). The rectangles indicate state variables, the rounded rectangles rate variables and the oval an auxiliary variable, the dotted lines the flow of information and the solid lines the flow of matter.

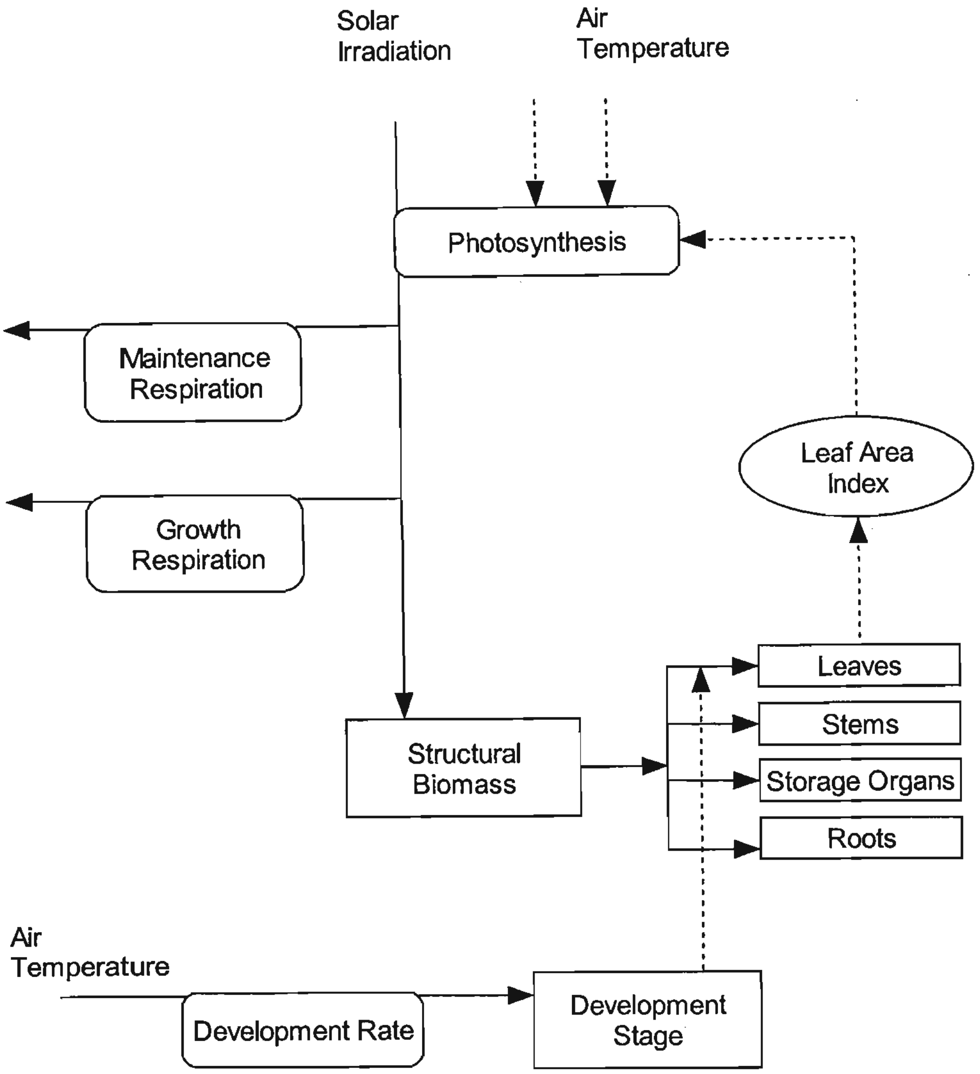


Figure 3.1.2 Relationships in a standard 'School of de Wit' crop model (after Bouman *et al.*, 1996)

In the SUCROS model the physical and physiological processes can be applied to a range of environmental conditions. The model simulates, from emergence to maturity, the time course of dry matter production of a crop, and is reliant on the daily total irradiation and air temperature. The dry matter produced is divided into roots, leaves, stems and storage organs (van Keulen *et al.*, 1982). Partitioning factors are introduced as a function of the phenological state of the crop. Simane *et al.* (1994) used the SUCROS-87 model to investigate moisture stress on potential yield of wheat in Ethiopia. The average simulated yields were found to be high compared with national yields. This could be due to influences on the agro-ecosystem such as pests or poor management not being incorporated.

The MACROS model was developed as part of a project to transfer technology and systems methodology to researchers in Southeast Asia (Jones *et al.,* 2001). The model is generic and consists of a series of basic modules for potential and water-limited crop growth, with parameters given for a large number of crops (Bouman *et al.,* 1996). Bouman (1994) used the MACROS model to illustrate the simulation of crop yield on rain-fed upland rice in the Philippines. The accuracy of the model was found to be dependent on the availability of accurate soil and management parameters.

3.1.2.3 International Benchmark Sites Network for Agrotechnology Transfer (IBSNAT)

The International Benchmark Sites Network for Agrotechnology Transfer (IBSNAT) Project has involved multiple institutions and organisations (Hoogenboom *et al.,* 1994). The overall aim of the IBSNAT project was to 'apply systems analysis to problems faced by resource-poor farmers in the tropics and sub-tropics, specifically in the area of evaluating new and untried agricultural technologies' (Uehara, and Tsuji, 1998; p. 1).

In order to achieve this purpose, the project organised researchers and resources to concentrate on the following objectives:

- Creation of a decision support system capable of simulating the risks and consequences of different choices;
- Defining the minimum amount of data required to make simulations;
- Testing and application of the decision support system on global agricultural problems requiring site-specific yield simulation (Uehara, 1998); and
- Using a systems analysis approach to assist developing countries in agrotechnology transfer and decision-making (Hoogenboom *et al.,* 1994).

One of the outcomes of the IBSNAT Project is a systems analysis based decision support system. As a result, the Decision Support System for Agrotechnology Transfer (DSSAT) Version 2.1 was released in 1989 (Hoogenboom *et al.,* 1994).

Decision makers require tools that will enable them to make choices now, and that will have favourable outcomes that are both environmentally safe and economically sound, perhaps up to 50 years into the future. DSSAT allows the user to answer 'what if' questions (Tsuji *et al.,* 1994).

A characteristic of IBSNAT crop models is that they have generic input files which can be used by all the models. The input variables required fall into five categories: climate, soil water, soil nitrogen, crop management and genetics (CIESIN, 1997). These are described in Section 3.1.3.

3.1.3 The Decision Support System for Agrotechnology Transfer (DSSAT)

'The goal of decision support systems is to improve the performance of decision makers while reducing the time and human resources required for analysing complex decisions' (Jones *et al.,* 1998 p.158).

The DSSAT was therefore designed to allow the user to:

- Input, organise and store data;
- Retrieve, analyse and display data;
- Calibrate and evaluate crop growth model; and
- Evaluate different management practices at a site (Jones *et al.,* 1998).

The DSSAT software consists of a Data Base Management System, a set of validated crop models and a program for analysing and displaying outcomes. Users of DSSAT are able to fit the biological requirements of the crops to the physical characteristics of the land (Tsuji *et al.,* 1994).

Climate related data required to operate the models includes the latitude and longitude of the climate station being used, as well as daily values of solar radiation (MJ/m^2/day), maximum and minimum air temperature (°C) and rainfall (mm) at that station. Atmospheric carbon dioxide concentration (ppmv) is also required for studies involving climate change impacts.

The soil water attributes required are soil albedo, permeability, drainage from the soil profile and first stage soil water evaporation. Every soil layer necessitates a value for thickness of soil horizon, saturated soil water content, soil water content at field capacity and permanent wilting point, initial soil water content and relative root distribution (Hoogenboom *et al.,* 1995).

The information needed to express crop management options comprises of planting date, plant density, row spacing, selection of cultivars and soil type (CIESIN, 1997). For the CERES models there is the ability of the program to incorporate irrigation management and nitrogen fertilizer management.

Each model uses one input file that contains parameters that characterise the growth and development traits for various cultivars (Hoogenboom *et al.,* 1995).

3.1.3.1 CERES suite of models: General structure

One of the crop model options in DSSAT is the CERES-Cereal model. This is a suite of models which operates on a daily time step and simulates the main physiological processes for barley, maize, millet, rice, sorghum and wheat. The main processes that CERES simulates are:

- Photosynthesis
- Respiration
- Accumulation and partitioning of biomass
- Phenology
- Extension growth of leaves, stems, and roots
- Soil water extraction
- Evapotranspiration and
- Nitrogen transformation processes (Wu *et al.,* 1989).

Potential dry matter production is determined by using a function of solar radiation, leaf area index and reduction factors for temperature and moisture stress. Six phenological stages of leaf and stem growth are replicated, based primarily on thermal time. Accessible photosynthate is at first partitioned to leaves and stems, and later for ear and grain growth. Any residual photosynthate is assigned to root growth unless the dry matter available for root growth is below a minimum limit, whereupon grain, leaf and stem allocations are reduced and the minimum level of root growth occurs (CIESIN, 1997).

CERES-Maize (Jones and Kiniry, 1986) is one of the options within the CERES-Cereal model.

In version DSSAT v3 the crop simulation modules require information from the DSSAT database. The association between the modules and input files is shown schematically in Figure 3.1.3. The experiment detail file is referred to as FILEX and contains information to document field experiments or farm management. The soil profile data are stored in a file that is accessed by the module with the profile data selected using a soil number from FILEX. Daily climate data are stored in yearly files. For the seasonal modelling discussed in Section 5.3 the IBSNAT30.INP file (Figure 3.1.3) is created outside the DSSAT shell and run consecutively for all Quaternary Catchments with the use of a batch file. The sequential modelling using CERES-Maize and the creation of input files within the DSSAT shell is discussed in Sections 6.2, 7.2 and 8.3.

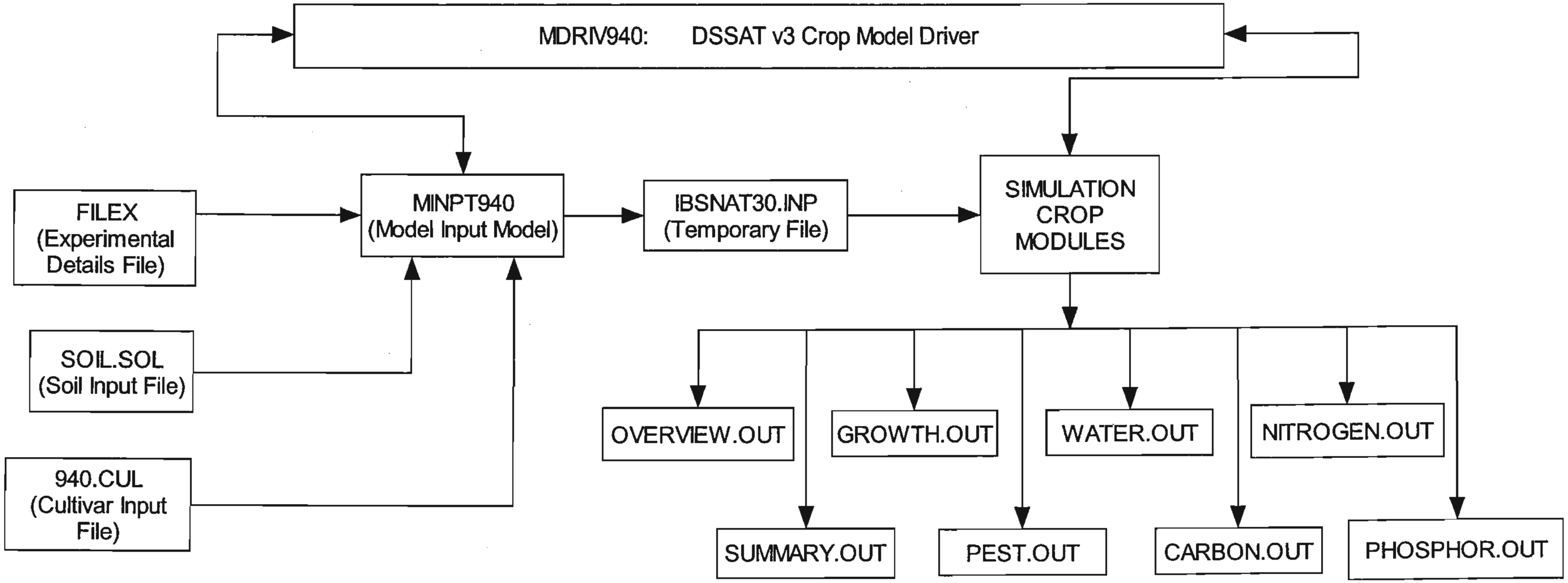


Figure 3.1.3 Schematic of relationships between the crop model driver program (MDRIV940.EXE), the crop model input program (MINPT940.EXE), the temporary files read by the crop model modules (IBSNAT30.INP), and the crop simulation model modules (after Jones *et al.*, 1999; p. 16)

Cultivar information is read from crop-specific files and FILEX specifies which cultivar to select from this file. Outputs files are from the crop model depend on the options selected in a simulation control in FILEX (Jones *et al.,* 1998).

The schematic relationships of the crop model driver program (MDRIV940.EXE), the crop model input program (MINPT940.EXE), the temporary files read by the crop model modules (IBSNAT30.INP), and the crop simulation model modules (Jones *et al.*, 1998) are illustrated in Figure 3.1.4. The model driver controls entry to the input module and to the correct crop model. It is performed every time a crop is to be simulated (Jones *et al.*, 1998).

The DSSAT v3 crop models were originally developed for simulating the growth of annual crops during a single season. The various crop models have a similar structure, which has allowed their use for long-term simulation of cropping sequences.

The term sequence in DSSAT models refers to the growing of a crop in continuous succession or a rotation of different crops for a stated length of time (Thornton *et al.*, 1995). Since DSSAT operates on a daily time step, the simulation of cropping in sequence necessitates continuous calculations of soil and water process on daily basis, which will include those days when no crop is growing. A temporary file named 'TMP.DAT', which contains the relevant variables to pass from one model to the next, assists the running of the models in sequence. Consequently, the majority of variables in the temporary file which are passed on from season to season are those that are required for the simulation of soil water, carbon and nitrogen processes (Bowen *et al.*, 1998).

The links between the model driver and crop simulation models are shown in Figure 3.1.5. At the beginning of the simulation the driver program reads the order of the cropping sequence from an experimental details file. The driver then continues running the respective models for the number of years specified in the same experimental details file (Bowen *et al.*, 1998).

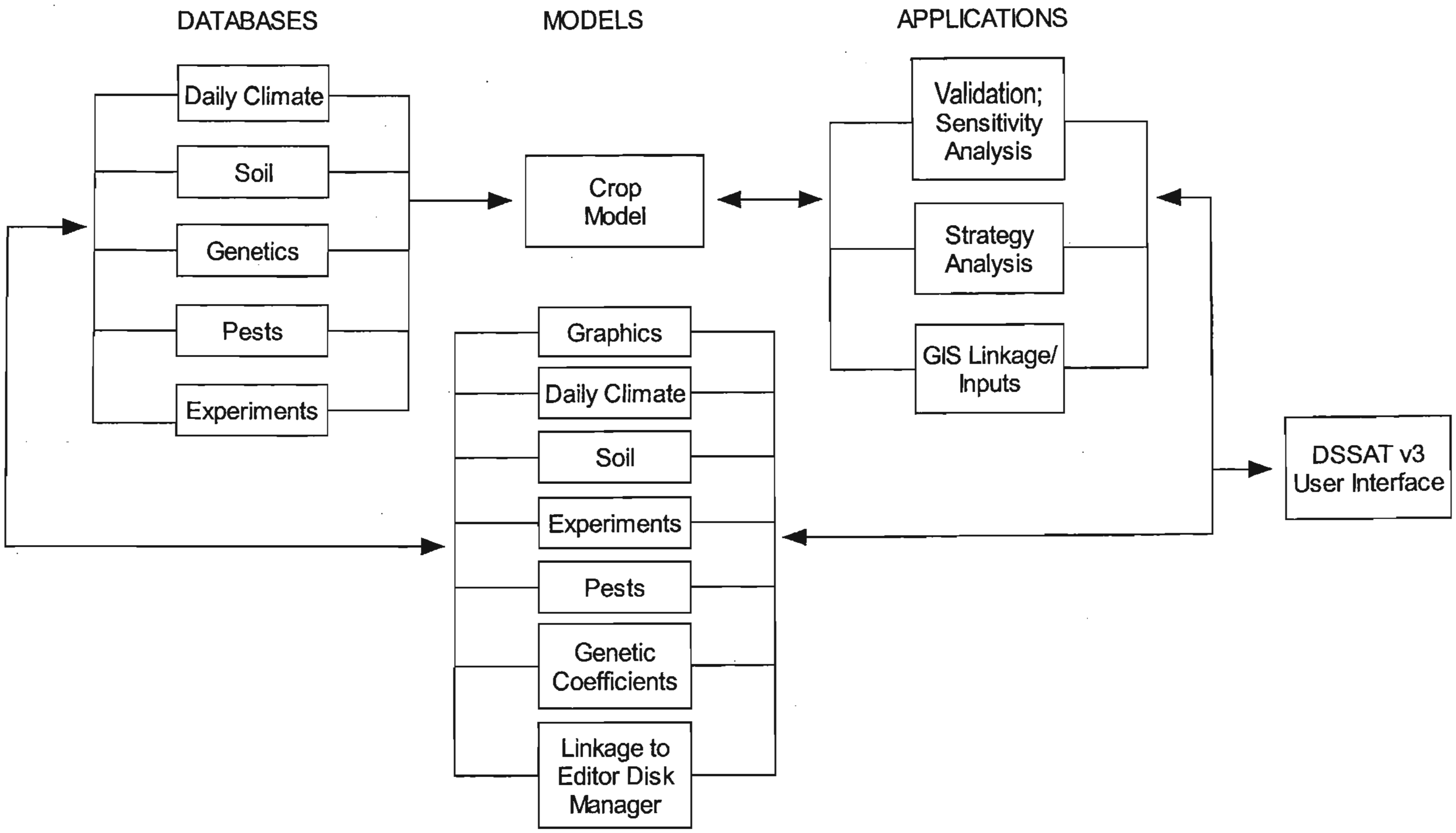


Figure 3.1.4 DSSAT v3 database components and linkages for crop model applications (after Jones *et al.*, 1998; p.164)

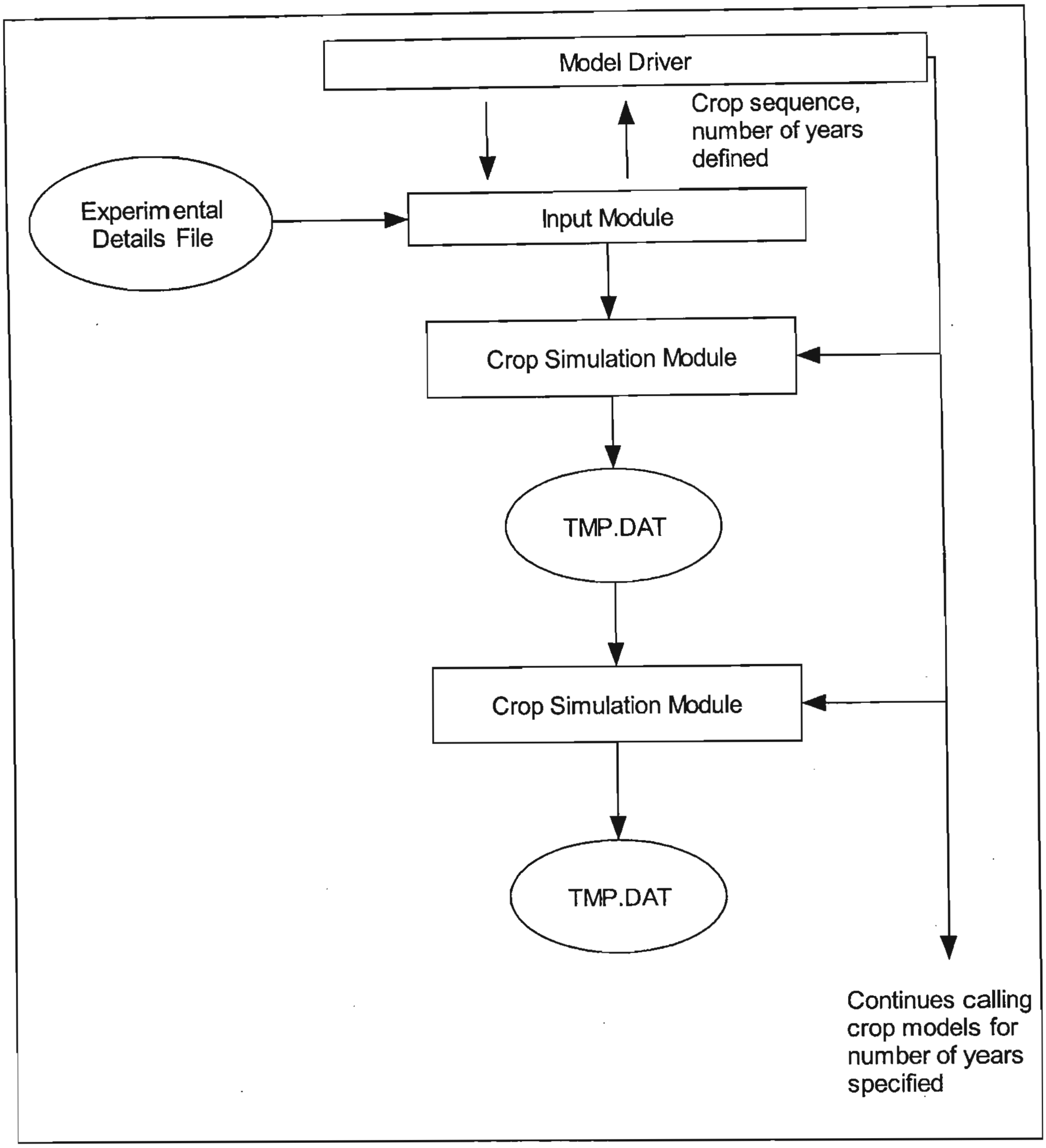


Figure 3.1.5 Linkages between the model driver and crop simulation models to simulate continuous cropping sequences in DSSAT v3 (after Bowen *et al.*, 1998; p. 317)

3.1.3.2 CERES-Maize applications in the USA

The CERES-Maize model has been used both on its own and in combination with other models to evaluate management and cropping strategies, predict yields, assess impacts of climate change on growth and yield, assess drought severity, and model the effects of irrigation, drainage, water flows and solute transportation as well as, nitrogen uptake, fertiliser impacts, root growth and pests. A few examples of its applications in the USA follow below.

CERES-Maize was utilised in the evaluation of maize irrigation strategies in Michigan, USA. Boggess and Ritchie (1998) found that profit maximising strategies called for significantly less water than maximum yield strategies and that irrigation was unique as a production input, in that increasing rates of application reduced the weather related variability in yield.

Paz *et al.* (1999) developed a technique to use the CERES-Maize model to characterise maize yield variability. The model gave predictions of the yield trend along field transects, explaining over half of the yield variability. Results showed high spatial distribution of optimum nitrogen fertiliser recommendation for grids across the field. Grid-level nitrogen fertiliser management and lower amounts of fertiliser produced higher yields and was found to be more profitable than either transect- or field –level fertilizer application rate.

Hook (1994) used crop models to plan water withdrawals for irrigation in drought years. The potential and the lowest yields for maize, soybean and peanut were calculated using three crop growth and water use models, *viz.* CERES-Maize, SOYGRO and PNUTGRO. Most of the irrigation needs of maize in the drought years occurred before those of peanut or soybean.

A methodology was developed to estimate the economic value of 'perfect information' concerning the optimum application schedule of nitrogen using CERES-Maize (Thornton and MacRobert, 1994). It was concluded that in farming areas of comparatively high levels of weather-related risk, use of appropriate forecasting and input optimisation techniques could result in moderate economic benefits over the long term.

Improving irrigation scheduling strategies for maize is important for both water conservation and growth of the crop. Hodges *et al.* (1987) identified optimal thresholds for several maize irrigation strategies in the south eastern USA. Net returns and irrigation amounts were determined for each growth stage using the growth simulator CERES-Maize.

CERES-Maize has been used widely for yield prediction. Hodges *et al.* (1987) applied the model in North American conditions to estimate production from the US corn-belt and tested the model to assess if it was able to accurately predict annual fluctuations in maize production. The results indicated that the model could be used in other parts of the world for large area yield estimation where daily maximum and minimum temperatures, precipitation, and solar radiation data are available.

CERES-Maize has been valuable in its use under North American conditions for a wide range of agricultural assessments. For it to be used effectively outside of these conditions adaptations are required to take into account different environmental conditions.

3.1.3.3 CERES-Maize applications in South Africa: Some examples

Various studies have been carried out in South Africa using the CERES-Maize model. Schulze *et al.* (1993) used the CERES-Maize model as part of an analysis tool investigating agricultural productivity in southern Africa and its response to climatic changes. The study revealed a large dependence of production and crop yield on the intra-seasonal and inter-annual variation of rainfall.

Tsuji *et al.* (2002) reported on the progress made by the South African Agricultural Research Council's Grain Crops Institute in Potchefstroom in adapting CERES-Maize to conditions in the dry western areas of the Highveld in South Africa. Several studies have been carried put to determine the necessary inputs, such as genetic coefficients, phenology and row widths, required to run CERES-Maize under South African conditions. These studies have enabled further research to be carried out with CERES-Maize, including work on yield prediction, drought impacts and climatic change.

An investigation by du Toit *et al.* (1994a) found that a significant difference existed between observed and optimised genetic coefficients. The conclusion was that the genetic parameters in the subroutines of CERES-Maize would need to be calibrated for South African growing conditions.

CERES-Maize was evaluated (du Toit *et al.,* 1994b) in regard to optimising the planting date of cultivars. Different stages of the plant growth were calibrated in CERES-Maize to improve phenological predictions. The silking date of maize is important as this coincides with the mid-summer drought which frequently occurs in the western Highveld of South Africa and which can affect yield negatively. As a result of the modifications made by du Toit *et al.* (1994b) systematic errors were reduced.

In the western Highveld region of South Africa rainfall is the major limiting factor to maize yields. Management practices employed to combat the lack of rainfall include reducing plant populations and widening row spacing. CERES-Maize was evaluated in regard to these production practices. Yield differences between observed and simulated were found to be due to the second ear on the predominant maize plant, which the CERES model does not simulate (du Toit *et al.*, 1994c). Furthermore, CERES-Maize v.3 was found to have low accuracy in simulating the kernel numbers of maize under western Highveld conditions. The factors that could have caused this were identified as the number of ears per plant and water stress before and during silking (du Toit *et al.*, 1997).

A field trial was carried out by du Toit *et al.* (1998) to improve the prediction of the silking date of maize by CERES-Maize, which has been linked to the problem the model has in simulation of the kernel number. The modifications made improved the simulation of the silking date (du Toit *et al.*, 1998; du Toit and Prinsloo, 2000).

The above adaptations made to the CERES-Maize model have been used to predict yields, assess drought impacts and investigate effects of future climatic conditions on maize production in South Africa. The El Niño-Southern Oscillation phenomenon is a significant cause of drought and, therefore, reduction in maize yields in South Africa. The CERES-Maize simulation was used with seasonal weather predictions and climatic data for historic El Niño years to simulate production practices so that management options could be ascertained that could help to reduce the negative impacts on yield of an El Niño year (du Toit and Prinsloo, 1998).

Using daily climate and soils databases, a Geographic Information System (GIS) in combination with the CERES-Maize and Putu Maize models, de Jager *et al.* (1998) developed a framework for drought assessment in the Free State Province of South Africa. Drought hazard in maize was quantified and mapped by employing climate characteristics of the Southern Oscillation Index and running crop models in a GIS.

Du Pisani (1987) developed a methodology in which the CERES-Maize model was employed to assess drought impacts on maize at an early stage in the season. The model was verified using South African data. Excellent correlations were found between yield predictions based on observed early season data in combination with median data for the remainder of the season, and yield predictions based on observed data over the entire season.

Using a calibrated version of the CERES-Maize v3.0 model, du Toit *et al.* (1999) investigated maize yield responses to climate change. Four potential scenarios were tested at 19 individual sites representing most of the current maize production areas in South Africa. Thirty years of model simulation were conducted for each site with average, standard deviation and yield distributions being calculated. The process was repeated using climate scenarios proposed by different General Circulation Models (GCMs). The GCMs were the Climate Systems Model, the Genesis Model, the Hadley Model with no sulphate forcing, and the Hadley Model with sulphate forcing. Descriptions of the GCM versions have been given by Perks *et al.* (2000). To investigate the effects of the different climate scenarios on a regional and national level, the CERES model was linked to a Geographic Information System.

The results of the crop model simulations run under the different climate scenarios showed that maize yields would either remain at more or less current levels or decrease by between 10 and 20%, depending on which GCM scenario was used. In some of the marginal areas of the Free State and North-West Province maize production would not be economically sustainable under certain future climate scenarios.

De Vos and Mallet (1987) evaluated CERES-MAIZE with another simulation model, CORN F (Stapper and Arkin, 1980), using South African data. The results indicated that both models agreed well with observed values of total above-ground plant dry mass, leaf area index, grain yield and soil water content. However, CORN F tended towards a systematic under-prediction of leaf area index compare with CERES-Maize, while CERES-Maize provided more realistic estimates of soil water content than CORN F.

The inability of CERES-Maize v3.0 to simulate a fluctuating shallow water table has been identified by du Toit *et al.* (2002b) as a major constraint in using the model under irrigated conditions in South Africa as well as in Kenya. A waterlogging sub-routine was therefore written, so that it is now possible to simulate the fluctuation of the water table without the need for additional soil inputs. It is now also possible to quantify the influence of oxygen stress on maize by simulating waterlogging.

Jones and Thornton (2003) modelled the possible impacts of climate change on smallholder maize production in Africa and Latin America using a third order Markov rainfall model, the CERES-Maize model and output from a GCM (HadCM2). The results showed an overall 10% reduction in maize production to 2055. On a regional scale large variability in yields occurred, and Jones and Thornton's conclusion was that climate change needed to be assessed at the household level so that the people who would be most vulnerable to its impacts could be targeted with appropriate research and development. The results for South Africa showed that the simulated baseline yield for smallholders was 1310 kg/ha compared with the FAO yield figure for 2000 of 2029 kg/ha, with the simulated yield for the year 2055 being 1061 kg/ha for smallholder rainfed production systems.

Lumsden and Schulze (2004) studied management strategies for small-scale farmers producing maize under conditions of climate variability, using the CERES-Maize model. An analysis was made of the accuracy of yield forecasts based on rainfall forecasts, and to ascertain whether these forecasts could be valuable to the small-scale farmer when planning crop management strategies.

3.1.4 Discussion on Selection of Crop Models for Sustainability Modelling

South African agro-ecosystems respond to mechanisms that are interdependent and rely on water, nutrients and crops. There is considerable variation of those factors from site-to-site. For the purposes of this thesis a modelling system is required that can simulate maize growth. From the model, outputs are required that can be used as indicators to assess farmer and community well-being, the ecological integrity of the system and then the overall likelihood of that system being sustainable. Two yield models were briefly explained (*ACRU* and GAPS in Section 3.1.1) and three research groups (APSRU, IBSNAT and 'School of de Wit') that have produced complex maize growth models were described in Section 3.1.2.

Similarities exist between APSIM, DSSAT and the School of de Wit models. The three groups each have models of the main food groups with the crop components being separate from the environmental routines. This separation of components has allowed for routines of the different processes to be 'borrowed' by another modelling group and to build on that existing work. For example, as was already mentioned in Section 3.1.2.1, the soil nitrogen model for APSIM has been adapted from the DSSAT-CERES model.

However, there are also considerable differences in the modelling systems. This is particularly true of the file conventions and data formats, which appear to be quite dissimilar from each other. In terms of being able to measure model performance from the literature, this seems particularly difficult due to the different requirements of the models for inputs, initial conditions and environmental information.

There appear to be three major differences in how maize is modelled in the 'School of de Wit' WOFOST model and how it is modelled in the CERES-Maize model:

- The maize development in WOFOST is driven primarily by availability of assimilate from photosynthesis, while temperature is the primary driving force in CERES-Maize model.
- Growth respiration and maintenance respiration are used in WOFOST to determine dry matter production whereas in CERES-Maize dry matter production is derived from intercepted solar radiation.
- In terms of phenological specification, CERES-Maize requires specification of six phenological stages whereas WOFOST requires phenological specification of growing degree days (Yang *et al.*, 2003).

The APSIM model, WOFOST, or the *ACRU* model could have been used for the sustainability modelling in this thesis. Nonetheless, this author determined that a more complex growth model that had been regionally calibrated was the most suitable for the research. The CERES-Maize model from the DSSAT suite of models met the criteria. Extensive regional calibration has been carried out using CERES-Maize, particularly in the dry western areas of the South African Highveld (du Toit *et al.,* 1994 a, b, c; Tsuji *et al.*, 2002). This model is not only internationally recognised, but is also used widely within South Africa and many field trials have been performed to derive genetic coefficients for the various maize varieties grown in the country. The routines that simulate the runoff and drainage of water from the soil in CERES-Maize are not as sophisticated as the ones in *ACRU*, especially for South African conditions (the routines for runoff and drainage for CERES-Maize are described in Sections 4.2.1.6 and 4.2.1.7 respectively). Despite this, the author concluded that sensitivity of maize yield response to environmental conditions in CERES-Maize was appreciably higher than in *ACRU*. The primary function of the *ACRU* model is to simulate the soil water budget. As the grain yield forms an important part of the sustainability assessment, particularly on a regional scale, a model that was highly sensitive to changing environmental conditions was required.

The vast majority of the work carried out to calibrate CERES-Maize to South African conditions has been carried out primarily to improve the estimates of yield. Therefore, the ability of the routines that simulate runoff, drainage and nitrogen movement in the soil, particularly at a regional or even at a Quaternary Catchment scale, has not been assessed to the same extent as yield estimations. Therefore, when assessing sustainability at a regional scale (i.e. South African Highveld, Chapter 5) this author decided to base the sustainability assessment on estimations of yield and the variations in yield only. The author recognises that this presents a narrower view of what is happening in the overall agro-ecosystem, particularly in term of goods and services performed by the agro-ecosystem. However, agro-ecosystems exist primarily to produce food and fibre so that farmers can provide for their families and supply urban areas with products. Focusing on yield is still valid in regard to sustainability, as 'unprofitable agricultural systems will not continue' (Edwards-Jones and Howells, 2001; p. 32).

Many studies (described in Section 3.1.3) have been carried out using the CERES-Maize model in South Africa. This particular study will build on the work by Schulze *et al.* (1993) by incorporating the information available in the South African Quaternary Catchments Database (Chapter 5). The research carried out by the South African Agricultural Research Council's Grain Crops Institute in Potchefstroom in adapting CERES-Maize to South African conditions (du Toit *et al.*, 1994 a, b, c; du Toit *et al.*, 1997; du Toit *et al.*, 1998; du Toit and Prinsloo, 2000) has improved the simulation of maize growth, particularly in the drier western areas of the Highveld (Chapters 6 and 7). Lumsden and Schulze's (2004) work on management strategies serves as useful guide in modelling small-scale agriculture with CERES-Maize (Chapters 6 and 8).

3.2 Spatial Databases

3.2.1 Linking Crop Model Output with Geographical Information Systems (GIS)

A comprehensive list of GIS-model interfaces may be found in Hartkamp *et al.* (1999). The benefit of linking a GIS database to a crop model is that 'the spatial data contained within a GIS system can be used as the inputs to the models to simulate various scenarios which can then be graphically depicted' (du Toit, 1999; p. 99).

There are GIS databases available in South Africa that can be used in conjunction with crop models. These databases have been linked with both simple and complex crop models to estimate potential yield and suitable cropping areas (Kiker, 1999; p. 23). Schulze (1997) used a high spatial resolution database, which had its beginnings in the Water Research Commission's rainfall mapping project carried out by Dent *et al.* (1989), in conjunction with Smith's (1994) rule-based yield models to explore areas of climatic suitability and yield potential for range of crops.

The School of Bioresources Engineering and Environmental Hydrology (BEEH) at the University of KwaZulu-Natal in Pietermaritzburg has developed an environmental database comprising of the 1946 Quaternary Catchments which have been delineated over South Africa, Lesotho and Swaziland (Schulze *et al.*, 2004). A Quaternary Catchment is the smallest drainage area that the South African Department of Water Affairs and Forestry considers for operational planning.

3.2.2 Quaternary Catchments Database

The South African Quaternary catchments database has been described by Schulze *et al.* (2004). In this database, the so-called Primary drainage regions of South Africa have been divided into Secondary, then Tertiary and followed by Quaternary catchments. The hydrologically (and agriculturally) relatively homogenous Quaternary Catchment areas are delineated according to the prevailing hydrological regime, i.e. the more spatially variable the hydrological responses of a region, the smaller the QCs are. The QCs have been numbered alphanumerically in a downstream order. An example of a QC number is V12F, which lies close to the town of Ladysmith in KwaZulu-Natal. The Quaternary Catchment number is interpreted in the following way:

- The letter V would denote the Primary drainage region of V.
- The number 1 denotes the Secondary drainage region of the Primary region V.
- The next number, 2 denotes the Tertiary sub-drainage region 2 within Secondary region 1 of V.
- The final upper case letter F refers to the specific Quaternary Catchment of Tertiary region 2 (Midgley *et al.*, 1995).

The School of BEEH's environmental database of the 1946 QCs includes, together with other more hydrologically related information, soils characteristics, land cover attributes, daily rainfall, daily maximum temperatures, daily minimum temperature, and daily as well as monthly reference potential evaporation information for each QC.

The soils information contained in the Quaternary Catchment Database is derived from the Land Type information from the Institute for Soil, Climate and Water (ISCW). From this information quantitative input of, for example, soil horizon thickness, soil water contents at critical retention levels and drainage rates have been derived using a set of working rules and equations. This work is detailed in Schulze *et al.* (1995c).

The database used in this study contains a daily rainfall record of 45 years (1950-1994) for each QC. Meier (1997) used an automated inverse distance weighting technique to synthesise any missing rainfall records occurring at the stations selected for the database. The method involves the weighting of the recorded rainfall from stations surrounding a driver station inversely, depending on the distance of those stations from the driver station. This gives the closest station the highest and the furthest station selected the lowest weighting. Data from over 9000 daily rainfall stations were considered in the process of selecting a rainfall station (driver station) to represent as closely as possible the typical daily rainfall regime occurring over each QC. The criteria for selecting a rainfall station to represent a QC included that they require daily values to reflect short term temporal rainfall variations, have a sufficient record length to account for inter-annual variation in rainfall and be positioned within the catchment boundary (Meier, 1997). This database has been recently updated and expanded (Schulze *et al.*, 2005). The mean annual precipitation of the South Africa Quaternary Catchments is shown in Figure 3.2.1. The Quaternary Catchments database has been further refined (Schulze *et al.*, 2004) to be able to perform spatially comparative simulations of:

- land use change impacts
- climate change impacts (using output from four GCMs)
- crop yields
- sediment yield
- irrigation demand and
- hydrological risk analysis.

A variety of models is available that can simulate processes which occur in a range of agro-ecosystems. This information can assist in evaluating the possible sustainability of an agro-ecosystem. Crop growth simulation models require detailed data and often operate the agro-ecosystem functions on a daily time-step. Therefore, environmental databases that contain daily rainfall and temperature values are invaluable. Chapter 4 discusses further how tools such as crop growth simulation models, e.g. CERES-Maize, and environmental databases can be incorporated into a goal-orientated framework to assess agro-ecosystem sustainability.

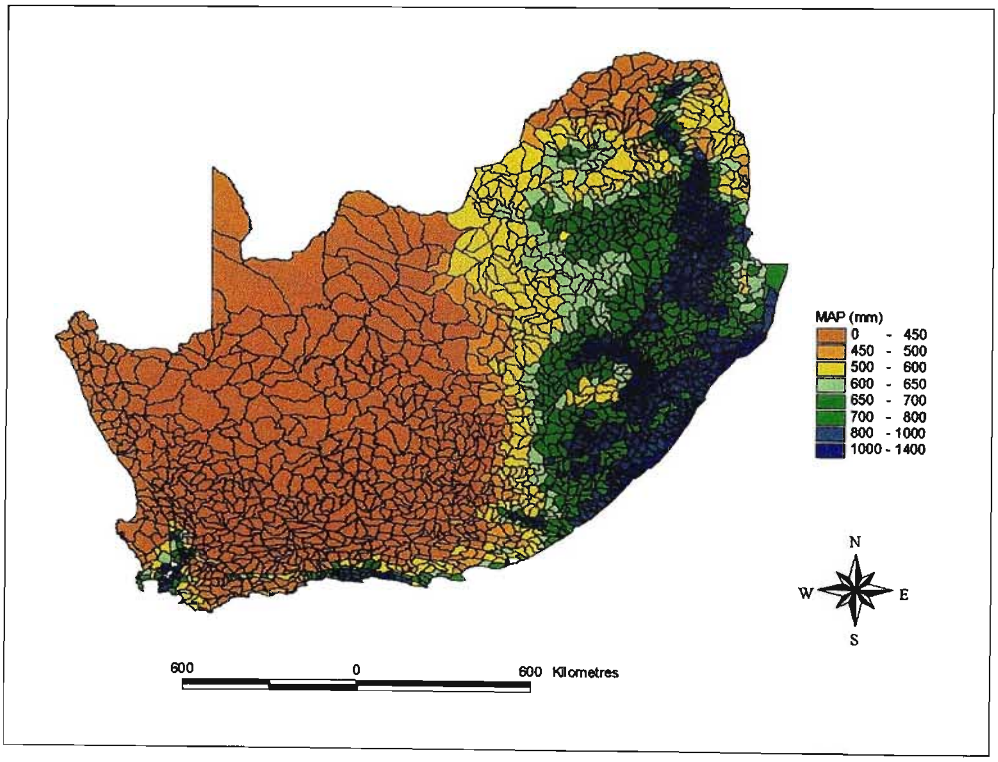


Figure 3.2.1 Mean Annual Precipitation of Quaternary Catchments in South Africa

4 DESIGN OF A SYSTEM TO ASSESS AGRO-ECOSYSTEM SUSTAINABILITY

A systems approach to sustainability is essential in attempting to understand the inter-relationships between social, economic and environmental influences that are associated with sustainability (Ikard, 1993; Hansen and Jones, 1996). While there is debate about what a sustainable system is, there is a consensus that the concept considers the distribution of resources over long time frames and is based on maintaining system function for future generations (Belcher *et al.,* 2004). For a true systems analysis of sustainability, biophysical assessments need to be complemented with socio-economic analysis before it will result in benefits at any scale (Kropff *et al.*, 2001).

In Section 4.1 a review of background literature is presented in regard to systems and the framework components for assessments of agro-ecosystem sustainability. In Section 4.2 the framework used by the author for sustainability assessments in Chapters 5, 6, 7 and 8 is given. Section 4.2 includes the selection and evaluation of biophysical indicators used in this study.

4.1 Literature Review of Using a Systems Approach to Investigate Agro-Ecosystem Sustainability

According to Farshad and Zinck (2001), a system requires six key requirements to be considered sustainable. The requirements are:

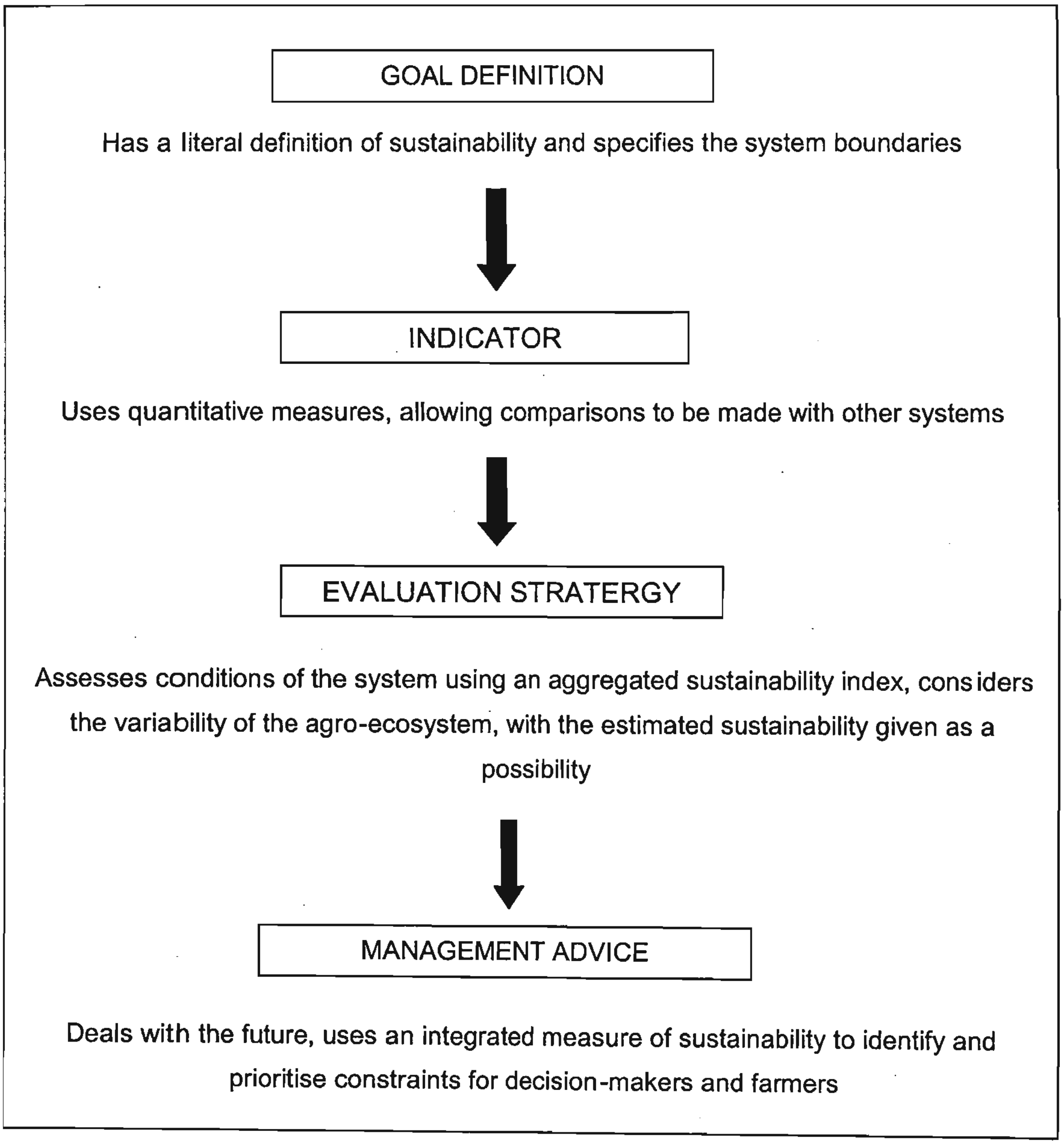
- environmental soundness
- economic viability
- social acceptability
- institutional manageability
- agro-technical adaptability and
- political acceptability.

Criteria for each of the six requirements are given in Table 4.1.1. Farshad and Zinck (2002) continue that in order to assess sustainability in these six areas would require a team of people each with specialist knowledge. Even when assessing one or two of the key requirements, many data from different sources are needed to satisfy the criteria.

Table 4.1.1 Requirements and criteria of sustainable agricultural systems (after Farshad and Zinck, 2001)

Requirements	**Criteria**
Political Acceptability	Ease of employment
	Government willingness
	Life expectancy
Economic Viability	Attractiveness of land to non-agricultural users
	Food self-sufficiency
	Efficiency of inputs
	Meeting market requirements
	Net-farm profitability
Institutional Manageability	Favourability of age distribution
	Labour availability
	Migration balance
	Security of water supply
Social Acceptability	Human health
	Infant mortality
	Labour availability
	Degree of welfare
	Literacy of rate
Agro-technical Adaptability	Access to water
	Agricultural production density
	Attractiveness of land to non-agricultural users
	Weed control
	Pest control
	Irrigation system status
	Tillage
Environmental Soundness	Soil pH
	Soil compaction
	Soil erosion status
	Soil drainage
	Water quality
	Influence of agro-ecosystem on soil, water and air
	Biological activity in soil
	Attractiveness of land to non-agricultural users

Von Wiren-Lehr (2001) proposed a goal-oriented system to assess sustainability and identified four concepts for the system as goal definition, indicator selection, evaluation based on indicator sets and final formulation of management advice. The goal-orientated approach is based on the formation of a desired sustainable state which is characterised by a set of indicators. To assess the sustainability of agro-ecosystems, a combination of the goal-oriented strategy proposed by von Wiren-Lehr (2001) and the elements of characterising sustainability of agricultural systems suggested by Hansen (1996) could be employed (Section 2.6). This combined system is shown in Figure 4.1.1



Has a literal definition of sustainability and specifies the system boundaries

Uses quantitative measures, allowing comparisons to be made with other systems

Assesses conditions of the system using an aggregated sustainability index, considers the variability of the agro-ecosystem, with the estimated sustainability given as a possibility

Deals with the future, uses an integrated measure of sustainability to identify and prioritise constraints for decision-makers and farmers

Figure 4.1.1 Combined system to assess sustainability (Sources: Hansen, 1996; von Wiren-Lehr, 2001)

In regard to Figure 4.1.1 the following should be noted:

- In assimilating Hansen's (1996) approach to characterising sustainability with von Wiren-Lehr's (2001) goal-orientated strategy, elements of Hansen's characterisation were assigned to the various stages of the goal-orientated system.
- In defining the goal of the agro-ecosystem, a literal definition of sustainability is used. The literal definition should make clear that the system is to continue through time and has to consider ecological, economic and social perspectives.
- The indicators selected should have a quantitative measure, allowing the comparison of different strategies to managing the ecosystem.
- Sustainability deals with the future. Therefore, any assessment of a system in regard to sustainability can only be an estimate. This is due to the variability of the system. Therefore, prediction of system sustainability is expressed as a probability (Hansen, 1996).
- Any management advice given as a final output of the system, whether in the form of recommendations or alternative options, should be predictive with any constraints to sustainability identified.
- Accurate information is necessary to estimate with any certainty whether a farming system is sustainable. Ikard (1993; p.159) states that 'sustainable farming systems are fundamentally knowledge-based systems of farming'.

Systems approaches can quantify achievable yields of a specific genotype at different input levels in different environments (Kropff *et al.*, 2001). Background literature on the different stages of von Wiren-Lehr's (2001) goal-orientated system is presented in Sections 4.1.1 to 4.1.4.

4.1.1 Selection of Indicators

Indicators have been described as tools to measure and monitor progress towards a particular goal. They play a pivotal role in conveying information about progress towards objectives and should be included in sustainability methodologies or frameworks (Walmsley and Pretorius, 1996). Indicators should be:

- directly related to the subject investigated

- give adequate knowledge of the performance of a system
- be able to apply to a number of systems
- show changes over time and
- be calculated at a reasonable cost (Stein *et al.*, 2001).

Environmental indicators are typically quantitative measures of a specific condition which can be compared with an existing threshold value (Stein *et al.*, 2001). The variety of indicators used in an environmental indicator system should be able to give a broad view of the state of the environment and not concentrate on specific selected environmental problems (Walz, 2000). Table 4.1.2 shows a wide range of indicators, with the areas covered including economic, environmental and social indicators.

Sets of indicators have been suggested by Eswaran *et al.* (1993), Constanza *et al.* (1997), and Dumanski and Pieri (2000) that measure both ecosystem function and directly visible land changes. Indicators suggested include natural habitat loss, biodiversity, soil formation, soil loss, nutrient cycling, food production, and reduction in water flows, water quality, human resources and food security. Sustainability indicators will vary both temporally and spatially (Rigby and Caceres, 2001). Agro-ecosystem goods and services such as nutrient cycling and production of food and raw materials are central to the system's continuation. If the prescribed goal of an existing agro-ecosystem is for food production to continue at the current level, or to increase, then the maintenance of goods and services that the agro-ecosystem provides is essential in achieving the goal. For example, an important service in rainfed agriculture is water availability for plant production in the agro-ecosystem. This will determine the nutrient release through biodegradation in the system and the facilitation of infiltration and soil protection (Gordon and Folke, 2000). Any goal assigned to an agro-ecosystem should stress the importance of maintaining agro-ecosystem services for the goal to be realised.

Constanza *et al.* (1997) propose various indicators that could be used to create a performance-based index for the agro-ecosystem. The index is determined by identifying services provided by the ecosystem. The agro-ecosystem is split into functions and potential indicators for that function are listed.

Table 4.1.2 Examples of indicators (Walmsley and Pretorius, 1996)

Field	Example Indicators
Quality of Life	Population numbers; Human Development Index
Atmosphere	CO_2, SO_2, NO_x emissions; Ground level ozone emissions
Water	Population served by treated water supply; Chemical properties
Biodiversity	Wildlife species at risk; General biodiversity situation
Land	Rural to urban land conversion
Productivity	Agricultural yields
Income	Income level
Soil	Chemical properties; Level of erosion; Pesticide use
Natural vegetation	Percentage of land under forestry and natural vegetation
Economic	Employment; Total GDP; Food production; Inflation

4.1.2 Sustainability Modelling of Agro-Ecosystems

To gauge whether or not a system is sustainable, it is essential that methodologies be developed to enable this process to be carried out (Rigby and Caceres, 2001). The simulation of agro-ecosystems at a range of scales, as a component of such methodology and as part of the goal orientated system, is explained in this section.

Agricultural decisions makers require information and recommendations concerning the effects of climate variability on agro-ecosystems at a variety of scales. This has increased the use of process-level crop models, with the assumption that the models are able to encapsulate intra-seasonal and inter-annual responses to climate variability. However, there are potential issues that should be considered when using crop models that have been tested at the scale of homogenous plots to broader scales, and these include:

- variability in space and time
- regional calibration of the model
- the level of model complexity
- imperfect data

- current and future climatic conditions and
- management (Hansen and Jones, 2000).

The inputs into the model define the environment of the simulated system. These inputs include: daily climate input, soil properties and management decisions (Hansen and Jones, 2000). In this study this information is required on a regional basis to investigate agricultural sustainability in the Highveld, as well at the subsistence farm level. The South African Quaternary Catchments Database contains a daily rainfall record of 45 years (1950-1994) for each QC, as well as soils information, land cover attributes, daily maximum temperatures, daily minimum temperature, and daily as well as monthly reference potential evaporation information for each QC.

Sustainability in this study is also modelled at the farm level for emerging farmers at Potshini in the Bergville district of KwaZulu-Natal. From a climate station in Bergville, 10 km from Potshini 50 years of daily rainfall data are available along with 50 years of daily maximum and minimum temperatures from the South African Quaternary Catchments Database (Schulze *et al.,* 2005).

4.1.3 Socio-Economic Impacts

Socio-economic considerations are vital in assessing the sustainability of an agro-ecosystem, as in reality people are at the centre of agro-ecosystems (Dent *et al.*, 1995) and unprofitable agricultural systems will not continue *ad infinitum* (Edwards-Jones and Howells, 2001). There are a number of inter-linkages between the environmental and socio-economic facets of a system.

The inter-linkages and outside influences will vary, depending on the spatial scale at which sustainability is being assessed. Figure 4.2.4 illustrates general inter-linkages that are relevant to the three spatial scales modelled in this study. Crop yield is of crucial importance to the revenue and profit of the system. The individual farmer will decide if the profits are of a sustainable nature. Unprofitable farms could warrant a change in land use. The yield variability, or risk level, will also influence the farmer in terms sustainable land use. Other agro-ecosystem functions such as nitrogen and carbon levels and soil quality affect sustainability, i.e. if the soil quality is declining the external inputs would need to increase, which in the long run may not be sustainable. If external inputs are increasing, pollution from the agro-ecosystem is likely to increase. This could fall foul of environmental legislation and will not be socially acceptable; thus the system is not sustainable.

Sustainability is a human centred concept that encompasses numerous attributes and objectives of different interest groups (Zander and Kächele, 1999). The social influences on agro-ecosystems are, therefore, important to identify. The farmer often makes decisions after discussions with family and friends, or at least is influenced by their views and needs. Important social influences and interactions also occur beyond the farm boundaries (Dent *et al.,* 1995). However, this is difficult to quantify, owing to the dynamic nature of sustainability coupled with subjectivity of stakeholder interests.

It is, therefore, essential to identify amongst stakeholders the importance and interests of key people, groups, or institutions that significantly influence policy making process. A range of participatory methods for extracting information has been developed (an example of this is stakeholder analysis, Table 4.1.3). Workshops, focus group discussions or community meetings are useful for bringing together groups of stakeholders, with either similar or contrasting perspectives in a particular issue. Smith *et al.*, (2004) have used community meetings to great effect in rural KwaZulu-Natal, South Africa. The meetings have been used to bring together stakeholders to express views and for training and disseminating information.

Stakeholder analysis (Table 4.1.3) is a method of investigating and analysing stakeholder interests, attributes, relative power and circumstance (Pasteur, 2001). This could be derived from a series workshops or community meetings with stakeholders. A stakeholder/sustainability matrix based on Hurni's (2001) five pillars of sustainability can be used to identify what circumstances would be socially acceptable to stakeholder groups. An example of a stakeholder matrix developed for agriculture in the Highveld is shown in Table 4.1.4.

Table 4.1.3 Basic premise of a stakeholder analysis (after Pasteur, 2001)

Stakeholder Group	Nature of Interest in Policy Decision	Potential Impact of Policy	Relative Importance of Interest	Importance of Group	Influence of Group
Primary					
Commercial Farmers	Sustained yields	High	High	High	High
Small-scale Farmers	Improved income & food security	High	High	High	Medium
Farm Workers	Higher wages & better working conditions	High	High	High	Low
Secondary					
Rural Community	Improved business opportunities	Medium	Low	Medium	Medium
Urban Community	Improved business opportunities	Low	Medium	Medium	High
Ministry of Agriculture	Increasing production and regional food security	Medium	Medium	Medium	Medium

Table 4.1.4 Example of a stakeholder and sustainability matrix for the Highveld region

Stakeholders	Agro-Ecosystem Resilience	Economically Viable	Economically Productive	Reduction in Risk
Commercial Farmers		y	y	y
Smallholder Farmers		y	y	y
Farm Workers			y	y
Rural Community	y		y	y
Urban Community	y	y	y	y
Institutions	y	y	y	y

In Table 4.1.4 the agro-ecosystem resilience column refers to whether the stakeholder would be concerned with that particular 'pillar of sustainability'. People's understandings of an issue will be influenced by their particular agendas and perspectives (Pasteur, 2001). A stakeholder matrix helps to visualise possible conflicts of interest that may occur between stakeholders. Again this would be derived from interaction with stakeholders in the form of workshops or community meetings.

Although the practical implementation of the stakeholder analysis presented in Tables 4.1.3 and 4.1.4 go beyond the scope of this thesis and are ultimately not used to derive the sustainability index, the author considers stakeholder analysis and understanding stakeholder perceptions as essential in maintaining sustainable agro-ecosystems.

4.1.4 Indices for Agro-Ecosystem Assessment

Liebig *et al.* (2001) have developed a weighted index using agro-ecosystem functions in order to compare various management practices. An example of how some of the indicators in Table 4.1.2 have been developed into a weighted index is shown below. It is a four-step process:

- Step 1: Group data within agro-ecosystem functions

  For example:

  Food Production = *f* (grain yield, grain N content)
  Raw Materials Production = *f* (stover yield, stover N content)
  Nutrient Cycling = *f* (soil NO_3, soil NH_4, soil organic N)
  Greenhouse Gas Regulation = *f* (soil organic C, early spring soil NO_3)

- Step 2: Calculate the averages for each indicator. These can be calculated from historical datasets.
- Step 3: Rank and score the treatment. Treatment values are ranked for each indicator in ascending or descending order, depending on whether a higher value for the indicator is considered negative or positive with respect to enhancing agricultural sustainability.
- Step 4: Sum the scores within and across agro-ecosystem functions. If one indicator has a dominant effect on an agro-ecosystem function, then the indicator should be given a greater numerical weight to convey this.

Problems with this index are that social and economic indicators are not considered, the weighting of agro-ecosystems is subjective and it is best used with long-term agro-ecosystem experiments.

Nambiar *et al.* (2001) proposed an agricultural sustainability index to measure sustainability as a function of biophysical, chemical, economic and social indicators in order to determine sustainability in the broader sense. The preliminary indicators were required to meet the following criteria:

- social and policy relevance
- analytical soundness and measurability
- suitability for application at different scales
- inclusion of ecosystem processes and process orientated modelling
- sensitivity to variations in management and climate and
- accessibility to multiple users.

The index comprises of broad categories with several indicators within each category, as illustrated by Table 4.1.5.

Using long term crop yield trends to provide information on the biological capacity of agricultural land can assist in estimating the aptitude of agriculture to sustain resource production. The agricultural nutrient balance is an importance category, as excessive fertiliser can contribute to eutrophication, contamination of soil, water and air. Lack of fertiliser application may cause soil degradation. This has implications for soil quality and agro-environmental pollution. Soil quality indicators include physical, chemical and biological properties.

The index is calculated by first rating each indicator, then calculating a rating for each category and finally obtaining an overall index for each agro-ecosystem by multiplying the category ratings.

Table 4.1.5 Indicator categories (after Nambiar *et al.*, 2001)

Category	Indicator
Long Term Crop Yield Trends	Crop yield
Agricultural Nutrient Balance	Nutrient balances of nitrogen, phosphorus, and potassium
Soil Quality	Soil texture; depth; bulk density; water retention characteristics; pH; organic matter
Agricultural Management Practices	Fertilizers, irrigation systems; planting dates
Agro-Environmental Quality	Soil degradation; water pollution
Agricultural Biodiversity	Number of organisms; variety of plants and livestock
Economic and Social Viability	Farming practices; incomes for owners and workers
Net Energy Balance	Fossil fuels per unit of output; biomass production

Indicators are useful as they can quantify what is happening in an ecosystem. However, in assessing the health of an agro-ecosystem in the context of sustainability, ecological thresholds need be known. Unfavourable threshold levels have been called critical zones for resource conservation (Ciriacy-Wantrup, 1963) or thresholds of probable concern (Rogers and Bestbier, 1997). If information in establishing thresholds is initially limited, then arbitrary values could be used to act as warning flags in the system (Rogers and Bestbier, 1997).

4.1.5 Discussion on the Use Indicators to Characterise Sustainability

The working definition of sustainability stated in Section 2.7 is 'Sustainability is applying long term perspectives, in regard to human well-being and ecological integrity, to policies and actions.' Indicators are then required to assist the decision-maker in knowing where the system is in regard to this definition, which direction the system is headed towards and how far the system is away from the desired goal.

Indicators are required when there is a need for informed decision-making and associated cost-effective data collection. The value of indicators as policy instruments is enhanced when they are used in combination with goals that have been set as part of national policies. The reason for this is that decision-making has become increasingly data driven (Esty, 2002). The use of indicators can then assist decision-makers at all levels, and, with reference to this thesis, can increase the focus on agricultural sustainability.

Procedures have been proposed in Section 2.6 to characterise sustainability in this way (Troquebiau, 1992; López-Ridaura *et al.*, 2000; Sands and Podmore, 2000). Section 4.1.3 also describes proposed indices to evaluate the quantitative results from sustainability modelling. Combining quantitative indicators into indices such as those of Sands and Podmore (2000) presents the question of how indices measured with different units can be integrated. The choice of using a weighting system has been dismissed by some as arbitrary or lacking in theoretical rigour (e.g. Stoorvogel *et al.,* 2004). However, this author believes such a weighting system can be useful if there is sufficient knowledge of the agro-ecosystem under consideration.

Stoorvogel *et al.* (2004) present an approach involving trade-off analysis where high-priority indicators are identified by the researchers and stakeholders and then provide decision-makers with quantitative estimates of the relationships among those indicators. The task is then left to the decision-maker to subjectively assess the implied tradeoffs. Tradeoff analysis recognises that complex interactions between indicators are a key aspect of production systems. Although tradeoff analysis is not performed in this thesis, the interaction and relationships between indicators are recognised in the assessment of the results of sustainability modelling in Chapters 5, 6, 7 and 8.

This author believes that it is of value to characterise sustainability using quantitative indicators from a complex crop growth model. However, this method has its inadequacies in that the usefulness of the indicators is dependent on:

- The quality of the information which is inputted into the model
- The ability of the model to produce not only yield estimations but also estimations associated with other agro-ecosystem functions
- The ability of the model to simulate these functions at different scales

- The ability of the model to simulate the function under different climate scenarios and
- The technique used to integrate the indicators to produce an estimation of the 'likelihood of sustainability' (Table 4.2.4).

The choice between categorical and continuous approaches for analyses of indicators appears to have a substantial impact on how the results of a study are interpreted (Lindegarth and Gamfeldt, 2005). The choice affects the immediate impression on the importance of different agro-ecosystem processes which, if used as a basis for choosing management strategies, will have further consequences. For example, the choice of method for analysis might affect the emphasis and formulation of new hypotheses within the research, even though both approaches are valid. Lindegarth and Gamfeldt (2005) suggest that where possible both types of analyses should be performed in order to identify contrasting results. The categorical approach was chosen in this study as the classification into categories of agro-ecosystem processes reduced the complexity of analysis and interpretation of results. The weighting given to the indicators in this study is subjective and is meant to be illustrative.

A problem encountered in selecting indicators for the framework (described in Section 4.2) is one of scale. A general framework that can be applied at different scales is one of the major aims of this research (Figure 1.1). Some of the indicators used from the DSSAT model output are perhaps limited in this regard. This is particularly true of runoff and drainage, which are important at a farm scale and, indeed, at a Quaternary Catchment scale, but limited in value for a region as large as the Highveld. Also, at a regional scale the routines included in the DSSAT models for hydrological processes are not accurate enough to be incorporated into an index for sustainability. This is one the reasons why grain yield was the only indicator used at a regional scale (Chapter 5).

4.2 Adaptation of the Goal Orientated System for Use as a Framework to Assess Agro-Ecosystem Sustainability at Various Scales in South Africa

The main aim of this study is to assess agro-ecosystem sustainability at the following scales: regional (Chapter 5), Quaternary Catchment (Chapters 6 and 7) and at the small-scale subsistence farmer level (Chapter 8). The employment of a systems approach is deemed essential in achieving this and in understanding the inter-relationships between social, economic and environmental influences that are associated with sustainability (Ikard, 1993; Hansen and Jones, 1996). A general system that can be applied at a range of scales and that meets multiple goals and objectives is required. Henceforth in this thesis the adaptation of von Wiren-Lehr's (2001) goal-orientated system will be referred to as a goal-orientated framework.

The framework is required to answer the following questions:

- How can an actual existing agro-ecosystem be identified as being sustainable or not?
- What are the facets of a system that make it sustainable or unsustainable?
- How can a sustainable system be developed in a particular region, given realistic economic constraints? (Gliessman, 2001)
- Are there research and operational implications associated with climate change?

The goal orientated framework, with modifications, is the framework that has been selected to meet the criteria set about in the above questions. The general framework was described in Section 4.1. The sustainability modelling stage and evaluation strategy of the framework are described in the subsequent sections.

Ultimately the aim of the selected framework is to be able to state, with confidence, whether growing a crop in a pre-stated way is sustainable or not. For sustainability to be a likely outcome, then the working definition of sustainability given in Section 2.7 would need to be met this states that: *'Sustainability is applying long term perspectives, in regard to human well-being and ecological integrity, to policies and actions.'*

The information required to make an assessment and give a likelihood sustainability outcome is shown in Figure (4.2.1). The working definition of sustainability (Section 2.7) is central to the flow of information. Accurate information is required from a range of sources to assess if the criteria for farmer and community well-being and the maintenance of ecological integrity are being met. The information is then used to state the likelihood of sustainability. The goal orientated framework has been adapted to suit the specific context of sustainable grain production at different scales. Von Wiren-Lehr's (2001) goal orientated framework comprises of the following four sections:

- goal definition
- selection of indicators
- an evaluation strategy and
- formulation of management advice.

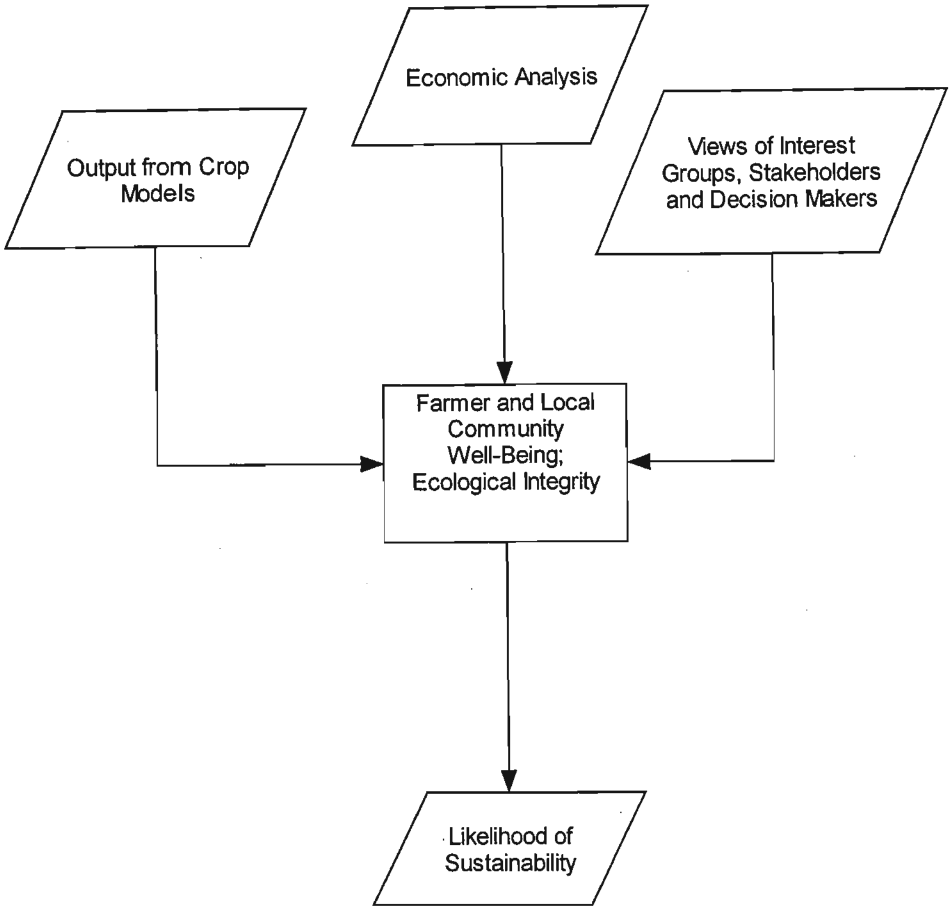


Figure 4.2.1 Flow of information in a system to investigate agro-ecosystem sustainability

The goal orientated framework used in this assessment meets the requirements of an integrated model environment (Kropff *et al.,* 2001). This integrated environment should be based on the latest model concepts, an information and communication technology (ICT), and on incorporating database management systems, as shown in Figure 4.2.2. The adapted framework incorporates the DSSAT suite of crop models, GIS and the South African Quaternary Catchments Database. Output from the CERES-Maize crop model can provide information on the changes in the agro-ecosystem functions and possible environmental effects. Economic information and stakeholder views are also required as inputs into the framework.

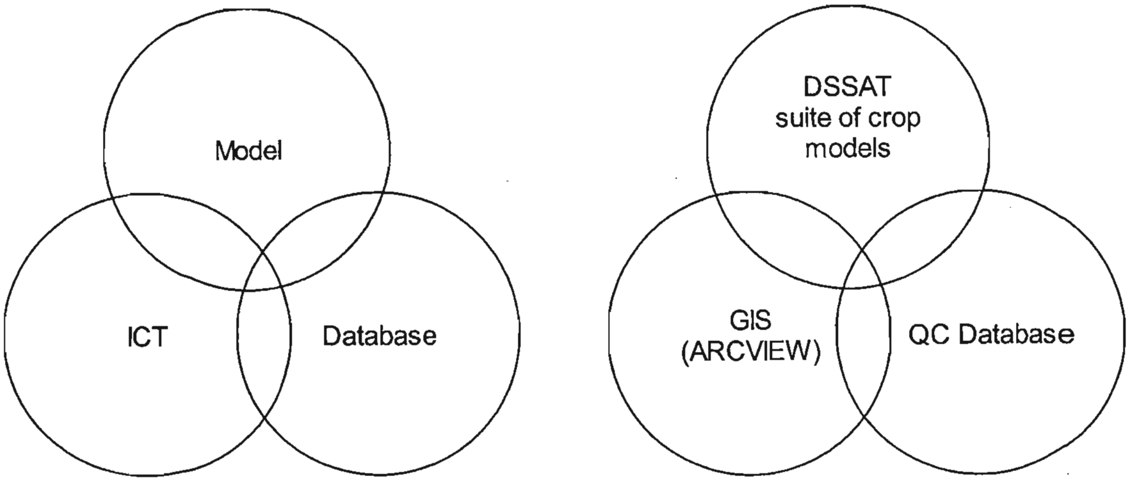


Figure 4.2.2 An integrated model environment (after Kropff et al., 2001)

In selecting a suitable goal for a sustainable framework it is important that the goal is not abstract, but one that is useful and realistic to obtain. The goals employed by this author for the assessment of sustainability are the ones stated in Section 2.7, which were derived from the sustainability literature review. For example, the goal or definition of sustainability within the spatial area of the Highveld region and in regard to grain production, as stated by this author, was:

'The goal is for the agro-ecosystems in the Highveld region to continue in the long term, providing quality well-being for farmers and local communities and to maintain ecological integrity' (Section 2.7).

The main adaptation to the original goal orientated framework of von Wiren-Lehr's (2001) is to replace the selection of indicators with an integrated model environment and to make the selection of indicators a sub-section of this. The rationale for the above adaptation is that this is an assessment of sustainability which is achieved by simulating agro-ecosystem functions rather than monitoring them. Although this study is based on simulation, there should nevertheless be ongoing monitoring of agro-ecosystem integrity in some form.

The adapted framework is illustrated in Figure 4.2.3.

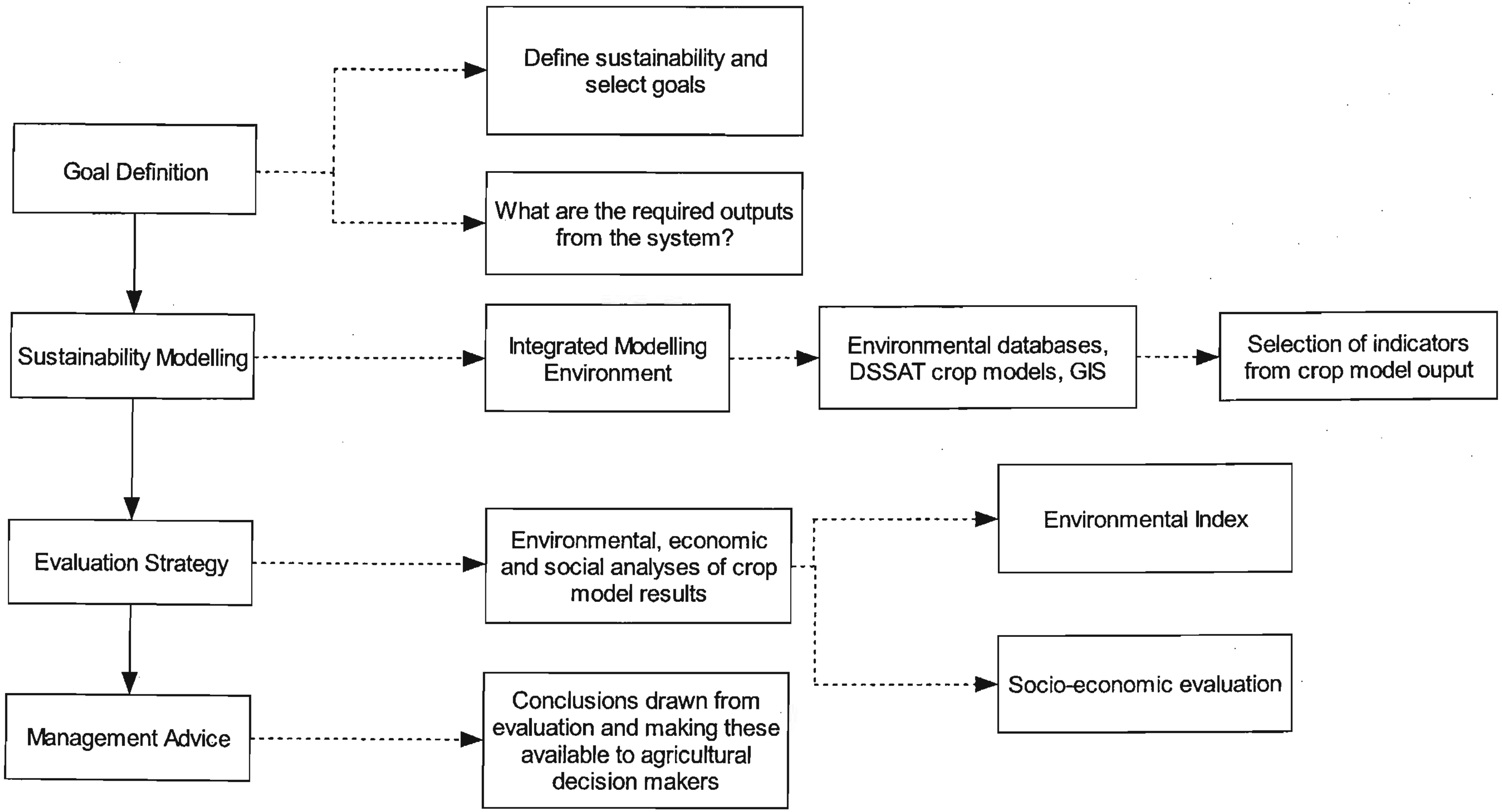


Figure 4.2.3 Adapted goal-orientated framework to assess agro-ecosystem sustainability

The assessment of agro-ecosystem sustainability requires an evaluation of the environmental, economic and social components and the inter-linkages between them. To evaluate the biophysical functions of the agro-ecosystem, an environmental index which is based on the outcome of the sustainability modelling is used. The impacts of the results of the modelling on socio-economic factors are then considered.

The formulation of management advice is based on the analysis of sustainability modelling and the use of indices to quantify sustainable pathways for agriculture. In analysing modelling results, the limitations of agro-ecosystem modelling need to be recognised. Sustainability deals with the future: therefore, any assessment of a system in regard to sustainability can only be an estimate (Hansen, 1996). The constraints to the estimate need to be identified and accurate information, in the case of this study accurate environmental information, is necessary to estimate with any certainty whether or not an agro-ecosystem is sustainable.

4.2.1 Sustainability Modelling with the DSSAT Suite of Crop Models

Indicators have been selected from the DSSAT suite of models for use in this thesis so that changes to the agro-ecosystem functions can be highlighted. These indicators are then used to derive a comprehensive index which is described in Section 4.1.3. Results from model runs need to show whether the agro-ecosystem, and way it is managed, is sustainable, along with identifying which components make it sustainable. Threshold figures for each of the indicators selected would need to be established.

The indicators used in the study described in this thesis are limited to the output from the DSSAT crop models. Crop model simulations will enable changes in climate variability, climate change as well as agricultural management decisions to be investigated. The crop models require inputs such as rainfall and temperature that consist of daily values. However, the foundations of the index are the annual or seasonal output variables.

The DSSAT suite of crop models has been chosen primarily because of the regional calibration carried out on CERES-Maize, particularly in the dry western areas of the South African Highveld, discussed in Section 3.1.4, and because of its range of management options. However, because management is seldom consistent from year to year, spatial representations of management variables are generally not available. Typical, or recommended, practices are therefore often applied uniformly across a region. Using several planting dates within the reported range can improve regional yield predictions relative to using a single average plating date (Hansen and Jones, 2000). Accordingly, in this study a range of management options that include multiple planting dates, fertiliser applications and plant densities are simulated (Chapters 5, 6, 7 and 8). The biophysical indicators chosen from the DSSAT crop model output (Sections 4.2.1.1 – 4.2.1.7) provide quantitative information on how the agro-ecosystem responds to both management and environmental changes. This information is not an absolute and is dependent on the complexity and accuracy of the crop growth model used and the quality of input information. Results from the biophysical indicators provide a basis for socio-economic analysis of the agro-ecosystem. A comprehensive assessment of the socio-economic components of the framework falls outside the scope of this thesis. However, the author recognises the important inter-linkages between the environmental, economic, social and political components of an agro-ecosystem. The sustainability index, therefore, is derived purely from biophysical indicators; the socio-economic impacts of the results of the index are then considered.

The working definition of sustainability stated in Section 2.7 requires indicators that can quantify farmer well-being and ecological integrity. The eight indicators taken from the output of the CERES-Maize crop models to attempt to quantify farmer well-being and ecological integrity are shown in Table 4.2.1.

Table 4.2.1 Indicators for sustainability assessment

Sustainability Criteria	Indicator
Farmer and community well-being	Yield at harvest Grain nitrogen content
Ecological integrity	Soil organic nitrogen Soil organic carbon Nitrogen recovery Extractable water Runoff Drainage

Yield at harvest and grain nitrogen content are the indicators used to assess farmer well-being. The yield is an indicator of whether an agro-ecosystem is economically productive and viable and, therefore, able to support the farmer and the farmers' families as well as supply business opportunities to the local, regional and possibly export communities. The yield is therefore of vital importance to the well-being and the quality of life to both the commercial and small-holder farmers. The yield has significance both economically and socially on the local communities. Since yield is of such importance to the agro-ecosystems in the South African Highveld and also to the small-holder farmers in rural KwaZulu-Natal, it is given a higher weighting in the sustainability index (Section 4.2.2). Nitrogen is crucial for the production of proteins in maize, and in turn, the protein content in the grain. The protein content of the grain is particularly important for the subsistence farmer for whom a low protein diet is often common.

In order to try and quantify ecological integrity, six indicators have been selected. Three of these give an indication of the soil quality. They are: soil organic carbon, soil organic nitrogen and extractable water. A reduction in the level of organic matter along with organic nitrogen and carbon could reduce the soil biodiversity of the agro-ecosystem. This would in turn reduce the resilience of the agro-ecosystem to major disturbances such as drought or climatic changes.

Nitrogen recovery reveals the efficiency to which the agro-ecosystem uses added nitrogen, whether in the form of inorganic fertiliser or manure. Manure takes longer to break down than inorganic fertiliser of which a significant proportion can be lost during rainfall events. This is why it is important to estimate runoff and drainage of water from the system. Even if the routines for runoff and drainage in CERES-Maize are not sophisticated ones, it is important to obtain an idea of the magnitude of water leaving the system. High runoff or drainage coupled with low nitrogen recovery of inorganic fertiliser could mean that surface and groundwater are being polluted with high levels of nitrates.

To assess the impact of different management practices on agro-ecosystems, knowledge and an assessment of those changes are required for informed evaluation. Selection of key indicators as described above and their associated threshold values are required to monitor changes and determine trends in improvement or deterioration of the agro-ecosystem at various scales (Arshad and Martin, 2002).

Thresholds for agro-ecosystem assessment at the various scales assessed in this study where derived from existing literature. The thresholds for yields in the South African Highveld where taken from du Toit and Durand (1999). Even though this work was already several years old at the time of writing and much has changed, it still provides a useful basis by which to compare Quaternary Catchments within the Highveld. The grain nitrogen threshold used is one that is a suggested level required to produce maize grain of a good quality (Pioneer, 2004).

The nitrogen recovery level of 50% is an average figure given for agriculture in the world rather than being regional specific (Godwin and Sing, 1998). A 50% level of nitrogen use by the crop is an inefficient one, so any improvement on that is deemed favourable. The other indicators used for assessing ecological integrity (soil organic carbon and nitrogen, extractable water, runoff and drainage) have thresholds which are specific to the region, the Quaternary Catchment or the farm, depending on the spatial scale at which the assessment is performed. An acceptable change in these indicators is suggested by Arshad and Martin (2002) to be up to ± 15% from baseline. The baseline figures were derived from running simulations with CERES-Maize using suggested management practices by du Toit and Durand (1999).

From CERES-Maize the eight outputs which have been selected as indicators to evaluate farmer and community well-being and the ecological integrity of the agro-ecosystem are discussed below.

4.2.1.1 Yield at harvest

For an acceptable yield estimate, accurate modelling of both duration of crop stages and crop growth rates is a necessary. In the CERES models the various stages of development of the crop are simulated by quantifying the physiological age of the plant and the duration for the growth stages. During the different stages of development the model partitions biomass into the growing organs of the plant. This process is affected by environmental factors and the choice of cultivar. The duration of growth is dependent on temperature and the length of the photoperiod during floral induction (Ritchie *et al.*, 1998).

Hensley *et al.* (1997) carried out statistical tests of model reliability on the CERES-Maize and CERES-Wheat crop models by comparing simulated results with observed data in South Africa. The model output investigated was yield and soil water content. The following indices relating to output were compared: root mean square error (RMSE), systematic root mean square error ($RMSE_s$), unsystematic root mean square error ($RMSE_u$), the index of agreement (D-index), and coefficient of determination (R^2).

In terms of yield prediction it was found that CERES-Maize tended to over-predict yields in the range between 2 000 - 3 000 kg/ha, which causes there to be relatively high $RMSE_s$. Yields above 3 000 kg/ha were well predicted by the model, and the D-index and R^2 (0.64 and 0.67 respectively) were considered acceptable.

In a study by Durand and du Toit (1999) a grain yield of 2 200 kg/ha was used as the breakeven figure for the western Highveld, with the figure rising to 3 600 kg/ha in the eastern parts of the region. These figures were calculated with a maize price of $95 per 1 000 kg with a total production cost of $200 per hectare for the western region and $300 per hectare for the eastern Highveld. Prices were based on those of the 1997/1998 season. Another useful figure given by du Toit *et al.* (1999) is 900 kg/ha as the famine level. This is the estimated yield a family of four needs to survive to the next harvest using a one hectare plot. These breakeven figures were used as threshold values for the yield indicator.

4.2.1.2 Grain nitrogen content

For plant growth an adequate supply of nitrogen is vital, as it is needed for the synthesis of chlorophyll, proteins and enzymes, as well as for carbohydrate use. Higher concentrations are found in plant tissue in the early stage of plant development as nitrogen compounds are needed for photosynthesis and growth (Godwin and Singh, 1998).

In cereal agro-ecosystems the crop has usually employed the majority of the nitrogen available to it in the soil by the time the important phenological stage of grain filling occurs. To compensate for this, the plant, as well as utilising nitrogen from the soil, will make available protein nitrogen from vegetative organs. If soil nitrogen supply is then increased, the plant will use the soil nitrogen and will decrease the amount of protein nitrogen taken from vegetative organs to meet the demand from developing grains (Godwin and Singh, 1998).

The rate of nitrogen accumulation in single grain cells is simulated as a function of temperature, so that at higher temperatures grain nitrogen concentration will be higher. If the plant is stressed as a result of the unavailability of moisture, this can increase grain nitrogen concentrations as the plant has a reduced ability to dilute nitrogen in the grain. The growth routines and nitrogen transformation processes in the DSSAT suite of crop models provide pathways so that nitrogen stress during gain filling will have an effect on yield and grain nitrogen content (Godwin and Singh, 1998). For grain at harvest 16 g nitrogen per kg of grain is considered a valuable guide in terms of an adequate level of nitrogen.

4.2.1.3 Soil Organic Nitrogen and Carbon

In attempting to provide guidelines for setting critical limits for changes in soil organic matter, Arshad and Martin (2002) suggest that a 15% increase or decrease from the average baseline would be an appropriate limit. Should the change exceed the 15% limit, it can be assumed that a positive or negative effect is occurring within the agro-ecosystem. If the result is a decrease of greater than 15% and this would mean that remedial measures should be put in place.

Nitrogen, both in organic and inorganic form, can undergo various changes while in the agro-ecosystem and both forms are impacted upon by climate. Owing to these changes and their complex interaction with the climate, the management of nitrogen in the system can prove to be difficult. The use of models which simulate these processes and describe the effects can prove to be useful in providing information on crop growth and crop water requirements (Godwin and Singh, 1998).

4.2.1.4 Nitrogen recovery

In the routines contained in DSSAT for the simulation of cereal crop growth, the movement of nitrogen across layer boundaries is reliant on the water movement. The movement of urea and nitrate are simulated in the same way, but the movement of ammonium is not considered. Nitrate loss from each soil layer is calculated from the volume of water present and volume of water moving through each layer in the soil profile (Godwin and Singh, 1998).

Nitrogen uptake and use by the crop is also modelled by the DSSAT models. This enables the nitrogen recovery from added fertiliser to be calculated, i.e. the amount of added nitrogen that is actually used by the plant. The figure is given as a percentage and is calculated as: (N uptake/fertiliser N added *100). The general efficiency by which crops use added nitrogen is considered poor. An average for grain crops world-wide is 50% recovery of added nitrogen (Craswell and Godwin, 1984).

4.2.1.5 Extractable water

The potential supply of water to the root system is dependent on the relationship between the potential evaporation and the current soil water status, with the root system also playing a role. The supply of water will exceed potential evaporation when the soil is wet and the root system is established. When the soil is dry, the conductivity of the soil will decrease to a value below potential transpiration, and actual transpiration will them be reduced due to the partially closed stomata in the root water uptake. In the model routine it is assumed that when this occurs, the potential biomass production rate is reduced in the same proportion as transpiration (Ritchie, 1998). Predicted values for soil water content were found in the study by Hensley *et al.* (1997) to be generally good when all the data for the different ecotypes simulated were pooled, with the D-index being 0.90 and $RMSE_u$ 94% of the RMSE.

4.2.1.6 Runoff

The water balance subroutine used by DSSAT is based on an adaptation of the USDA Soil Conservation Service curve number method. The SCS method uses total precipitation for a single day to estimate runoff, with the intensity of rainfall not being considered. Explicitly the routines developed for layered soil incorporates the wetness of soil near the surface as a factor. This concept was derived empirically so that an approximate amount of runoff could be estimated (Ritchie, 1998), and not to provide accurate runoff and infiltration information for a specific storm as would be done with the *ACRU* model (Schulze, 1995).

In research performed by Hensley *et al.* (1997) it was shown that in predicting runoff from South African soils, the DSSAT suite of models yielded unsatisfactory results when its simulated runoff was compared to actual measured data.

4.2.1.7 Drainage

From field drainage information a functional model has been developed to calculate the redistribution of water in the soil profile and drainage out of the root zone. Field drainage information was required, as many agricultural soils drain slowly and provide considerable amounts of water for plant use before the drainage, driven by gravity, ceases. Water can be taken up by plants while drainage out of the root zone is occurring (Ritchie, 1997).

Hensley *et al.* (1997) found at four sites in the Highveld region that drainage prediction from DSSAT v3 was much higher than measured data.

An example of critical limits for a Quaternary Catchment (QC) is shown in Table 4.2.2. For extractable water, cumulative runoff and drainage, simulated baseline figures were acquired by running the CERES-Maize model for the most appropriate management option observed from the results of operating CERES in seasonal mode. The table gives QC specific thresholds against which comparisons can be made when investigating the impacts of different climate scenarios. A change from the baseline value of ± 15% is considered as exceeding the critical threshold and will affect the sustainability pathway of that agro-ecosystem (Arshad and Martin, 2002).

In this section the selection of indicators from sustainability modelling when using the DSSAT suite of crop models has been discussed. The following section describes how the results from the modelling can be used to assess agro-ecosystem sustainability.

4.2.2 Evaluation of the Results from Sustainability Modelling

It is imperative that any evaluation strategy utilised has the capacity to assess the condition of the agricultural system. One way of achieving this is by using an aggregated sustainability index.

The flow of information required to investigate the changes in an agro-ecosystem functions is shown in Figure 4.2.4. An investigation was carried out on a Quaternary Catchment scale with the required soil and climate information extracted from the South African Quaternary

Catchment database. This information was then turned into an input file for use with the DSSAT crop models so that different climate scenarios and management decisions could be examined. The output from the crop models was evaluated using a weighted index. The steps involved in calculating the index were a modified version of the weighted index of Liebig *et al.* (2001), described in Section 4.1.3, and this process formed part of the evaluation.

- Step 1: Initially, after the indicators have been decided, they need to be grouped into agro-ecosystem functions. Table 4.2.1 shows how the eight indicators chosen from the CERES model have been grouped into two agro-ecosystem functions. The variables are grouped so that the facets that make a system sustainable or not can be identified.

- Step 2: Averages were calculated for each indicator, i.e. for grain yield, grain nitrogen content, cumulative runoff and drainage, as well as extractable water in the soil at the end of the season, from the simulated values over 44 seasons of maize production. For soil organic carbon and nitrogen, the content in the soil at the end of 44 seasons was used.

- Step 3: The average figure was compared against a critical limit or threshold value (Table 4.2.2) and was then scored accordingly. If the value for a variable was within the critical limit, then it was scored 1 and if it was outside then it is scored 0.5. Grain yield was the exception to this, it being given a higher weighting due to its importance in commercial agriculture. If it was above the break-even value it was given a score of 2 and if the value was below the break-even value then it scored 0.5. An example of this is shown in Table 4.2.3.

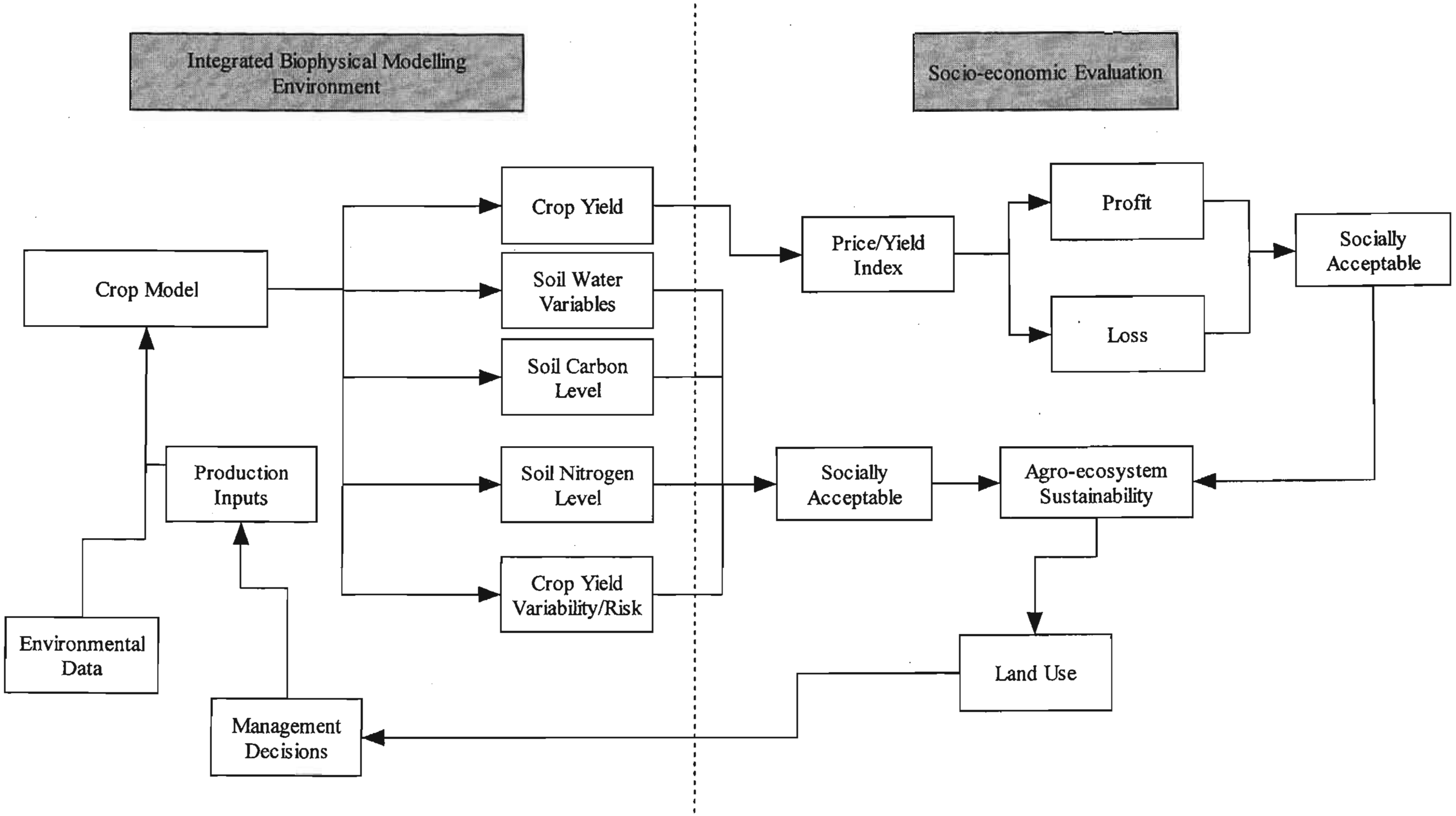


Figure 4.2.4 Schematic diagram showing important agro-ecosystem inter-linkages considered in this study

Table 4.2.2 Summary of thresholds used in the Sustainability Index for the Bothaville Quaternary Catchment

Farmer and community well-being	Threshold Description	Threshold level	
Grain yield (kg/ha)	Breakeven level (Durand and du Toit, 1999)	2 200	
Grain N content (g/kg)	Pioneer (2004)	16	
Ecological integrity			
Nitrogen recovery	Craswell and Godwin (1984)	50%	
		lower	**upper**
Soil organic C (kg/ha)	±15% Baseline (Arshad and Martin, 2002)	53	71
Soil organic N (kg/ha)	±15% Baseline (Arshad and Martin, 2002)	5 175	7 001
Extractable water (mm)	±15% Baseline (Arshad and Martin, 2002)	9	12
Runoff (cumulative, mm)	±15% Baseline (Arshad and Martin, 2002)	15	21
Drainage (cumulative, mm)	±15% Baseline (Arshad and Martin 2002)	32	44

- Step 4: The scores for each agro-ecosystem function were summed for the treatment. The result of this gave a likelihood of sustainability for the agro-ecosystem under a particular management or climate regime. Four options are given for likelihood of sustainability: minimal, low, medium and high (Table 4.2.4). The likelihood of sustainability is one way of interpreting the score given for each treatment in the sustainability index. The four categories of minimal, low, medium and high give an indication of long term ability of the agro-ecosystem to produce maize under the prescribed management practices and environmental scenarios for each treatment.

Table 4.2.3 Example of Sustainability Index for treatment 14, with a 15 October planting date, a high plant density and a 120 kg/ha of inorganic fertiliser applied

Bothaville: Treatment 14				
Food Production	**Simulated Result**	**Threshold level**		**Score**
Grain yield (kg/ha)	2 596	2 200		2.0
Grain N content (g/kg)	37	16		1.0
Soil Quality and Function				
Nitrogen recovery (%)	73	50		1.0
		lower	**upper**	
Soil organic C (kg/ha)	45	53	71	0.5
Organic N in soil (kg/ha)	4 357	5 175	7 001	0.5
Extractable water (mm)	10	9	12	1.0
Runoff (cumulative, mm)	16	15	21	1.0
Drainage (cumulative, mm)	45	32	44	0.5
	Total Score			7.5
	Likelihood of Sustainability			**Medium**

Table 4.2.4 Spectrum of sustainability

Score	Likelihood of Sustainability
4.0-5.5	Minimal
5.5-7.0	Low
7.0-8.0	Medium
8.0-9.0	High

These concepts will be used to assess agro-ecosystem sustainability at different scales, i.e. at regional scale (Chapters 6 and 7), for five selected Quaternary Catchments in the Highveld and at the farm level (Chapter 8) for smallholders in the Bergville district of KwaZulu-Natal, South Africa.

Using threshold values and the upper and lower limits (Table 4.2.2), an index was created which could give an indication of the likelihood of whether specific management choices were sustainable. The thresholds and limits serve as guidelines, and are not considered absolute values.

For a particular set of management choices (i.e. treatment) at a particular location, for example, with a planting date of 15 October, a high plant density and a 120 kg/ha inorganic nitrogen fertiliser application the resulting likelihood of sustainability is shown in Table 4.2.3. In this case the likelihood of sustainability was considered to be medium, as the average yield over 44 seasons was above the break-even level of 2 200 kg/ha, and grain nitrogen level was well above threshold level. However, both the level of soil organic carbon and nitrogen depletion exceeded the thresholds suggested for the soil to remain at a similar level of productivity.

If the necessary information is not available to produce the agro-ecological index described in Table 4.2.3, then an index incorporating yields and the coefficient of variation (CV) of yields could be used. This method of analysis is used for regional sustainability analysis in Chapter 5. The CV of annual yields is an index of the risk of production, indicating a likelihood of fluctuations in crop yield from year to year, which enables different management scenarios to be assessed. Agriculturally it is, perhaps, a more crucial statistic in marginal areas than in either very dry areas, where farming practices have adapted to variability, or in wet areas, where relatively lower inter-annual variabilities are generally expected (Schulze, 1997).

The following steps were used to calculate the index using yields and CV of yields:

- Rank yields for the scenario simulated (highest to lowest) = Ryd
- Rank CVs for the scenario simulated (lowest to highest) = Rcv
- Multiply Ryd x Rcv
- Highest value is best treatment

In Chapter 5, a combination of five planting dates and three plant densities are modelled. The yields are ranked, with the highest yield given the highest score. The CVs of yields are also ranked, with the lowest CV receiving the highest score (as a low CV is favoured). The scores are then multiplied together to produce a total score for the treatment, with the highest score then considered the 'best' treatment (Figure 5.5.1). The purpose of multiplying the scores together and producing a total score was to produce a quick, uncomplicated yet meaningful index of the combination of yield and the inter-annual variation of yield, so that optimum planting strategies could be determined.

A high inter-annual variability could be viewed as favourable from an ecological perspective as it could produce systems that are resilient. However, high variability in yields in agro-ecosystems can be stressful for farmers and their families, especially if yields are low over a number of consecutive years. The small-scale farmer is particularly at risk to fluctuating yields and is unlikely to have insurance for crop failure. Farmers are generally cautious and circumspect in the face of downside risk. They exhibit risk aversion. This is particularly so for resource-poor small farmers whose livelihood can often be at stake from risk. Their basic risk management strategy of caution is displayed in a wide variety of operational strategies aimed at risk mitigation, such as use of tolerant cultivars, spreading sales of maize over time and maintaining flexible management strategies. Personal judgement is then exercised by the farmer to choose that alternative which, for him or her, has the most preferred probability distribution of outcomes. Such a process of choice is generally carried out by the farmer in an informal rather than a formal manner. This is particularly true for the smallholder both subsistence and part-commercial (McConnell and Dillon, 1997). The author, therefore, considers a high yield, even if not the highest, together with a low CV of yield to be the most desirable scenario in general for the Highveld farmer and for the smallholder farmer elsewhere in South Africa. It is assumed by the author that this would provide the highest returns for the lowest risk.

Different frameworks have been proposed to aid understanding of decision making under risk. The methodologies contained in the DSSAT software are based on Bernoullian utility theory and stochastic efficiency criteria. Bernoullian utility theory hypothesises the existence of a utility function that relates outcomes to the decision-makers level of satisfaction with that particular outcome. The use of stochastic efficiency criteria entails a comparison of random variables that relate to financial gains and losses. For risk assessment using the DSSAT model the user can set seasonal strategies, for example planting dates and plant densities, and simulate these using historical climate data. Efficient or optimum strategies can then be identified on the basis of mean-variance analysis and stochastic dominance (Thornton and Wilkens, 1998).

This chapter has sought to adapt a goal-orientated framework so that it can be used to assist in assessing maize agro-ecosystem sustainability at different scales. A thorough investigation of sustainability necessitates that environmental, economic and social aspects be considered. In the framework proposed in this chapter, more emphasis is given to the biophysical than socio-economic aspects of the agro-ecosystem. From the results of the biophysical analysis, inferences about economic and social impacts are made, rather than modelling the socio-economic components of the system *per se*. The flow of information through the framework, from the initial inputs from the environmental database to the result of likelihood of sustainability, is shown in Figure 4.2.4.

This study sought to assess sustainability across a range of scales, the broadest of which is the regional scale. Regional sustainability of the Highveld is assessed in Chapter 5 using the adapted goal-orientated framework and in the chapter a range of management options for optimum planting strategies of maize is investigated.

5 AGRICULTURAL SUSTAINABILITY AT A REGIONAL SCALE: ASSESSMENT OF MAIZE PRODUCTION IN THE HIGHVELD SOUTH AFRICA UNDER DIFFERENT MANAGEMENT AND CLIMATE SCENARIOS

Agricultural land in the Highveld region produces 70 per cent of South Africa's cereal crops, with 90 per cent of the country's maize being cultivated there (du Toit *et al.*, 1999). Therefore, this region is of vital importance regarding food security for the nation, under both present climate conditions and for plausible future climate scenarios associated with global warming. The physical and environmental features of the Highveld vary across the region and are summarised in Section 5.1. In order to assess agricultural sustainability with respect to maize yields at the regional level of the Highveld, the adapted goal orientated system discussed in Chapter 4 is employed. This system has four stages:

- Identifying the goal (Section 5.2)
- Sustainability modelling (Section 5.3)
- Evaluation (Section 5.4) and
- Management advice (Section 5.5).

Impacts on food security at both household and regional levels are, to a large extent, associated with farm management. The objective of regional food security is strongly connected to yield stability. Information on yield stability at the regional level is of crucial importance. Consequently in sustainability modelling, the use of crop models can be useful for assessing production variability (Thornton and Wilkens, 1998) as well as changes in agro-ecosystem functions. The simulated changes that result from anticipated future climatic scenarios can then be examined under different management strategies.

5.1 Description of Highveld Region

The Highveld region of South Africa (Figure 5.1.1) ranges in altitude from 900 to 1800m above sea level. It is part of the inland plateau of the southern African subcontinent. The Highveld region includes parts of the provinces of North-West, Free State, Gauteng and the eastern part of Mpumalanga. The region is characterised by plains with low to moderate relief, generally low drainage density and low stream frequency. The section of the Highveld that stretches into Mpumalanga province has low mountains with high relief, as well as plains

(Schulze, 1997). The soils are of a sandy clay loam texture, with soil thickness ranging from 400-1200mm. Clay soils occur in parts of Gauteng and Mpumalanga (Schulze, 1997).

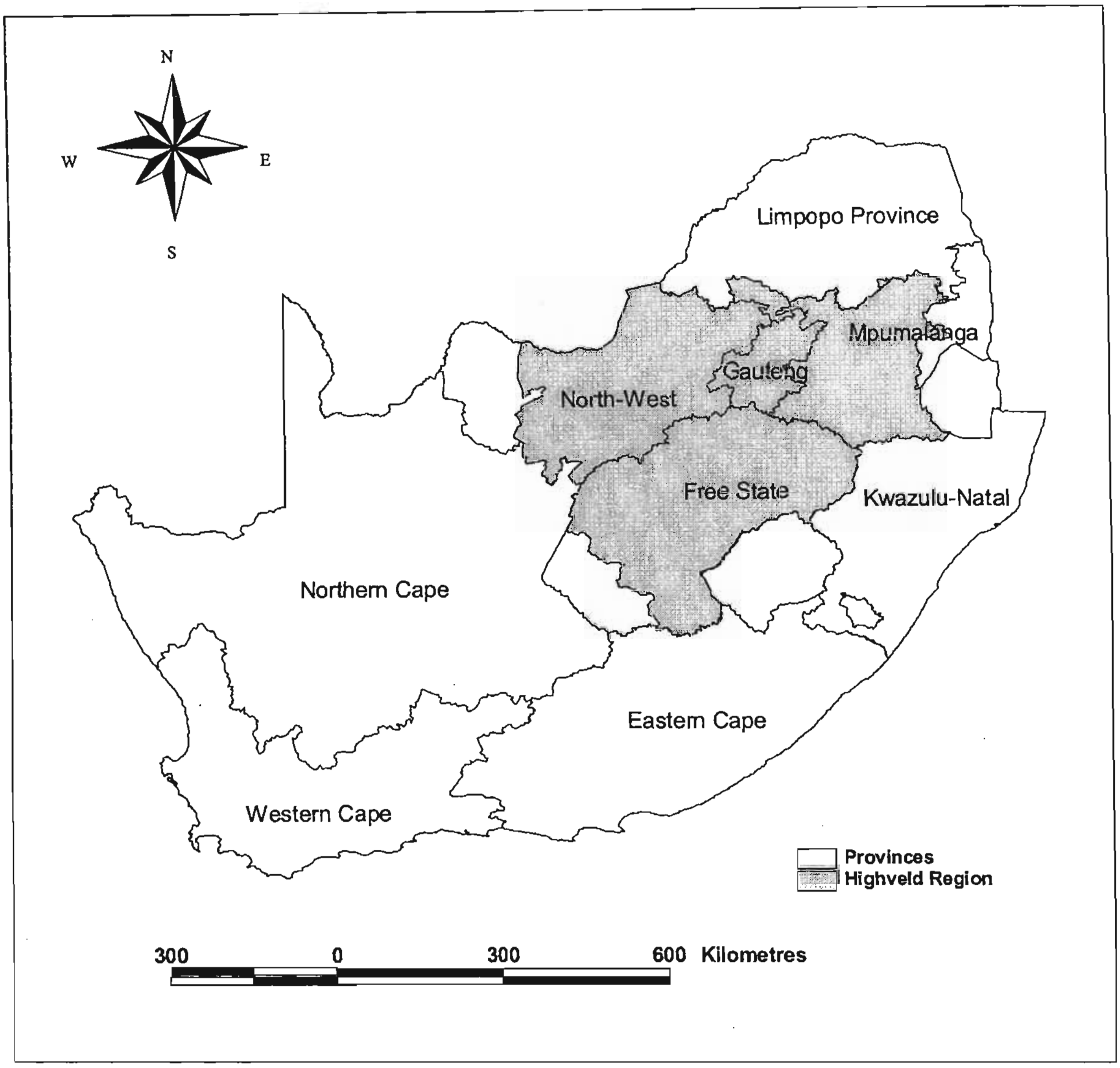


Figure 5.1.1 Highveld region of South Africa (after du Toit *et al.*, 2002a)

The Highveld region consists of what may be described as two agro-ecological zones, one sub-humid and the other semi-arid. The semi-arid west receives mean average precipitation (MAP) of up to 600 mm whereas in the eastern agro-ecological zone MAP is 600-1400 mm. Figure 5.1.2 shows that the MAP in the Highveld region increases from west to east. The

Highveld is a summer rainfall area which receives the vast majority of its precipitation between the months of October and March. Schulze (1997) used the Markham technique to delineate southern Africa into regions of rainfall seasonality. The eastern Highveld was designated an early summer rainfall area (December maximum), central Highveld a mid-summer rainfall area (January maximum), and the western Highveld as a late summer rainfall area (February maximum). A mid-summer dry spell occurs in 9 out of 10 years, with a low rainfall spell for days to weeks and high temperatures (du Toit *et al.*, 1999).

Solar radiation is higher in the western parts of the Highveld (Schulze, 1997). In January the solar radiation ranges from 32-34 $MJ.m^{-2}.day^{-1}$ in the west and 28-30 $MJ.m^{-2}.day^{-1}$ in the eastern parts of the Highveld. In midwinter, i.e. July, solar radiation is lower, ranging from 16-19 $MJ.m^{-2}.day^{-1}$ (Schulze, 1997). Monthly means of daily maximum temperature in the summer months, i.e. December to March, range from 28-30 °C in the west and 26-30 °C in the east, while the means of minimum temperatures in these months are between 12-16 °C across the region. The first heavy frost of the year occurs, on average, in late May. However, in the southern and eastern parts of the Free State the first frost can be experienced in early May. Heavy frost can continue to occur, on average, up until September (Schulze, 1997).

Average annual precipitation maps do not show the year-to-year variability of precipitation. The inter-annual coefficient of variation (CV) of rainfall for the Highveld region is shown in Figure 5.1.3. The CV of rainfall can be used for relative comparisons of variability between one region and the next (Schulze, 1997). The CV of inter-annual rainfall in the Highveld region decreases from west to east. As a general rule the drier areas, which are already the marginal areas for farming as a result of their low annual MAP, also have to contend with a more variable inter-annual rainfall.

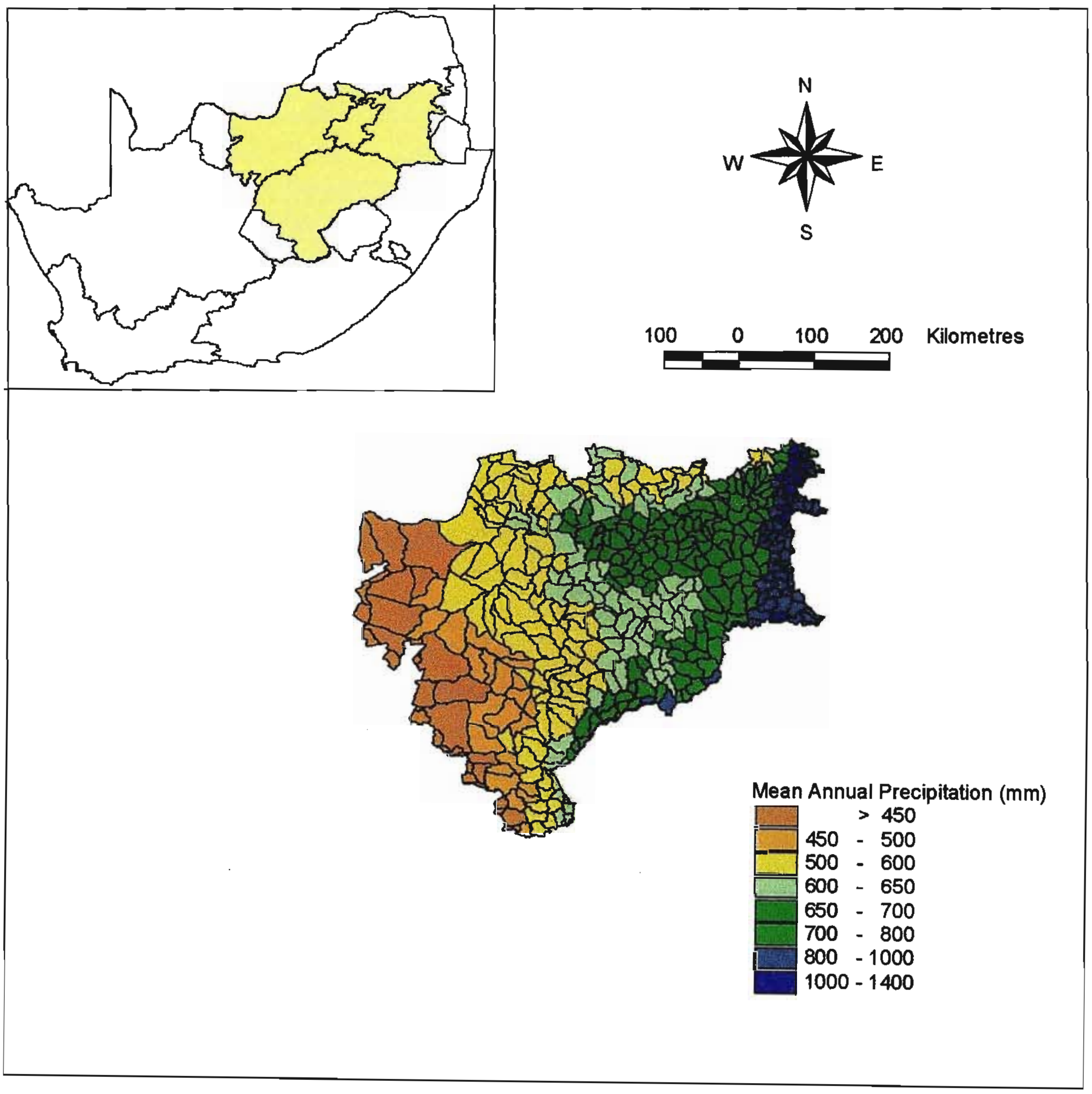


Figure 5.1.2 The mean annual precipitation for the Quaternary Catchments in the Highveld of South Africa (after Schulze, 1997)

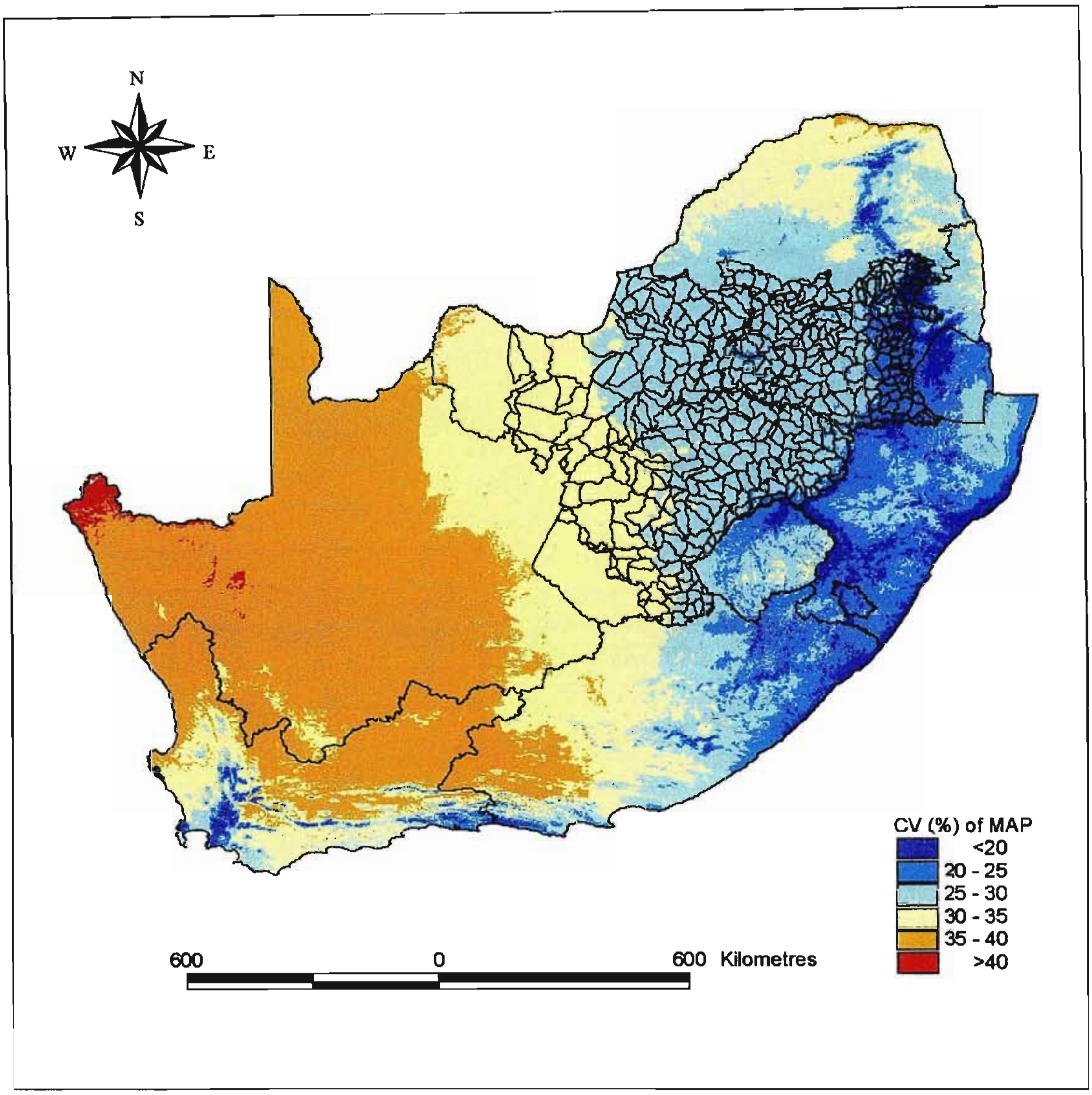


Figure 5.1.3 The inter-annual coefficient of variation of rainfall in South Africa (after Schulze, 1997).

The differences in the amount of rainfall, the CV of inter-annual rainfall, temperature ranges and frost severity across the region are important factors when identifying sustainability goals and strategies to achieve those goals. Those goals and strategies for regional agricultural sustainability are discussed in the sections which follow.

5.2 Goal Definition

In using the adapted goal orientated system, a suitable main objective, or goal, is obliged to be both relevant and obtainable. In this particular assessment the goal would need to encompass regional sustainability, under both current and changed climatic conditions. The identified goal regarding agricultural sustainability and the production of maize in the Highveld is as follows:

> *'The goal is for the agro-ecosystems in the Highveld region to continue in the long term providing quality well-being for farmers and local communities and to maintain ecological integrity of the agro-ecosystem'* (Section 2.7).

If different management scenarios are made up of 5 planting dates and 3 plant densities, then this assessment requires the following to be identified:

- Mean yields
- Regional yield differences
- Yields in the driest year in 5
- Yields in the wettest year in 5 and
- Inter-annual coefficient of variation of the yields.

The above statistics would assist in ascertaining optimum plant dates and plant densities at different locations within the region. Optimum planting strategies under certain conditions are important when identifying sustainable pathways for agriculture.

The profitable production of maize in a way that takes cognisance of the long-term is of crucial importance to the rural economy and the social structure of rural communities in the Highveld. Maize marketing in the Highveld region transformed completely in 1997 from a single channel marketing system to a free market system. Historically, the Minister of Agriculture determined the maize price after the February yield forecast by the National Yield Forecast Committee, and the Maize Board was the only marketing channel. After a transitional period the maize marketing system became a free market, unsubsidised by government and with only modest protection from imports (du Toit *et al.*, 2002a). With the current management practices, the economically profitable production of maize has become progressively more difficult to achieve, owing to variations in climatic conditions, rising input costs and unstable maize prices. This has had a negative bearing on the local economy and the rural communities involved in maize production.

In the western section of the Highveld the maize yields are likely to reduce and become less predictable with increased variability in the precipitation and possibly even a reduction in the mean annual precipitation associated with future climate change scenarios (du Toit *et al.,* 1999a). This area of the Highveld is considered especially vulnerable to any negative climatic changes as current yields, on average, range between only 1 and 3 tonnes per hectare.

The susceptibility of the drier western Highveld to potential climatic change was investigated by du Toit *et al.* (1999). The study is described in more detail in Section 3.1.3.3. The work carried out by du Toit *et* al. (1999a) highlights the necessity of identifying strategies to moderate yield variability. The CERES-Maize model has been used previously to simulate maize agro-ecosystems (Schulze *et al.*, 1993; de Jager *et al.*, 1998; du Toit and Prinsloo, 1998). The methodology behind using the CERES-Maize model for sustainability modelling on a regional scale in this study is described Section 5.3.

5.3 Sustainability Modelling in the Highveld

5.3.1 Background

The CERES-Maize model was adapted for South African conditions at the ARC Grain Crops Institute in Potchefstroom (du Toit *et al.,* 1994 a, b, c; du Toit *et al.,* 1997; du Toit *et al.,* 1998; du Toit and Prinsloo, 2000; du Toit *et al.*, 2002a; du Toit *et al.,* 2002b). The DSSAT input file for each Quaternary Catchment was created with environmental information from the School of BEEH Quaternary Catchment Database, QCDB (Schulze *et al.*, 2004).

The QCDB is now available in PC format and has been created using Microsoft Access. Input parameters can be selected for any of the Primary, Secondary, Tertiary or Quaternary Catchments. The database output is in the form of CSV files. Using a series of FORTRAN programs developed by the School of BEEH and adapting them from use in the UNIX environment to PC format, an input file for the DSSAT crop models can be created from the

CSV files. The extracted CSV files do not contain the daily rainfall data. The *ACRU* agrohydrological model has to be run and daily rainfall for each of the 1946 Quaternary Catchments for the years 1950-1994 is given as an output option. The output from the crop model is converted into a format for a GIS by another FORTRAN program written at the School of BEEH.

Modelling of maize yields on a Quaternary Catchment scale has been conducted previously by Schulze *et al.* (1993), Schulze *et al.* (1996) and du Toit *et al.* (1999a). The modelling performed for the Highveld region discussed in this chapter, builds on previous work by incorporating daily maximum and minimum temperatures in the model whereas previously monthly means of daily temperatures were used. Furthermore, the soils information used for each QC is from the current Land Type soils database of the Institute of Soil, Climate and Water in South Africa, whereas previous work used the soil input from the much simpler 84 soil zones (Schulze, 1997).

CERES-Maize was operated in seasonal mode when the aforementioned study by du Toit *et al.* (1999) was performed. Seasonal modelling refers to experiments of a single cropping season. Successive seasons can be run in a sequence, but there are no carry-over effects from one season to next, i.e. the system is reset with the same initial conditions. This method of modelling is valuable for evaluating management decisions such as planting dates, varieties of crop, or fertiliser application regimes (Thornton *et al.*, 1995).

In order to assess sustainability at a regional scale, estimations of yield and the variations in yield are the only indicators used (Section 3.1.4). This author recognises that this presents a restricted analysis of the agro-ecosystem assessed, particularly in term of goods and services performed by the agro-ecosystem. However, yield is an important indicator of sustainability and is linked to the other indicators that are used in more detailed studies in Chapters 6, 7 and 8.

5.3.2 Management and climate scenarios modelled

5.3.2.1 Management scenarios

In regard to management scenarios, five planting dates were selected along with three plant densities, based on typical practice in the area, the details of which are shown in Table 5.3.1. The designation 'low plant density' refers to a plant density of 1.5 plants/m^2 with a row spacing of 1.5 m, 'the medium plant density' is 2 plants/m^2 and row spacing at 1.2 m and 'high plant density' refers to 3.0 plants /m^2 with a row spacing of 0.9 m. Planting densities are those used in previous studies carried out by du Toit *et al.* (1999) and du Toit *et al.* (2002a). By investigating a range of planting dates and plant densities for maize, optimum planting strategies can be ascertained under present climatic conditions for any given QC in the Highveld region. Optimum planting strategies can then be utilised to investigate how climatic changes could impact the sustainability of maize agro-ecosystems. The planting dates are based on climatically optimum planting dates presented by Schulze (2003), which were determined with the *ACRU* maize yield model.

Table 5.3.1 Different management options investigated using CERES-Maize

Option No.	Planting Date	Plant Density (m^2)	Row Spacing (m)
1	15 October	1.5	1.50
2	15 October	2.0	1.20
3	15 October	3.0	0.90
4	1 November	1.5	1.50
5	1 November	2.0	1.20
6	1 November	3.0	0.90
7	15 November	1.5	1.50
8	15 November	2.0	1.20
9	15 November	3.0	0.90
10	1 December	1.5	1.50
11	1 December	2.0	1.20
12	1 December	3.0	0.90
13	15 December	1.5	1.50
14	15 December	2.0	1.20
15	15 December	3.0	0.90

5.3.2.2 Climate scenarios

In addition to modelling under present climatic conditions, climate change scenarios were also considered. The climate change strategy adopted was not to use perturbations *per se* of future climates generated from either a single General Circulation Model (GCM) or an ensemble of GCMs (as was the case in some earlier studies in South Africa, e.g. du Toit *et al.*, 1999; Schulze and Perks, 2000), but rather to use plausible climate change scenarios for the region. These plausible scenarios consisted either of an individual "driver" of climate change (e.g. an effective doubling of atmospheric CO_2 concentrations, or an increase in temperature or a change in rainfall by itself) or more than one driver changing simultaneously (e.g. $2xCO_2 + \Delta T$).

The plausible future scenarios were based on climate perturbations for South Africa from several GCMs which displayed consistent trends and magnitudes (Perks *et al.*, 2000; Schulze and Perks, 2000; Engelbrecht, 2005). These climate scenarios were used in what is tantamount to a sensitivity analysis. The scenarios used were:

- The enhancement of atmospheric CO_2 concentrations from present levels around 370 ppmv to 555 ppmv, abbreviated as the '$2xCO_2$' scenario. A $2xCO_2$ scenario implies enhanced photosynthetic rates plus stomatal closure, with resultant reductions in transpiration rates. The hypothesis is that this scenario would increase yields, more so with higher plant densities than with lower ones.
- An increase in both maximum and minimum daily temperatures by 2°C is designated the '+2°C' scenario. An increase temperature promotes rate of crop development, but simultaneously, through increased evaporative demand, can dry out soil more rapidly. An increase in the rate of development would reduce the time available for the crop to capture solar radiation and convert CO_2 to biomass. The hypothesis, in a southern African context in which climates are rainfall limited but not radiation limited, is that yields would generally decrease with an increase in temperature by itself.
- A 10% increase in rainfall constitutes a further scenario. In the Highveld, particularly in the western parts, rainfall is the major limiting factor to crop development. The hypothesis is that this scenario would increase yields.
- A 10% reduction in rainfall is another scenario used. A reduction in rainfall, particularly in the Quaternary Catchments that have a low MAP, would lead to the maize crop

becoming stressed and crop development being inhibited. The hypothesis is that this scenario would reduce yields.

- The combination of effective doubling of atmospheric CO_2 plus increased temperatures is abbreviated to the '2x CO_2 with +2°C' scenario. The hypothesis is that the "drivers" in this climate change scenario are self cancelling up to a point.
- The combination of effective doubling of atmospheric CO_2 and a 10% decrease in rainfall is termed the '2xCO_2 with 10% rainfall reduction scenario. The hypothesis is that the drivers in this climate scenario will be self cancelling up to a point, but that in the western drier areas of the Highveld the reduced rainfall would affect yields negatively even with 2xCO_2.

In order to model sustainability under climate change scenarios, optimum planting dates and plant densities for present conditions were retained. It is recognised that future climatic changes could result in the optimum planting date for a particular Quaternary Catchment to alter, most likely to on an earlier date. The two management options used were:

- 15 October planting date with high plant density and
- 15 November planting date with high plant density.

In practice fixed planting dates are not generally used in South Africa. Planting dates are based on sufficient spring/early summer rains having been received within a specified window. In South Africa this would be in the region of 25 mm in a five day period between 1 October and 31 December (Schulze, 1995). The planting dates would also be based on recommendations from crop insurance companies, fertiliser advisors and agricultural extension workers. These recommendations are often based on research of optimum planting dates. This research investigated early, medium and late planting dates so that a regional average optimum planting date could be given.

In this research with future climate scenarios the same fixed optimum planting dates that were used for present climate have been kept. Planting dates in future climate scenarios are likely to change as farmers adapt to the gradual changes in climate. The plausible scenarios that were used in this research involve quantum decreases or increases of input climate variables. In order to determine the climatically optimum planting date for a region under a future climate the distribution and magnitude of rainfall (and not merely a quantum increase or decrease) of that future climate would need to be investigated. This is because temperature and solar radiation are not limiting factors in South Africa under present conditions and research indicates that these variables will not be limiting in a future climate (Schulze *et al.,* 2005). Deriving optimum planting dates under future scenarios is an area for future research, and it is beyond the parameters of this thesis.

5.4 Evaluation Strategy

5.4.1 Responses under present climatic conditions

The results from the seasonal modelling are illustrated in Figures 5.4.1 through to 5.4.15. Each figure shows the average yield of each Quaternary Catchment over forty-four seasons along with the results for the driest year in 5, i.e. the 20th percentile of non-occurrence and the wettest year in 5, i.e. the 80th percentile of non-occurrence, as well as the coefficient of variation of yields. The average grain yield is used as a sustainability indicator, since unprofitable agricultural systems will not continue (Edwards-Jones and Howells, 2001). Yields in the western part of the Highveld are required to be above 2 200 kg/ha (Durand and du Toit, 1999) for maize production to be financially sustainable and in the eastern region over 3 600 kg/ha.

With an early planting date of 15 October and a low plant density (Figure 5.4.1) the majority of QCs in this region have an average yield below the breakeven yield (2 200 kg/ha) for this area. In the driest year in 5 the yields falls below the famine level of 900 kg/ha when using the low planting density. The majority of the QCs have a CV of over 80%, implying that the risk factor is high with this particular planting strategy. Even when the plant density is increased to a medium (Figure 5.4.2) or high (Figure 5.4.3) value, the average yield in most of the western parts is still below the 2 200 kg/ha breakeven level. However, with a higher plant density the variability in yield is reduced.

With a planting date two weeks later on 1 November and with a low plant density (Figure 5.4.4) the number of QCs with an average yields below 900 kg/ha is reduced. With a medium (Figure 5.4.5) or high (Figure 5.4.6) plant density no QCs are below the 900 kg/ha level. In a wet year most QCs in western parts are above the breakeven level. The CV of the yield are generally over 80% for a low or medium plant density, but with a high plant density the CV is reduced, in some QCs by as much as 40%.

A low plant density with a planting date of 15 November (Figure 5.4.7) produces yields between 1 000-3 000 kg/ha in an average as well as a 1 in 5 dry year. Many QCs in the western areas have yields below 900 kg/ha. In a 1 in 5 wet year yields are above breakeven in all but 13 QCs and in some QCs yields are over 4 500 kg/ha. However, the inter-annual CVs of yields remain high (at minimum >60%; in most QCs above 80%). An increase in the plant density (Figures 5.4.8 and 5.4.9) reduces variability in yields and reduces a number of QCs with a yields below 900 kg/ha for a dry year.

A planting date of 1 December increases the number of QCs in western parts with average yields over the breakeven figure of 2 200 kg/ha. With a medium planting density (Figure 5.4.11) the variability of yield is reduced when compared with that for a planting date of 15 November. The later planting date of 15 December (Figures 5.4.13, 5.4.14 and 5.4.15) is beneficial in terms of yield in those QCs which are on the fringe of the western Highveld. This later date enables maize production to be economically viable in an increased number of QCs. In a 1 in 5 wet year with a medium plant density all QCs in the western parts have yields above 2 200 kg/ha. The simulations favour a late planting date for the western Highveld only. This is a realistic result when compared with the common practice of farmers in the region, as described by du Toit *et al.* (1999).

In the eastern parts of the Highveld the mean grain yield is above 3 600 kg/ha in all of the QCs using all three plant density scenarios (Figure 5.4.1, 5.4.2 and 5.4.3) when using a planting date of 15 October. On the fringes of the eastern Highveld the grain yield is above 6 000 kg/ha. The CV of yield is low in comparison with the rest of the Highveld, with a vast majority of QCs having a CV below 50%. Using this planting date, the eastern Highveld has the potential to produce high yields with a low year-to-year variation.

With a planting date of 1 November (Figures 5.4.4, 5.4.5 and 5.4.6) the mean grain yield is reduced compared with the earlier planting date of 15 October. The yields are still above 4 500 kg/ha in those QCs which are on the periphery of the eastern Highveld, but in general the mean grain yield in many QCs falls below the break-even threshold of 3 600 kg/ha. In the eastern Highveld the later planting dates produce lower mean grain yields. The QCs in this area produced higher yields when the planting date was either 15 October or early November. The CV in yield increases with later planting dates as well. A high plant density coupled with a planting date of either 15 October or 1 November is the management strategy that will produce the highest maize yields.

In the central Highveld the average yields when the planting date is 15 October (Figures 5.4.1, 5.4.2 and 5.4.3) are commonly between 2 200 and 3 600 kg/ha. An increase in plant density generally realises an increase in the mean grain yield. At a lower plant density there is less variation in yields. In a 1 in 5 wet year the yields are above 4 500 kg/ha in many of the central QCs with all three plant densities. The yields in the central area increase with a planting date of 1 November or 15 November. The CV of yields is higher in the central areas with a November planting compared with planting on 15 October, but the CVs are lower when compared with those planting dates in December.

Some general trends may be identified regarding planting date and plant densities for different areas in the Highveld region. For maize production to be financially sustainable in the eastern Highveld, a planting date in mid-October coupled with a high plant density is favoured. In the central and western Highveld a later plant date is preferred as a result of the rains falling later in the season. In the eastern areas, where MAP is higher, the inter-annual variability of grain yields is lower than in the west.

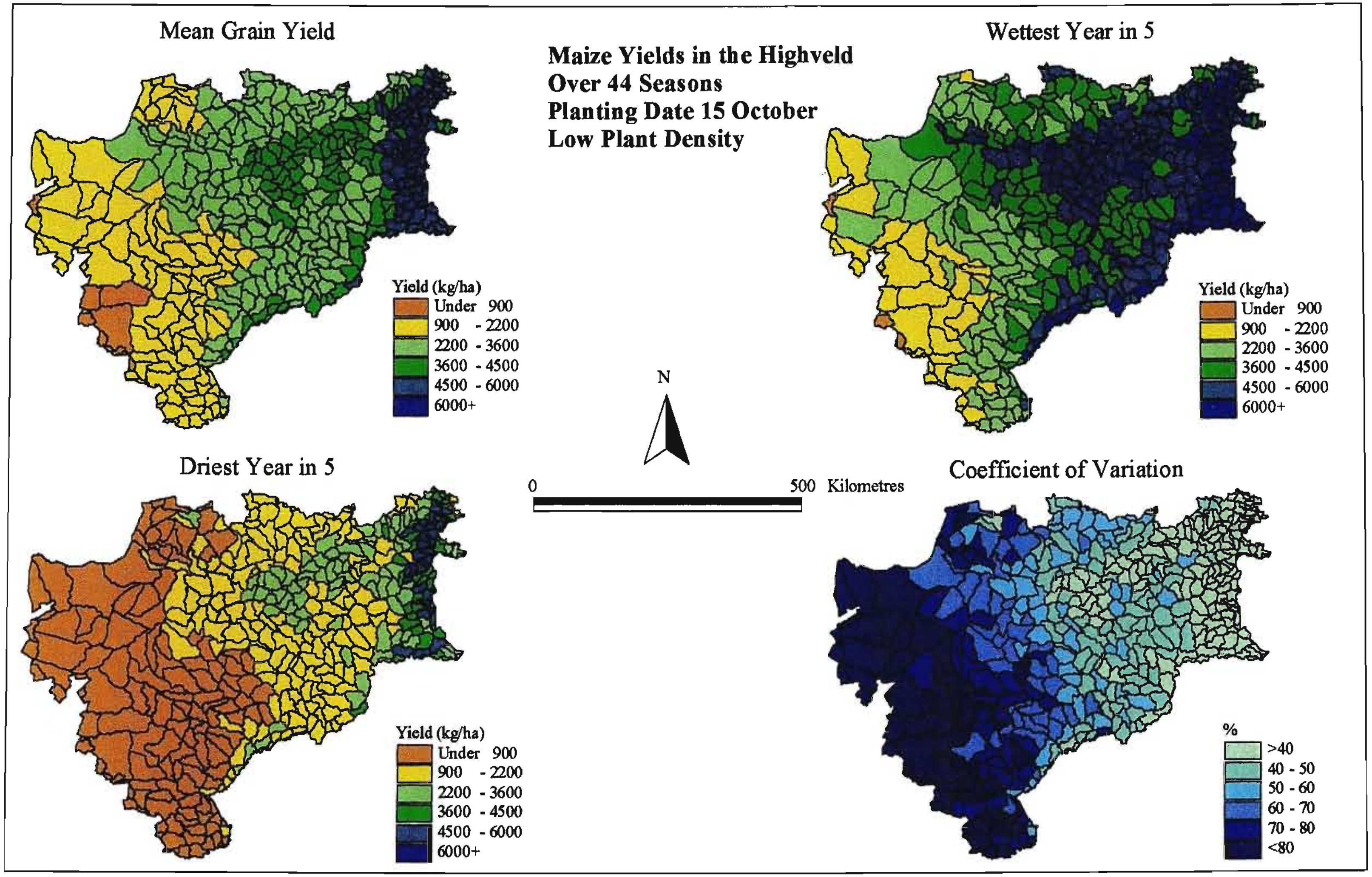


Figure 5.4.1 Simulated maize yields (mean, plus driest and wettest years in 5) and, inter-seasonal coefficient of variation of maize yields for a planting date of 15 October with low plant density

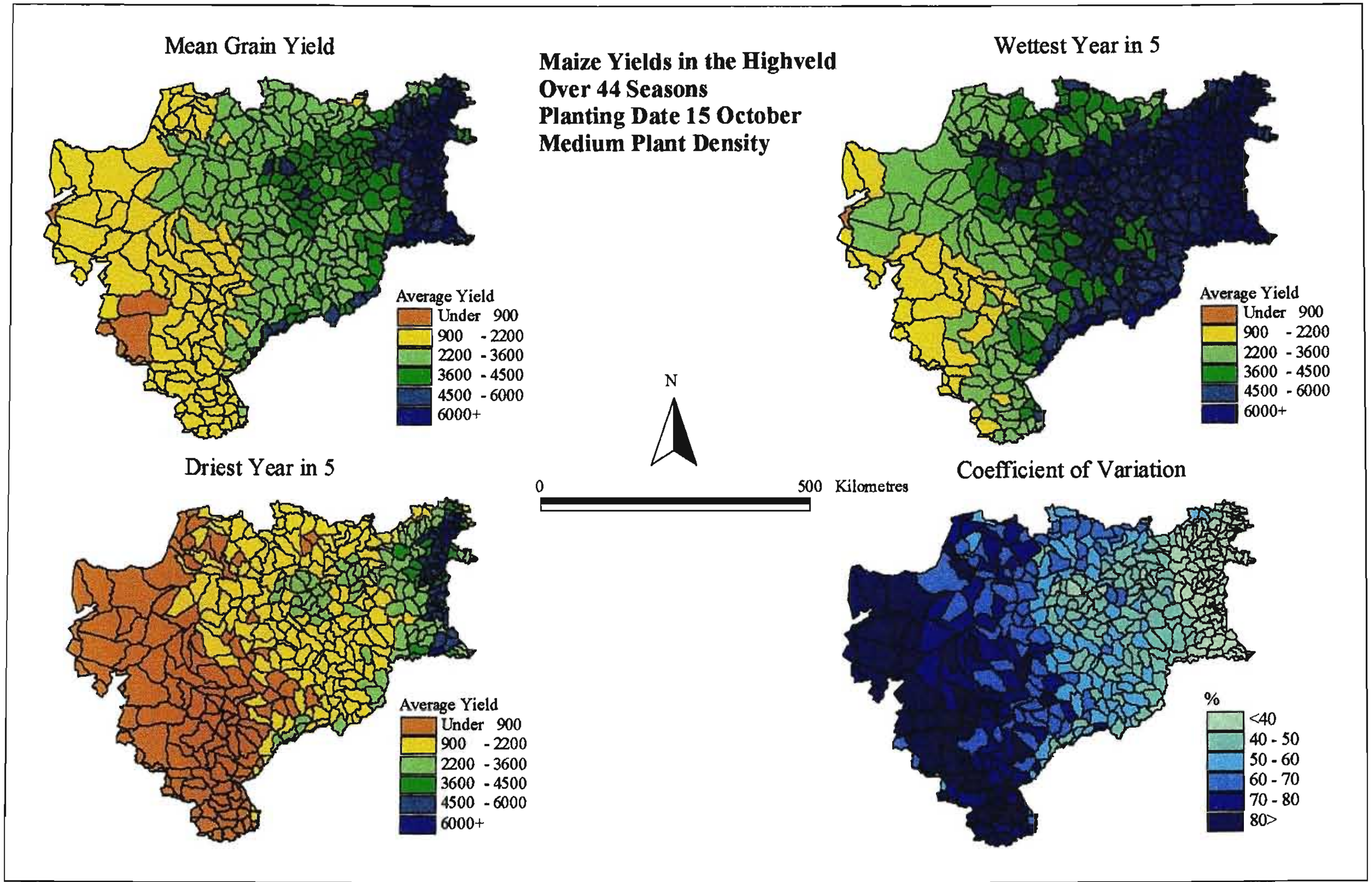


Figure 5.4.2 Simulated maize yields (mean, plus driest and wettest years in 5) and, inter-seasonal coefficient of variation of maize yields for a planting date of 15 October with medium plant density

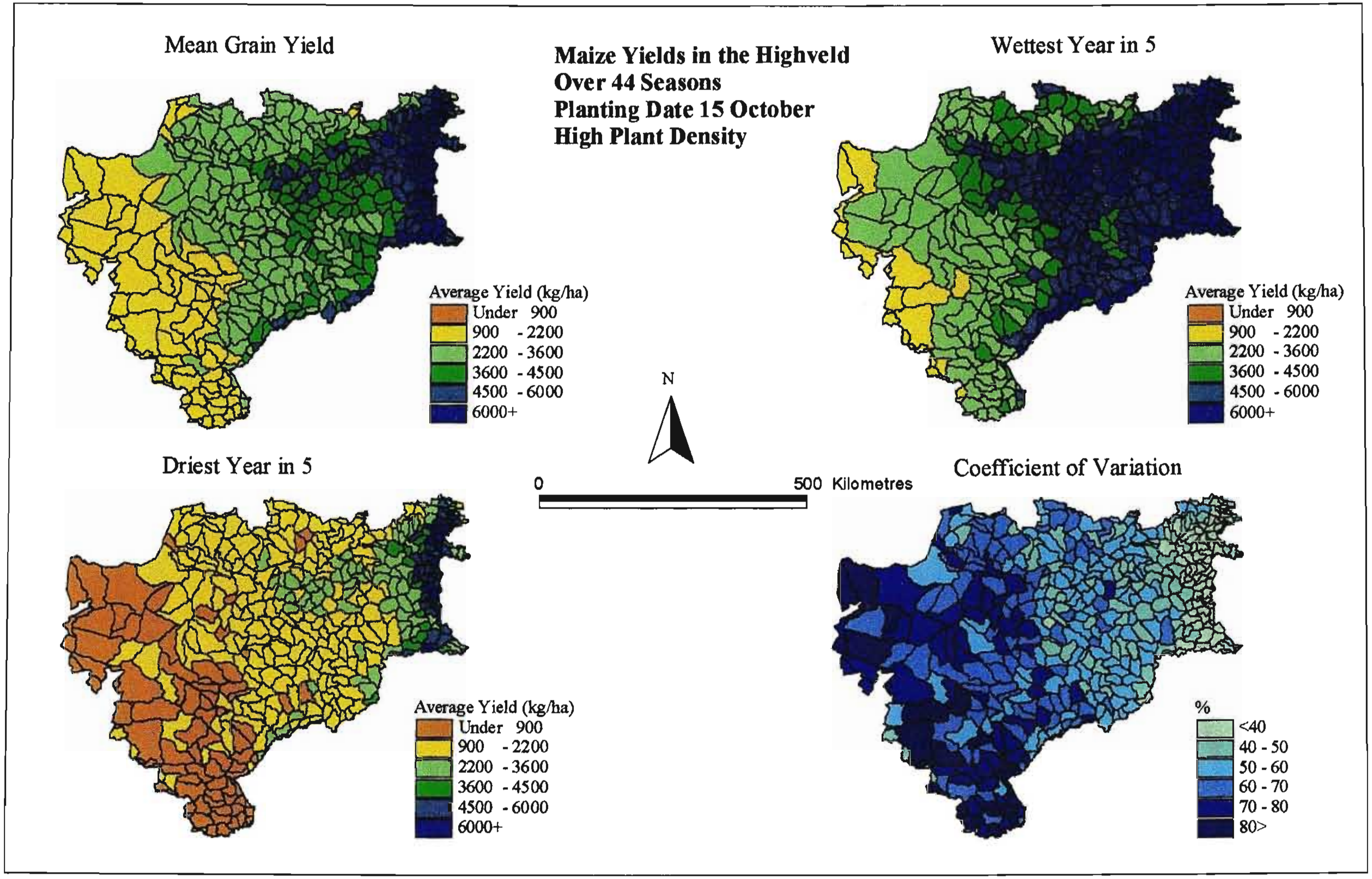
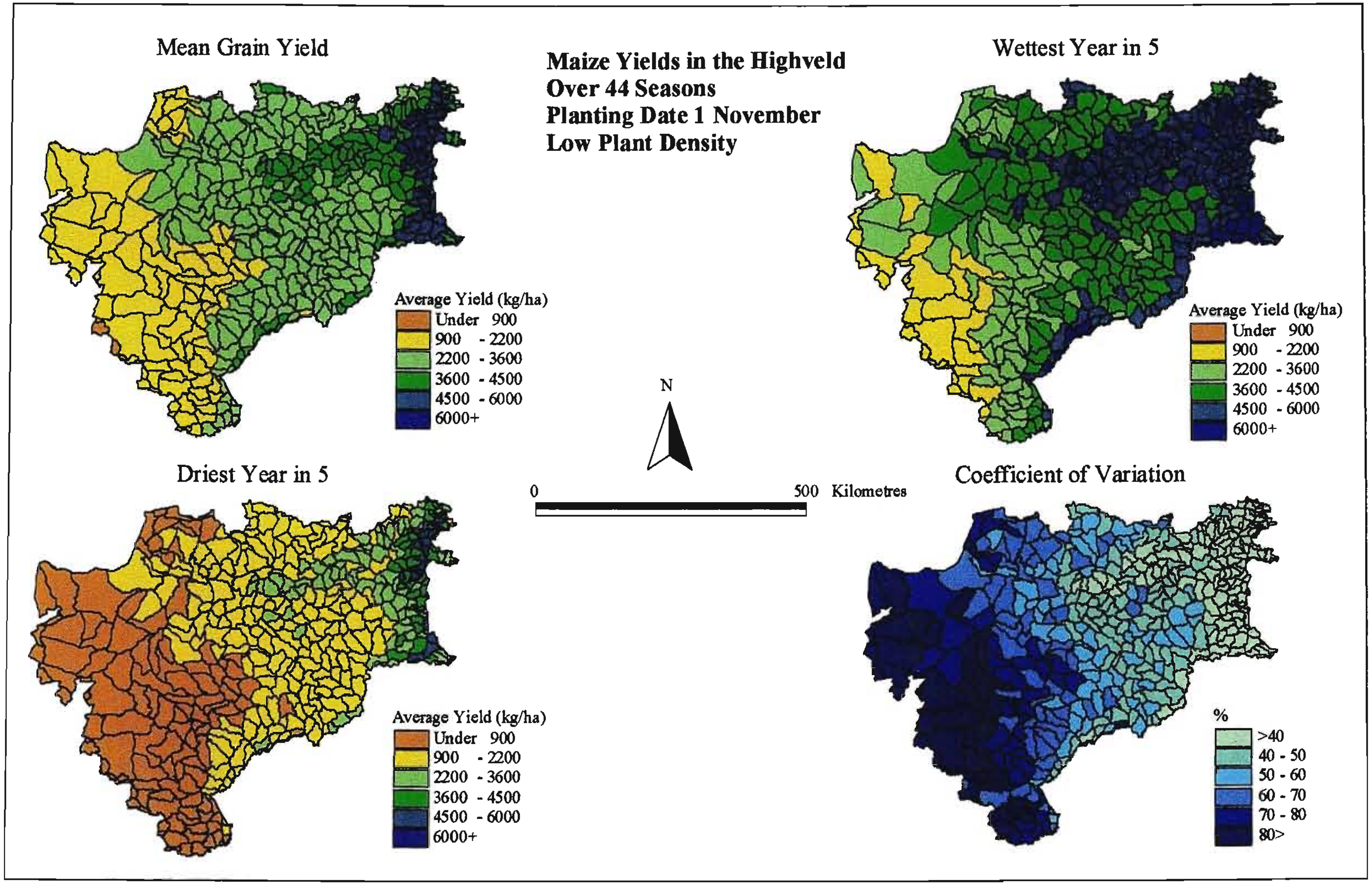


Figure 5.4.3 Simulated maize yields (mean, plus driest and wettest years in 5) and, inter-seasonal coefficient of variation of maize yields for a planting date of 15 October with high plant density


Maize Yields in the Highveld
Over 44 Seasons
Planting Date 1 November
Low Plant Density

Mean Grain Yield

Wettest Year in 5

Driest Year in 5

Coefficient of Variation

Figure 5.4.4 Simulated maize yields (mean, plus driest and wettest years in 5) and, inter-seasonal coefficient of variation of maize yields for a planting date of 1 November with low plant density

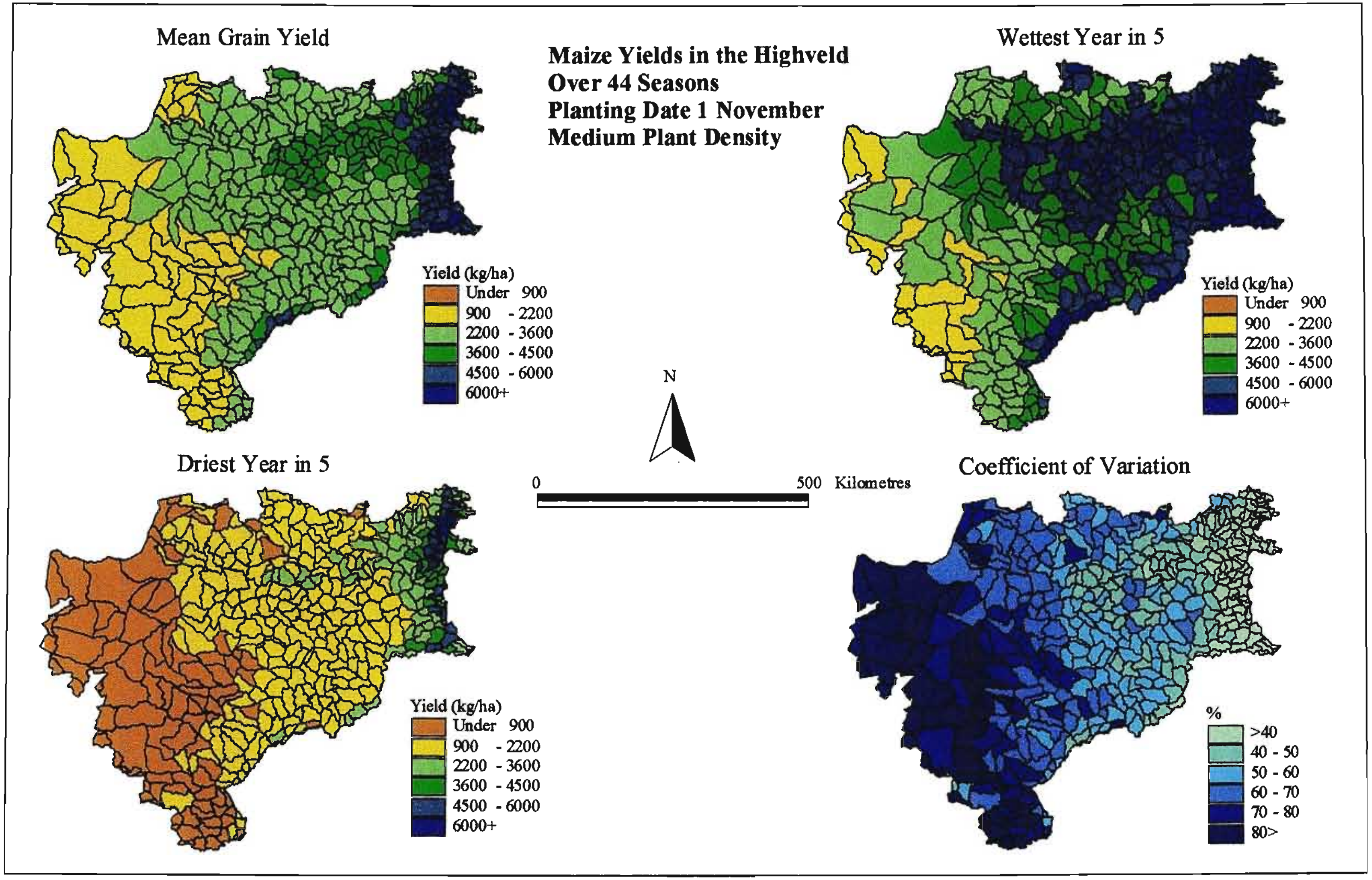


Figure 5.4.5 Simulated maize yields (mean, plus driest and wettest years in 5) and, inter-seasonal coefficient of variation of maize yields for a planting date of 1 November with medium plant density

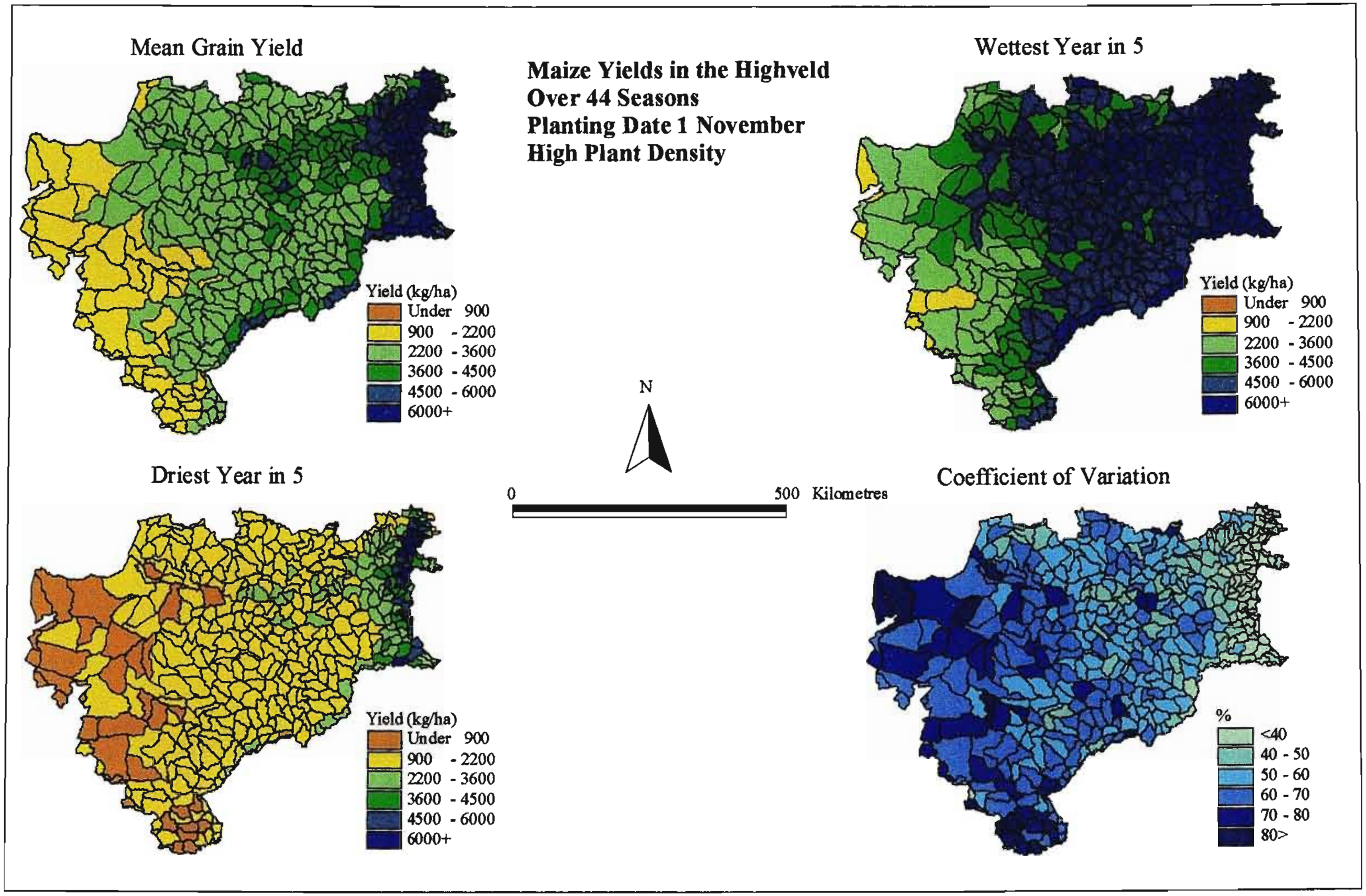


Figure 5.4.6 Simulated maize yields (mean, plus driest and wettest years in 5) and, inter-seasonal coefficient of variation of maize yields for a planting date of 1 November with high plant density

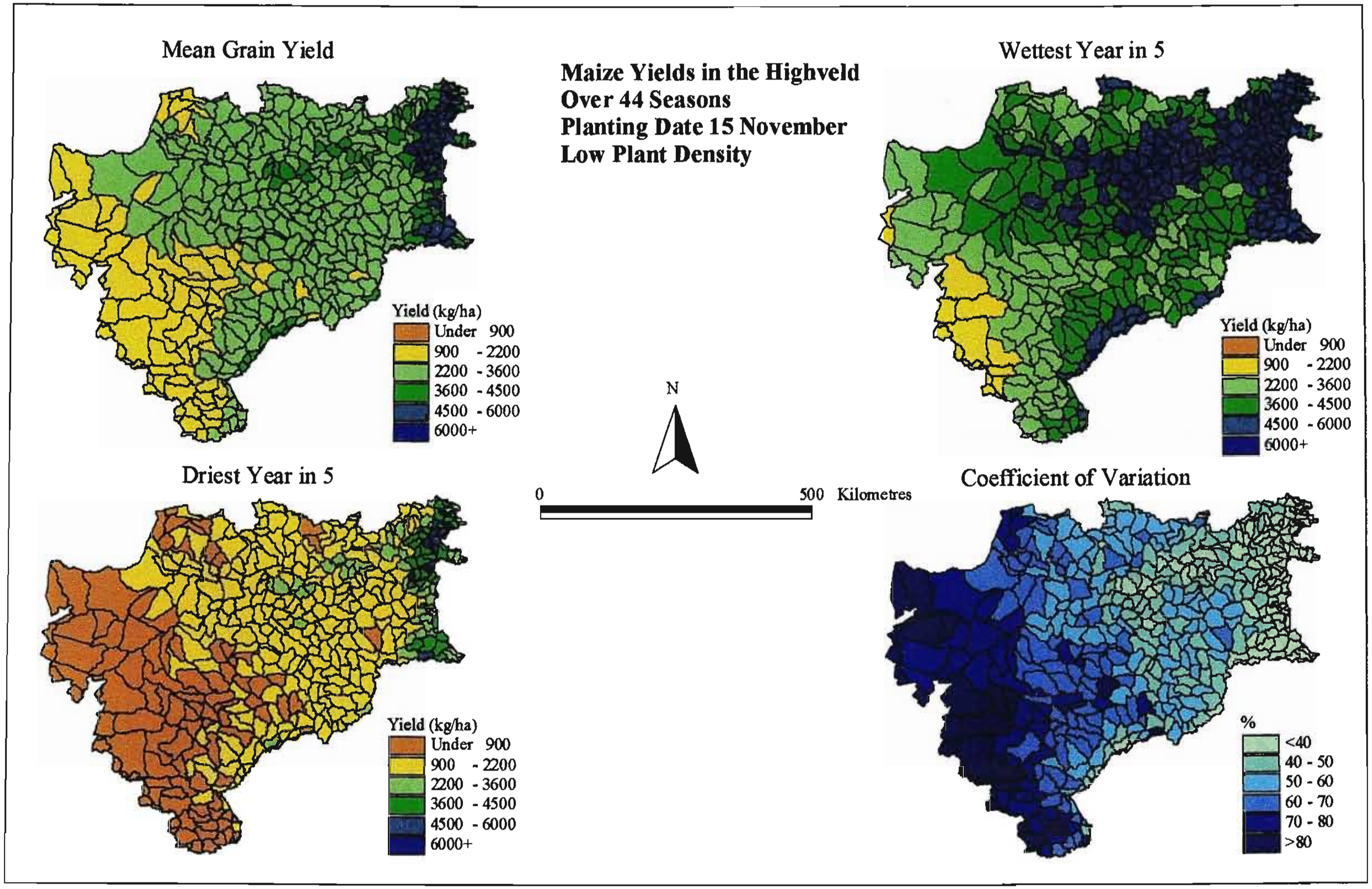


Figure 5.4.7 Simulated maize yields (mean, plus driest and wettest years in 5) and, inter-seasonal coefficient of variation of maize yields for a planting date of 15 November with low plant density

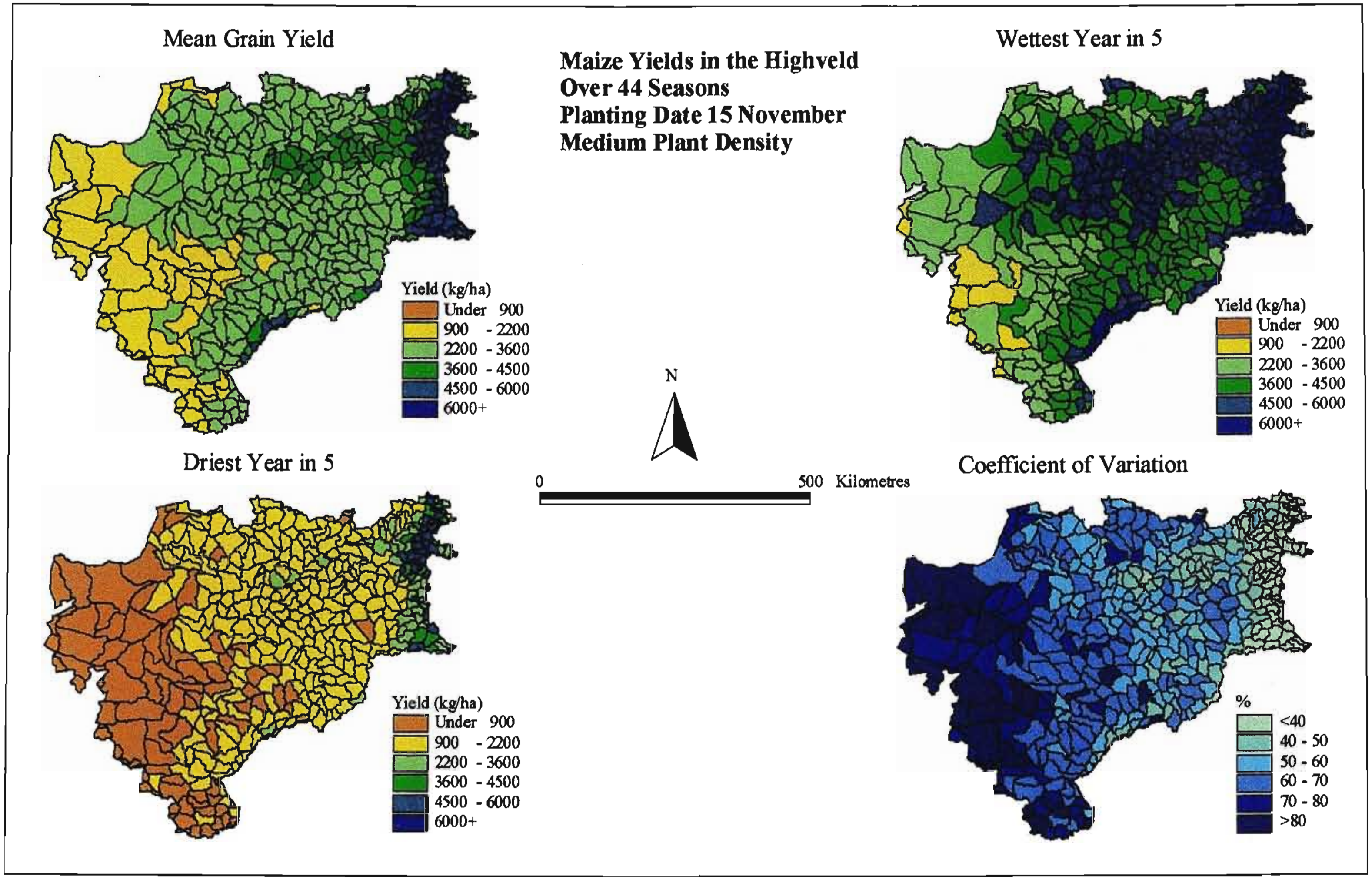


Figure 5.4.8 Simulated maize yields (mean, plus driest and wettest years in 5) and, inter-seasonal coefficient of variation of maize yields for a planting date of 15 November with medium plant density

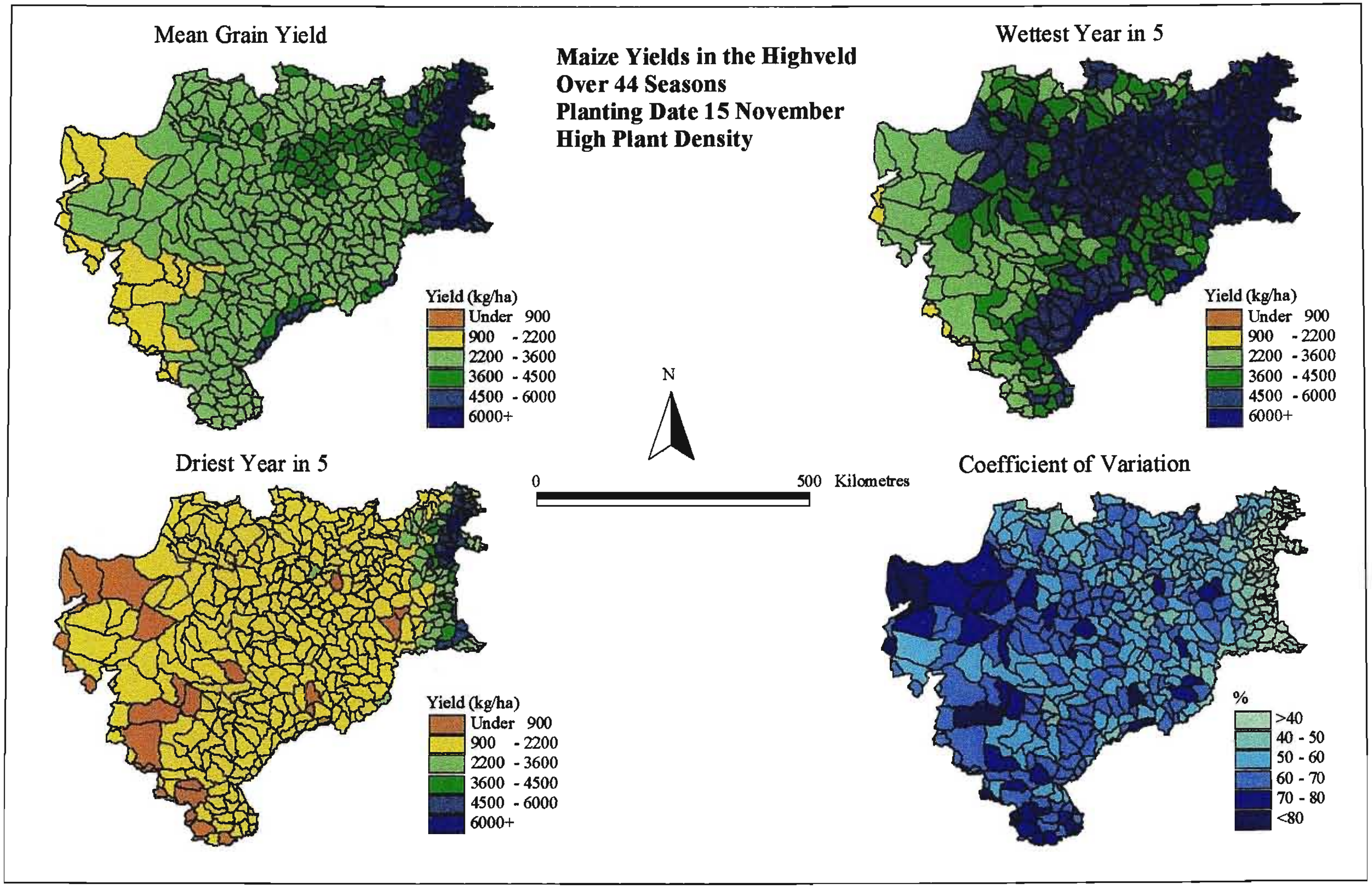


Figure 5.4.9 Simulated maize yields (mean, plus driest and wettest years in 5) and, inter-seasonal coefficient of variation of maize yields for a planting date of 15 November with high plant density

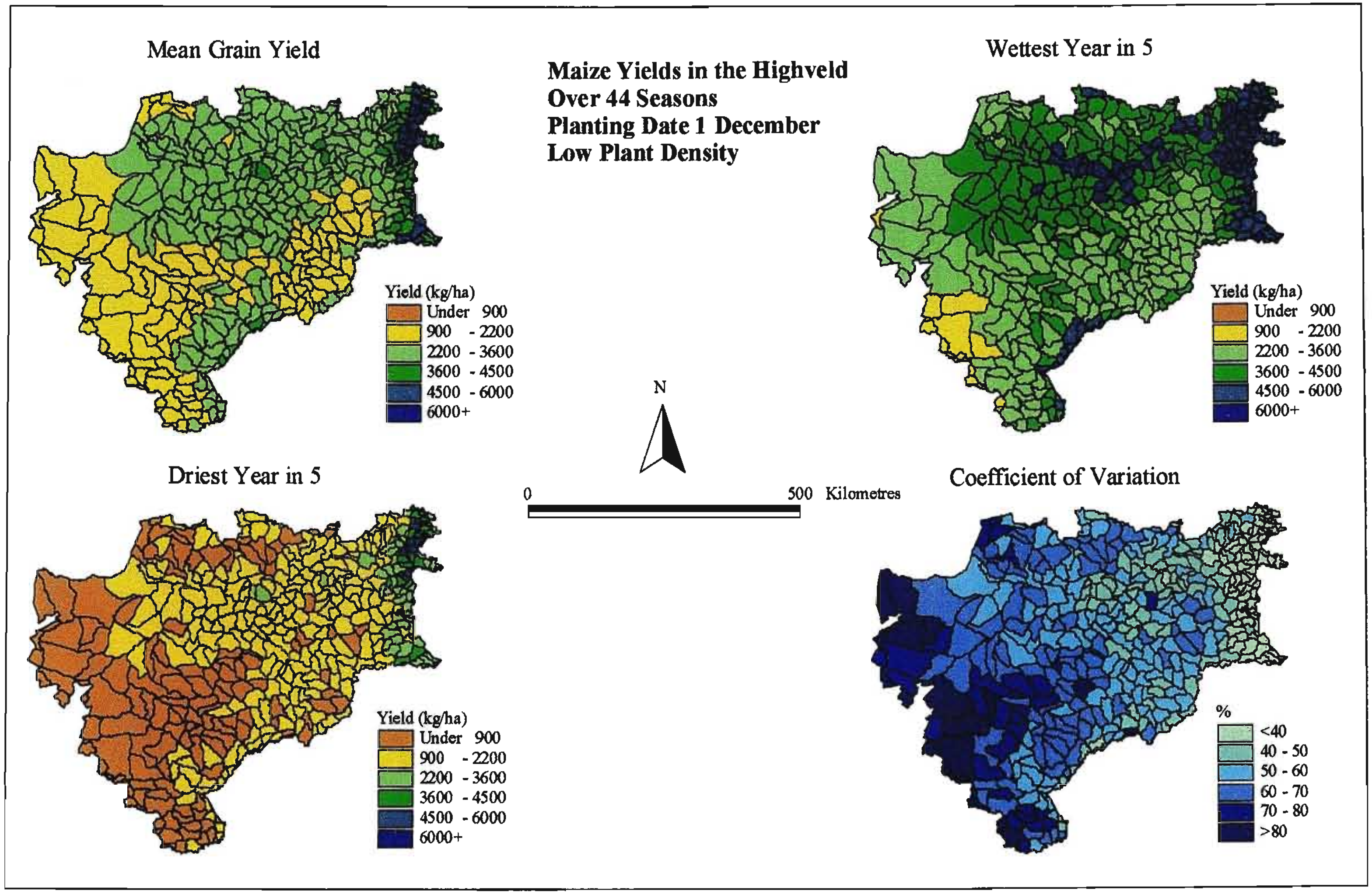


Figure 5.4.10 Simulated maize yields (mean, plus driest and wettest years in 5) and, inter-seasonal coefficient of variation of maize yields for a planting date of 1 December with low plant density

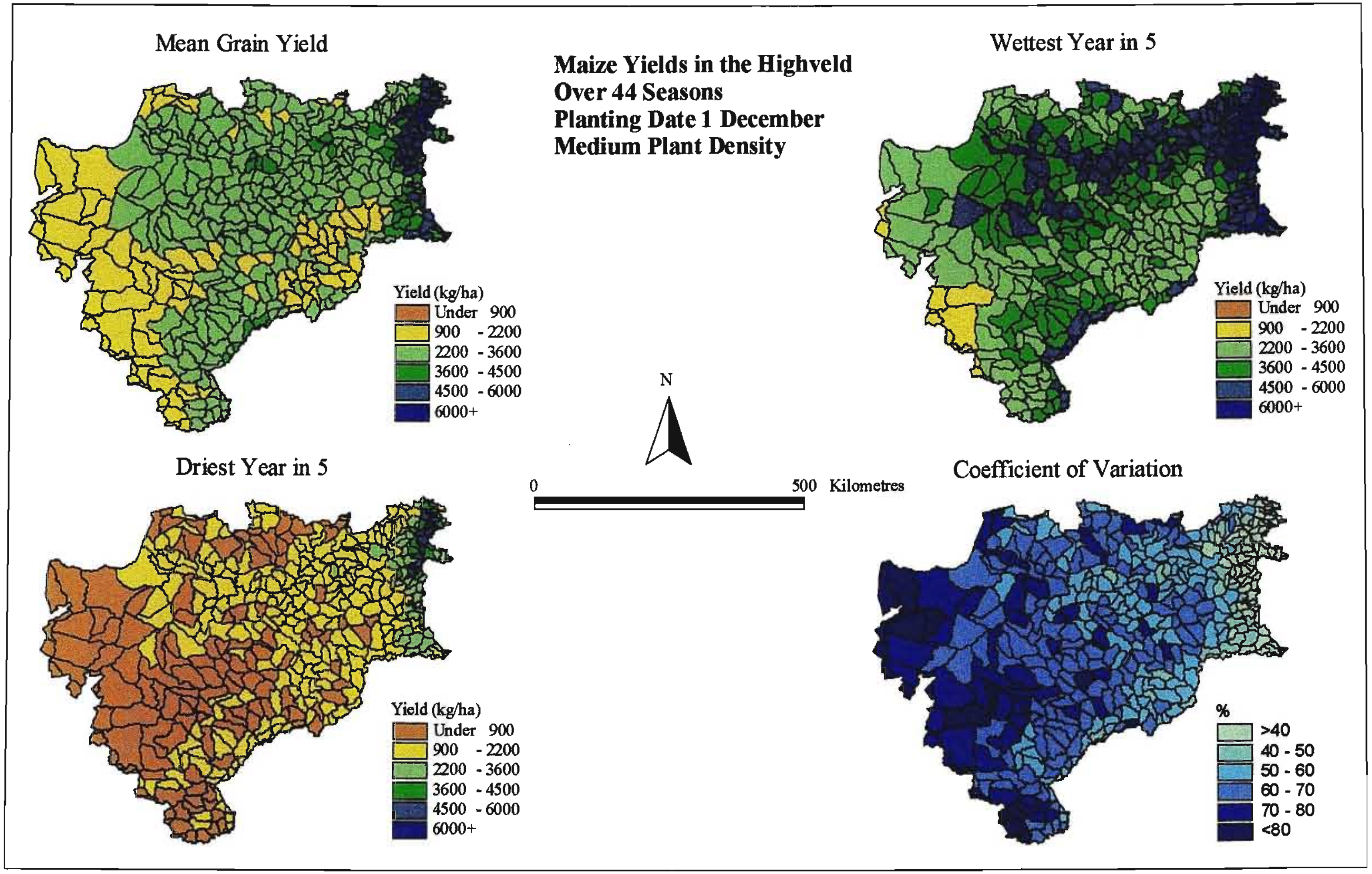


Figure 5.4.11 Simulated maize yields (mean, plus driest and wettest years in 5) and, inter-seasonal coefficient of variation of maize yields for a planting date of 1 December with medium plant density

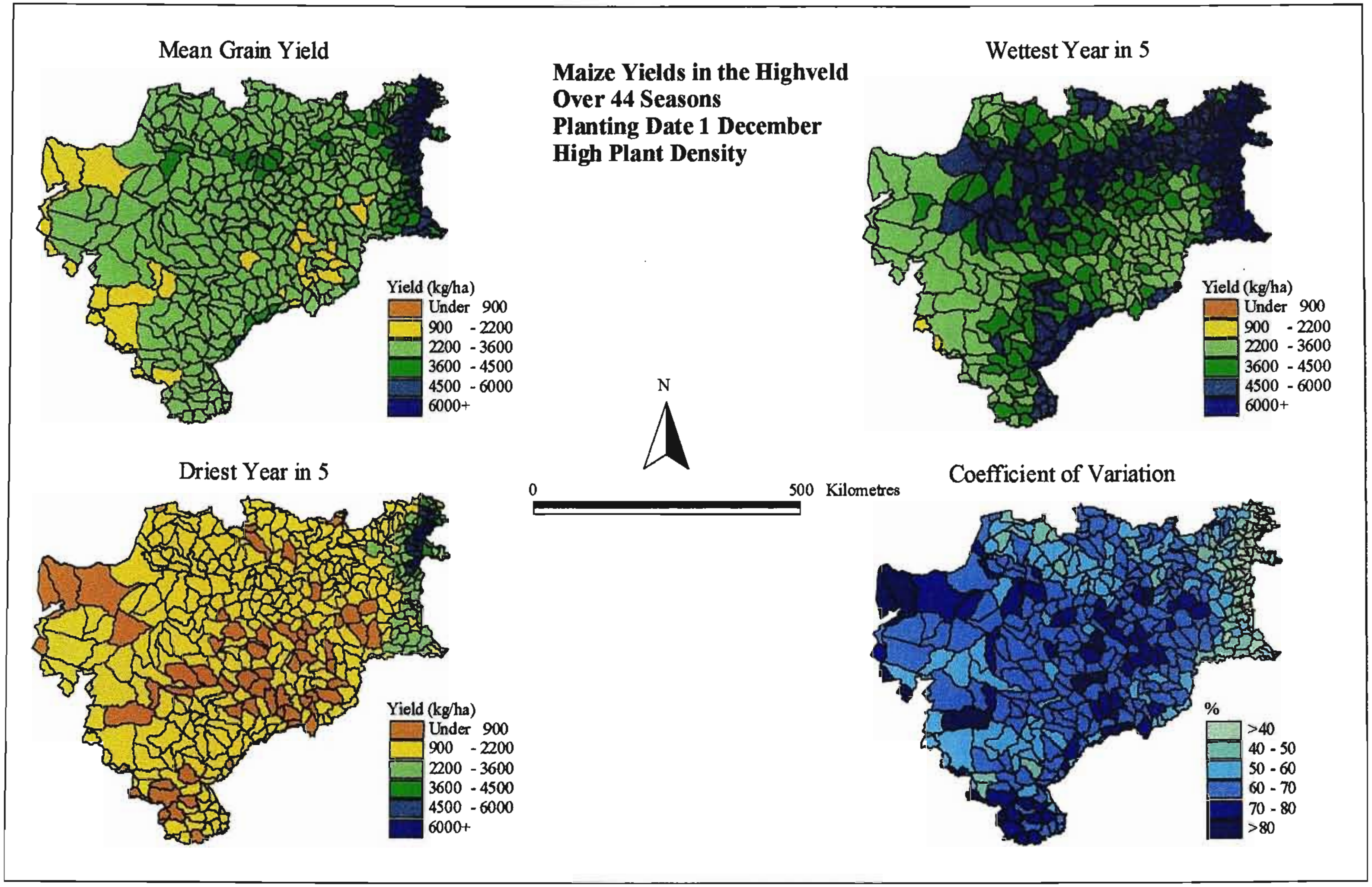


Figure 5.4.12 Simulated maize yields (mean, plus driest and wettest years in 5) and, inter-seasonal coefficient of variation of maize yields for a planting date of 1 December with high plant density

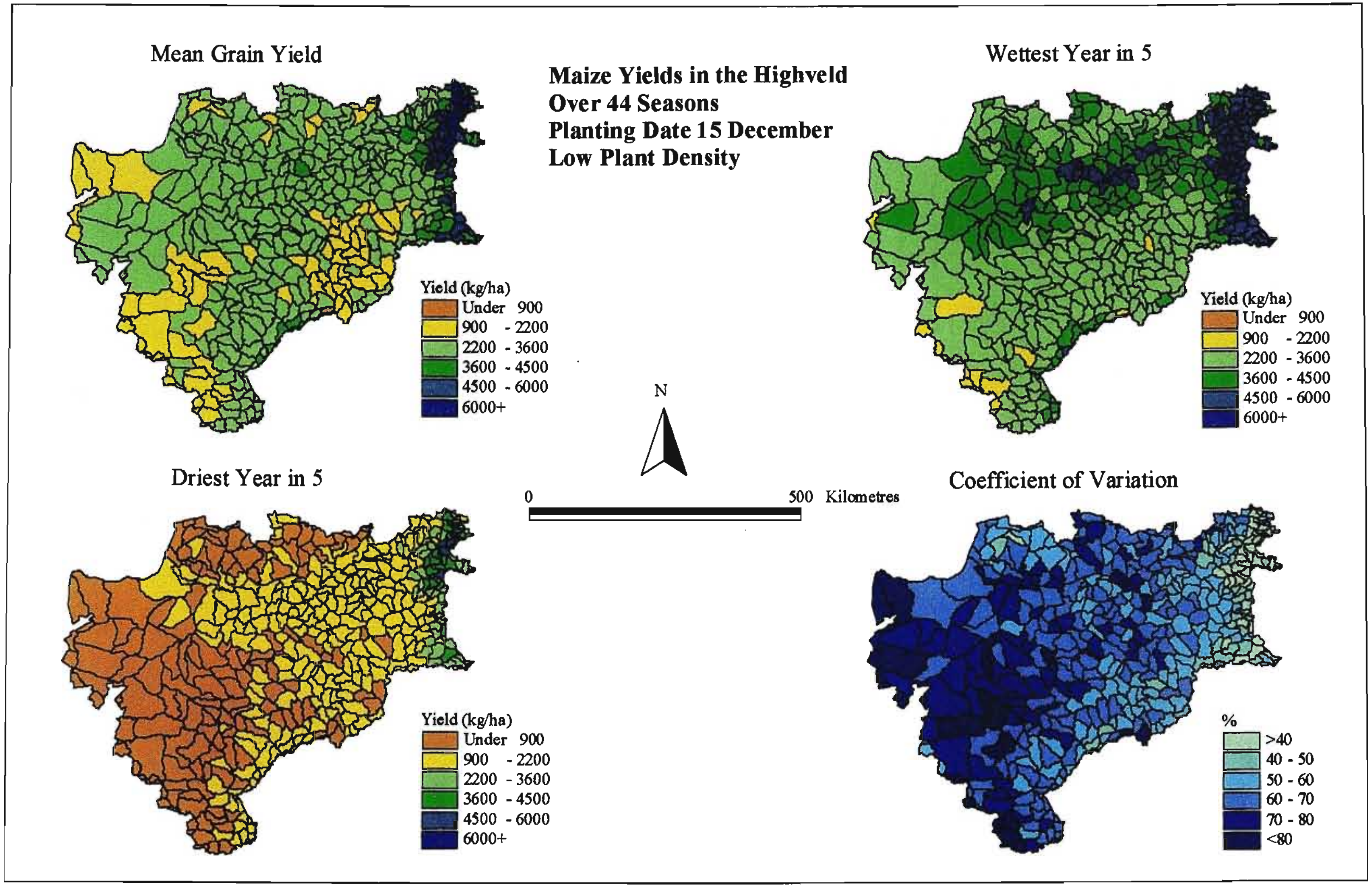


Figure 5.4.13 Simulated maize yields (mean, plus driest and wettest years in 5) and, inter-seasonal coefficient of variation of maize yields for a planting date of 15 December with low plant density

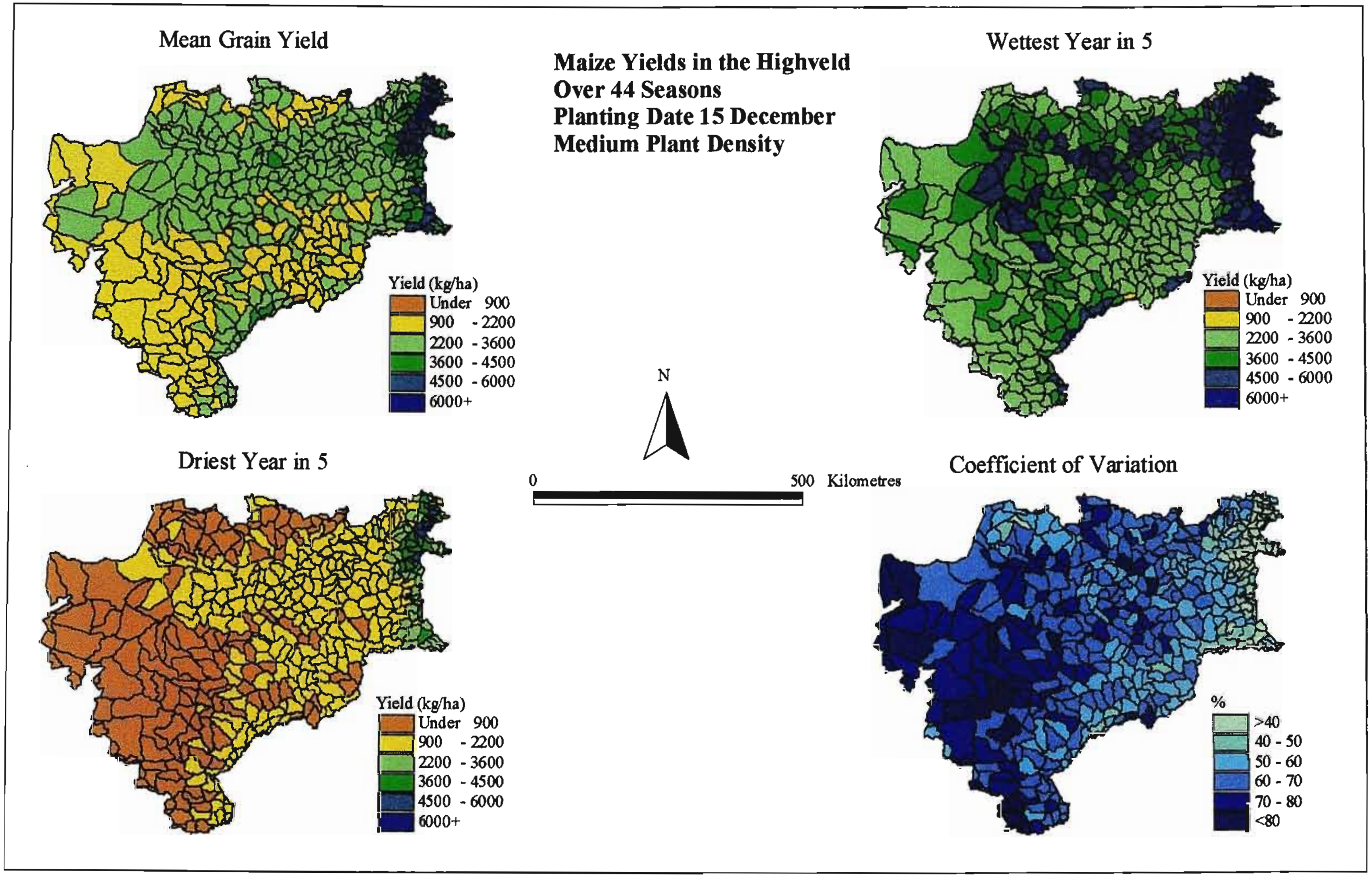


Figure 5.4.14 Simulated maize yields (mean, plus driest and wettest years in 5) and, inter-seasonal coefficient of variation of maize yields for a planting date of 15 December with medium plant density

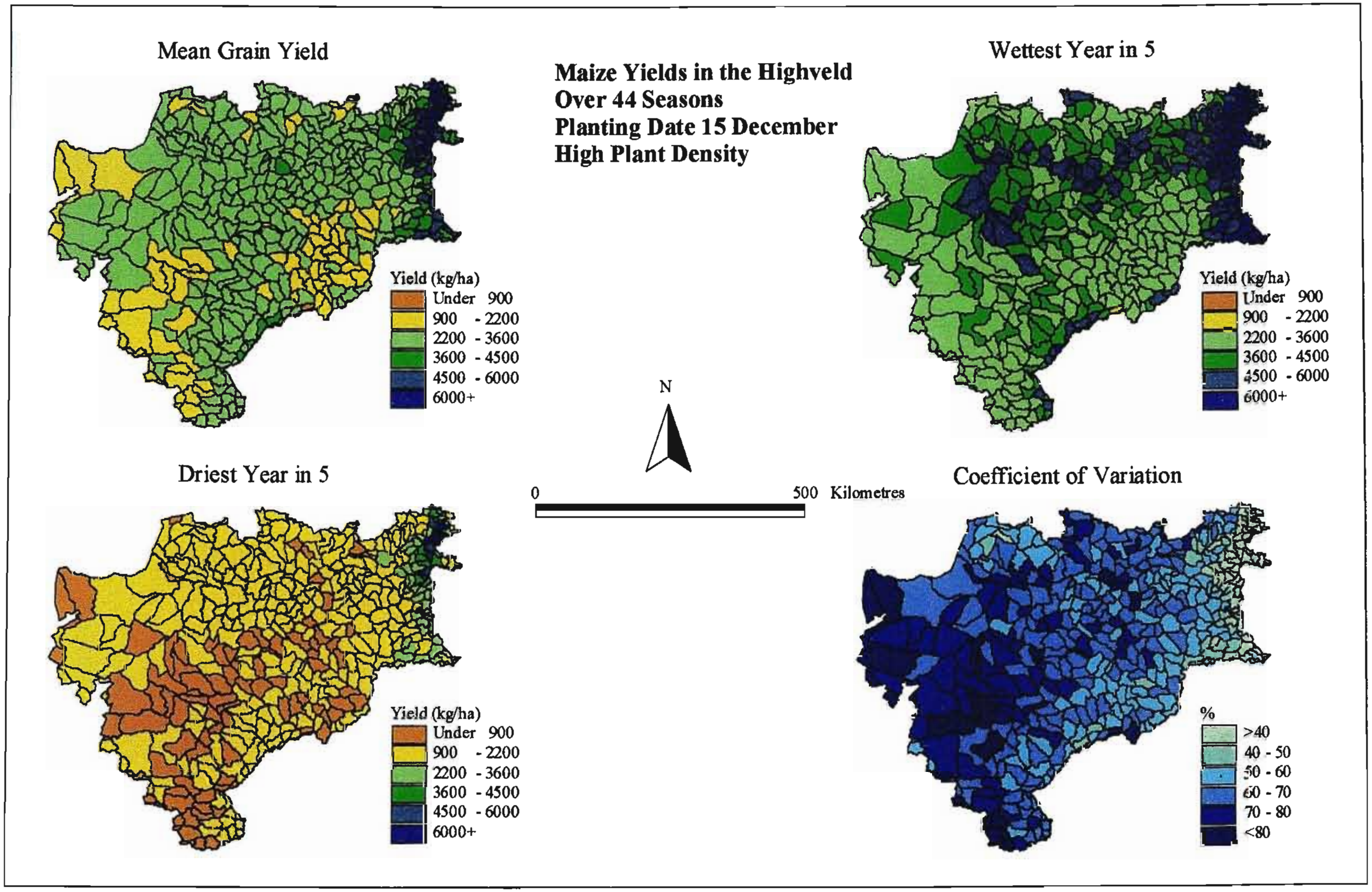


Figure 5.4.15 Simulated maize yields (mean, plus driest and wettest years in 5) and, inter-seasonal coefficient of variation of maize yields for a planting date of 15 December with high plant density

5.4.2 Future climate scenarios

The assessment of agro-ecosystem sustainability by definition requires an evaluation of the environmental, economic and social components and the inter-linkages between them. Yields and the variability of yields under present climatic conditions have been considered in the previous section. In a sensitivity analysis on future climates for the Highveld region the socio-economic impact of selected plausible climatic changes were considered. This has been determined by calculating possible effects on economic returns for different climate scenarios. A change in economic returns has consequences for the sustainability of agro-ecosystems of both the commercial and smallholder farmer in the Highveld.

The economic returns were calculated by using an average production cost per hectare for the entire Highveld region of R750 (~US$110) with a selling price of R1800 (~$265) per tonne of maize grain. These figures where taken from the study by du Toit *et al.* (1999), and although the figures are from several years ago, this author considers them a useful guide for purposes of illustration. Mean economic returns under present climatic conditions were calculated over 44 seasons and compared with mean economic returns from different climate change scenarios to establish the possible impacts climatic change could have on regional food security and sustainability.

With a planting date of 15 October an effective doubling of atmospheric CO_2 concentration by itself (Figure 5.4.16, top) is modelled to have a positive effect in regard to increasing economic returns throughout the region. Even in the western parts of the Highveld, where a later plating date is the preferred planting strategy, there is a significant increase in economic returns. An effective doubling of CO_2 coupled with a 10% reduction in rainfall (Figure 5.4.16, bottom) will see economic returns still increasing over most parts of the Highveld. Areas negatively affected are those on the western fringes of the Highveld, which have a low MAP and a later planting date. In those areas where 15 October is the optimum planting date, even a reduction in rainfall may increase economic returns. An increase in temperature of 2°C (Figure 5.4.17, top) will impact yields in the region considerably with a reduction in profit per hectare over most of the region. A temperature increase of 2°C in combination with an effective doubling of CO_2 (Figure 5.4.17, bottom) will increase returns. The negative impacts that a temperature increase causes are counteracted by the increase in plant growth and reduction in transpiration that is associated with a CO_2 increase.

An effective doubling of CO_2 by itself with a 15 November planting date (Figure 5.4.18, top) will have a positive effect on yields in the western areas compared to those in the eastern areas. There appear to be big increases in returns in the eastern Highveld, compared with reductions in the west. The increase is substantial in the east, considering that 15 November is not the normal planting date there (15 October is the optimum plant date). The economic returns in actual amounts are larger for a 15 October than a 15 November planting date. An effective doubling of CO_2 combined with a 10% rainfall reduction (Figure 5.4.18, bottom) reduces returns in those QCs that have a low MAP.

For a 15 November planting date an increase in temperature by 2°C (Figure 5.4.19, top) will impact the western Highveld substantially. This area is the drier zone with already generally higher temperatures in the growing season than the eastern part of the region. A CO_2 increase in combination with a temperature increase of 2°C (Figure 5.4.19, bottom) will reduce the negative effects of the higher temperature by themselves in many of the QCs in the western areas. However, in some QCs the benefits of an effective doubling of CO_2 on crop growth are nullified by the temperature increase.

Figure 5.4 .20 (top) shows the effect on returns for a 10% increase in rainfall by itself using a 15 October planting date. An increase in rainfall sees economic returns increase in all but 1 QC in the Highveld. In the eastern Highveld, where under present climate conditions 15 October is a planting date that is often used, some of the QCs see an increase in returns over 500 R/ha. With a reduction in rainfall by itself using a 15 October planting date and a high plant density sees a reduction in economic returns in every QC in the Highveld region (Figure 5.4.20, bottom). Changing the planting date to 15 November brings a similar response to that using a 15 October planting date, i.e. an increase in rainfall gives an increase in economic returns (Figure 5.4.21, top) and a reduction in rainfall causes a decrease in economic returns (Figure 5.4.21, bottom).

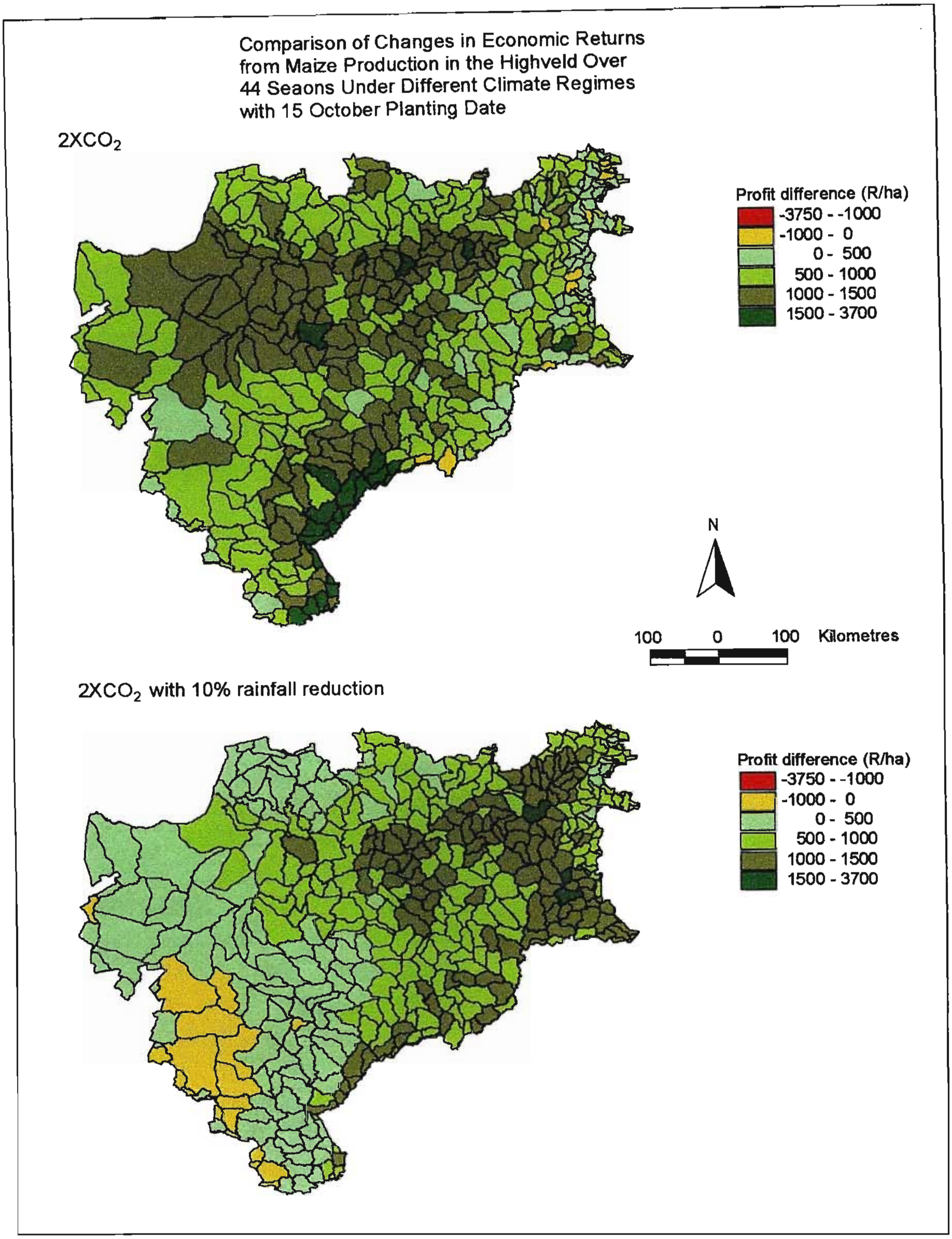


Figure 5.4.16 Comparison with present climate of changes in economic returns from simulated maize yields in the Highveld under different climate regimes ($2XCO_2$ and $2XCO_2$ with a 10% reduction in rainfall) with a 15 October planting date

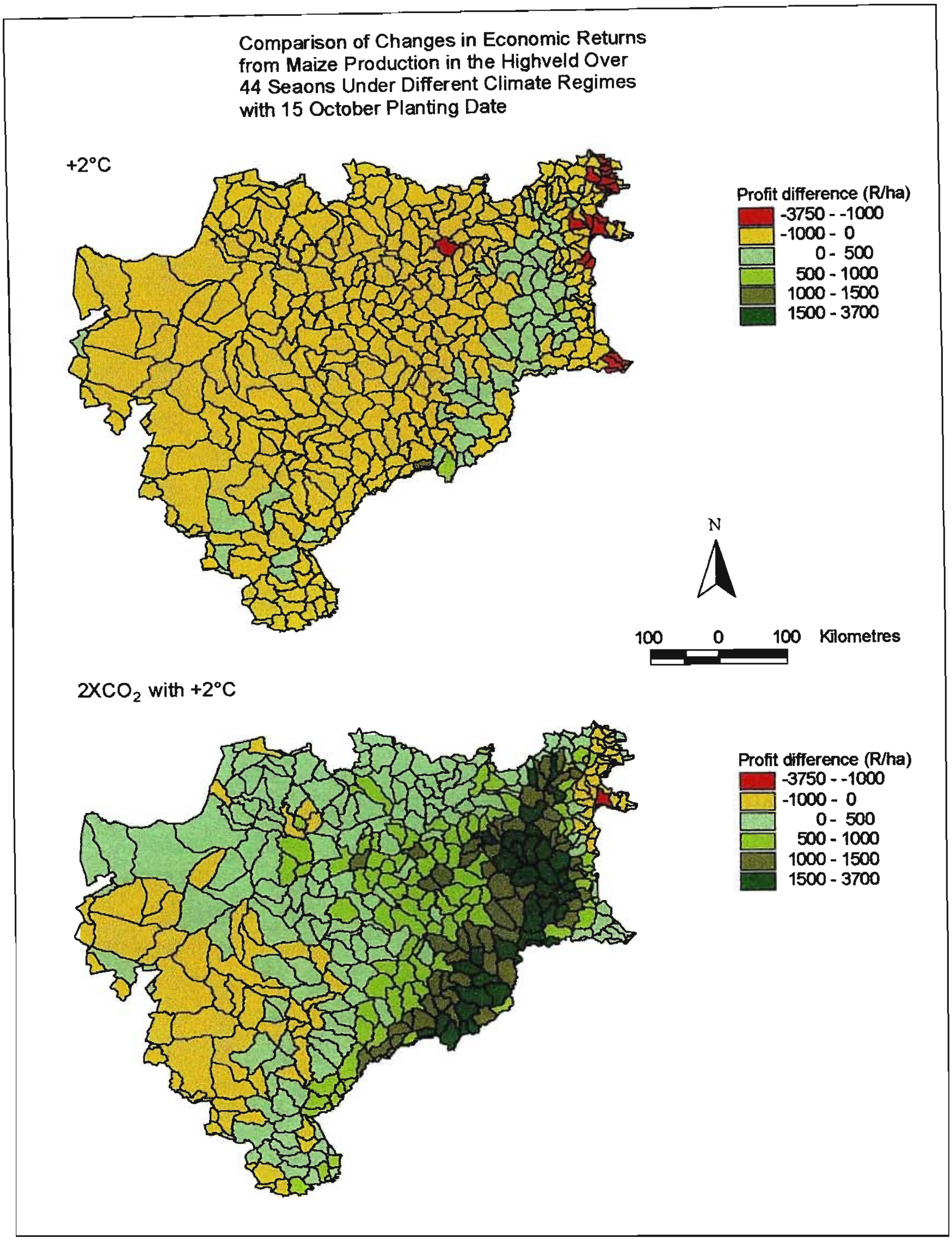


Figure 5.4.17 Comparison with present climate of changes in economic returns from simulated maize yields in the Highveld under different climate regimes (2°C temperature increase and 2XCO$_2$ with a 2°C temperature increase) with a 15 October planting date

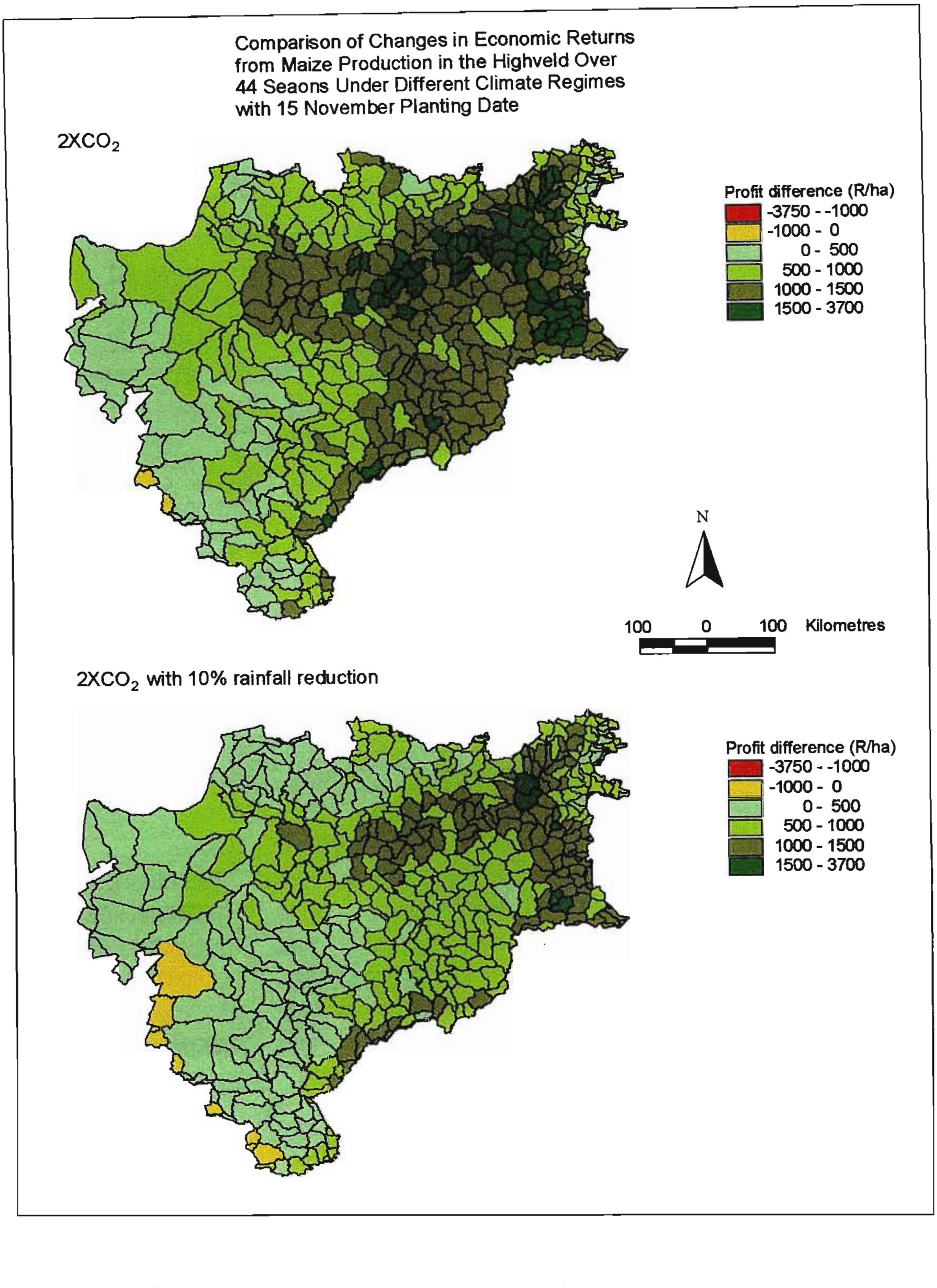


Figure 5.4.18 Comparison with present climate of changes in economic returns from simulated maize yields in the Highveld under different climate regimes ($2XCO_2$ and $2XCO_2$ with a 10% reduction in rainfall) with a 15 November planting date

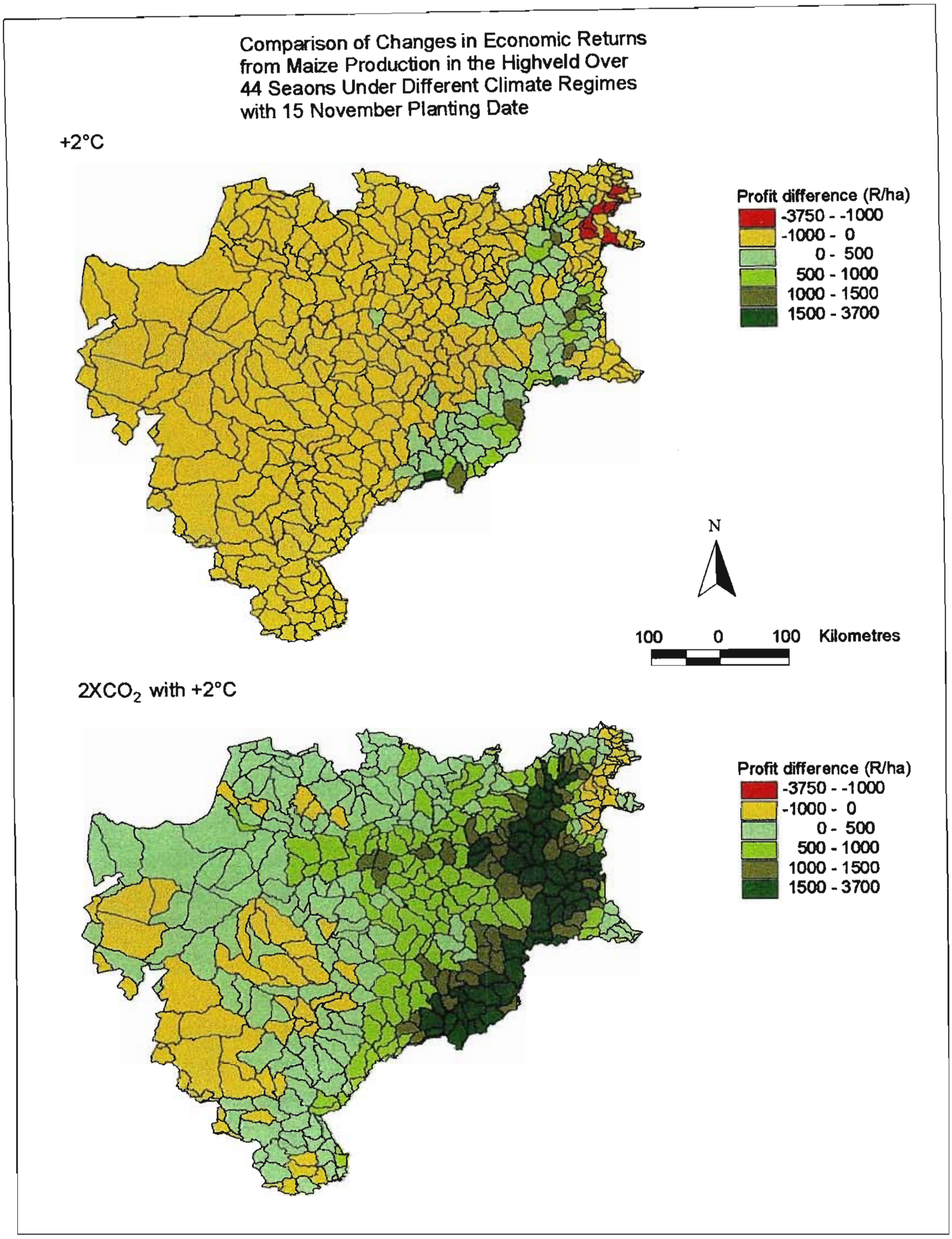


Figure 5.4.19 Comparison with present climate of changes in economic returns from simulated maize yields in the Highveld under different climate regimes (2°C temperature increase and $2XCO_2$ with a 2°C temperature increase) with a 15 November planting date

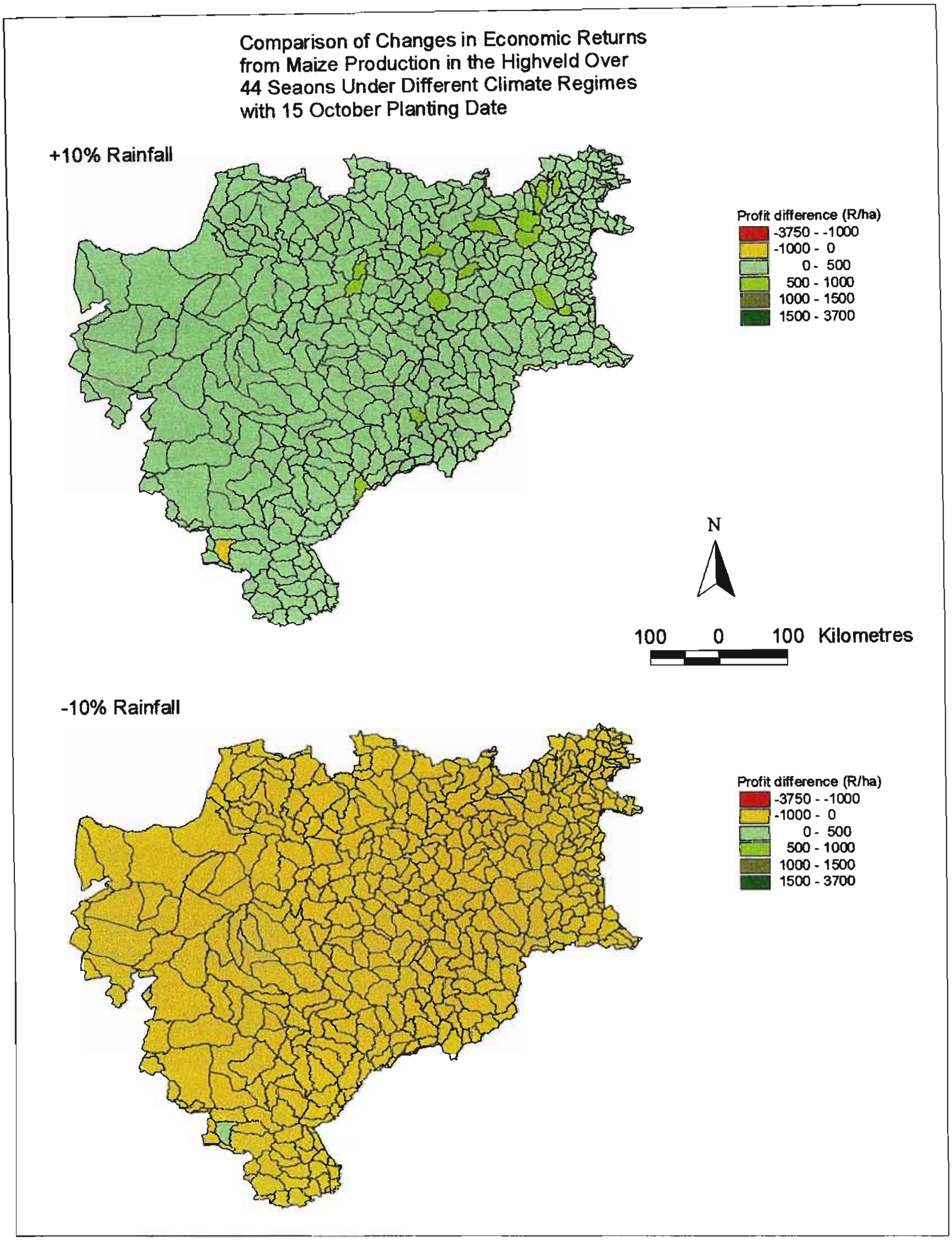


Figure 5.4.20 Comparison with present climate of changes in economic returns from simulated maize yields in the Highveld under different climate regimes (10 % increase in rainfall and a 10% reduction in rainfall) with a 15 October planting date

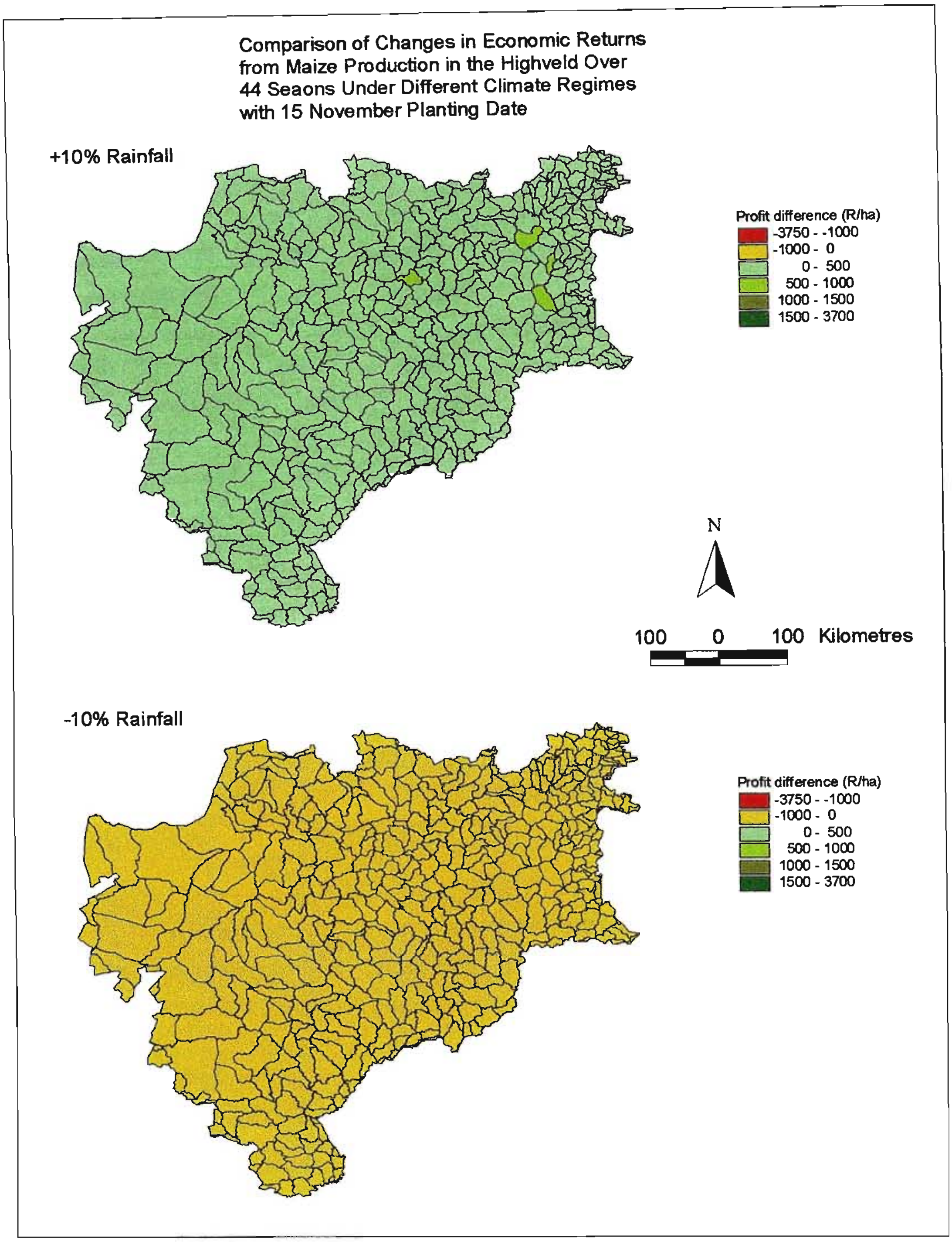


Figure 5.4.21 Comparison with present climate of changes in economic returns from simulated maize yields in the Highveld under different climate regimes (10% increase in rainfall and a 10% reduction in rainfall) with a 15 November planting date

5.5 Management Advice

The original goal of this assessment of sustainability at a regional scale, as set out at the beginning of this chapter, was as follows:

> *'The goal is for the agro-ecosystems in the Highveld region to continue in the long term, providing quality well-being for farmers and local communities and to maintain ecological integrity.'* (Section 5.2)

An important part of achieving this goal is applying management strategies that can reduce yield variability. For the optimum strategies to be established, maize production using five planting dates and three plant densities were simulated using CERES-Maize using current climatic conditions.

The optimum planting dates and plant densities for the Highveld Quaternary Catchments under current climatic conditions are shown in Figure 5.5.1. The final results were calculated using the index described in Chapter 4.4. This index ranked average maize yields and inter-seasonal CVs of yields for each Quaternary Catchment in the Highveld for the 15 scenarios simulated with CERES-Maize.

For the eastern Highveld 15 October is the planting date that generally produces the highest yields with least inter-annual variation in those yields. Surprisingly, the optimum plant density for most of the QCs in the eastern parts is a low or medium density. Although a high plant density will produce higher yields in above average rainfall years, it also produces high variability in yields. Optimum planting dates in the western Highveld are from 1 November through to 15 December. A higher plant density in the areas that have a later planting date generally reduces the variability in yields. Du Toit *et al.* (1999) state that generally in the western Highveld a medium plant density would be employed in practice, but simulated results show that a higher plant density would reduce variability in yields. Climatically optimum planting strategies are important when identifying pathways for agricultural sustainability.

In considering climate change, optimum planting dates and plant densities for present conditions were used. A decrease in rainfall by itself was found to reduce yields and economic returns with an increase in rainfall by resulting causing economic returns to increase. A 2xCO_2 climate scenario brought about an increase in economic returns in the vast majority of QCs with both planting dates used (15 October and 15 November). An increase in temperature by itself brought a reduction in most of the Highveld, except for those QCs in the eastern region that have high MAPs.

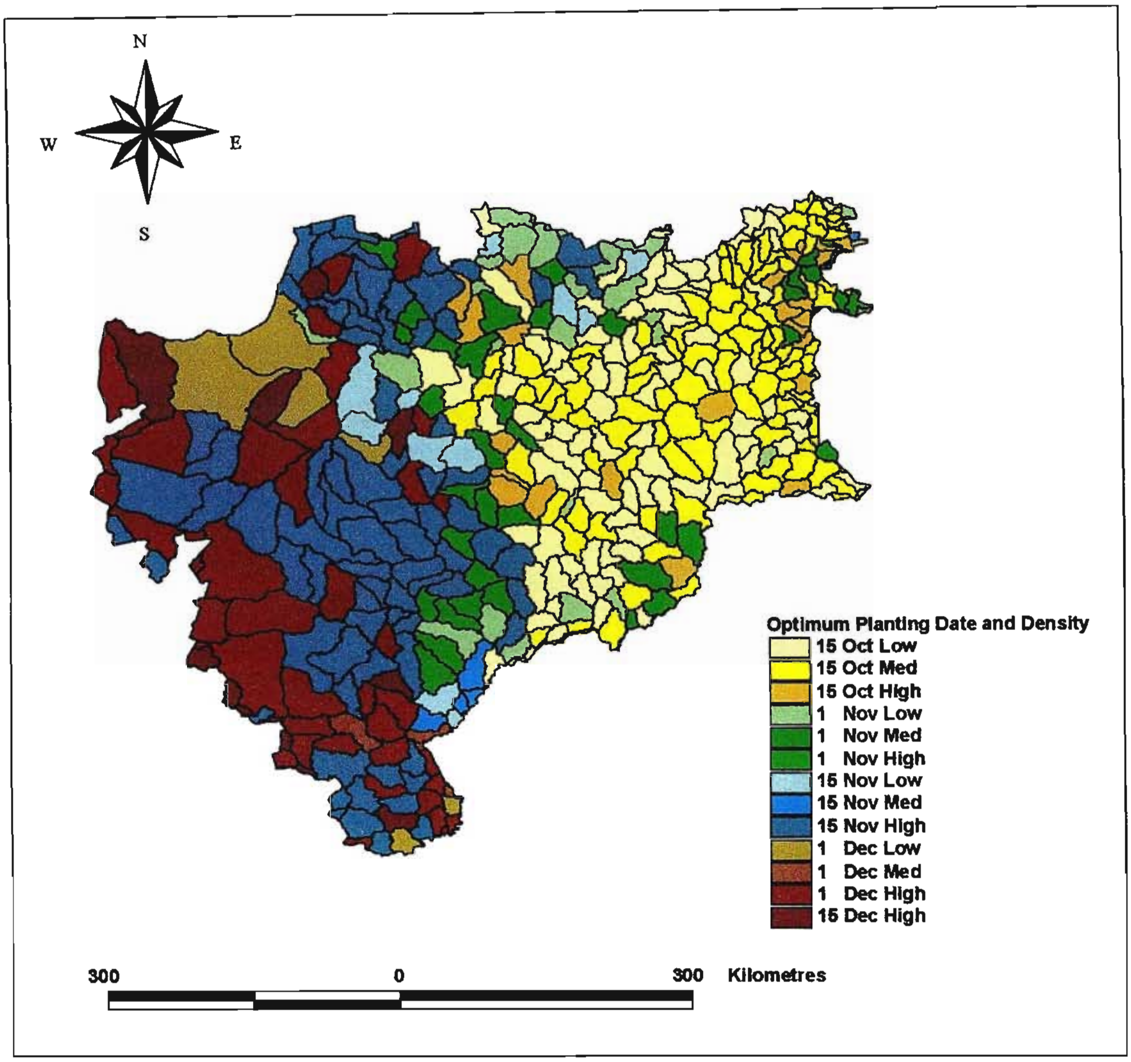


Figure 5.5.1 Optimum planting dates and plant densities for maize for the Highveld Quaternary Catchments under present climatic conditions, determined by considering simulated maize yields and the inter-seasonal coefficient of variation of yield

An increase in atmospheric CO_2 when in combination with an increase in temperature of 2°C was found to counteract the negative impacts of the temperature increase, except in the drier western fringe of the Highveld. An increase in atmospheric CO_2 was also found to counteract the negative effects of a reduction in rainfall in most QCs. It is recognised that future climatic changes could cause the optimum planting date for a particular Quaternary Catchment to alter. If the future climate is warmer, then the planting dates could shift to an earlier date compared with the present ones as soil would warm earlier. However, rainfall is the major driver of maize growth in the Highveld and the optimum planting sets are dependent on there being enough rainfall. There is as yet uncertainty as whether, and to what extent, seasonality of rainfall will change in the future.

The optimum climatic planting date for maize varies geographically as a function of rainfall distribution within the growing season rather than total seasonal rainfall amount (Schulze, 2003). Compared with other variables such as plant density and levels of fertilizer application, the "correct" planting date has a considerably greater effect on maize yields from commercial units than the other two (du Toit and Prinsloo, 2001). In deriving optimum planting dates for the different Quaternary Catchments in the Highveld, five planting dates were used in the modelling. These dates were chosen after consultation with previous work on optimum planting dates for maize in South Africa (du Toit et al., 1999; Schulze, 2003). The planting dates presented in Figure 5.5.1 are the climatically optimum ones for each Quaternary Catchment based on which date will result in the highest mean yield with the lowest inter-season variation. This is an optimum planting date as defined by the author, and it is recognised that it might not necessarily be the optimum date for the farmer or for other stakeholders who have other considerations and not just highest yield at the lowest risk, since no cognisance is taken for incidences of pests, diseases, and the occurrence of hail, or competition from other crops. Planting dates for rainfed agriculture are usually based on responses by the farmer to observed rainfall within a specified window for that geographical area rather than a fixed planting date. The fixed planting dates used in this chapter were based on previous research into climatically optimum planting dates for maize in the Highveld (du Toit *et al.*, 1999; Schulze, 2003). The optimum dates proposed are the best from the set of options modelled.

Identifying climatically optimum planting strategies for an important maize producing region such as the Highveld is vital in terms of a nation's food security. Chapter 6 explores sustainability at a Quaternary Catchment scale using an index based on a range of indicators from the CERES-Maize model.

6 AGRICULTURAL SUSTAINABILITY AT A QUATERNARY CATCHMENT SCALE: ASSESSMENT OF MAIZE PRODUCTION USING SUSTAINABILITY INDICATORS IN FIVE SELECTED QUATERNARY CATCHMENTS

The sustainability assessment in Chapter 5 focused on the Highveld region as a whole and investigated sustainable management strategies under various climate regimes. In this chapter, five Quaternary Catchments (QCs) have been selected that are considered representative of the wide range of MAP found in the Highveld. The sustainability modelling used concentrates not only on yield and the socio-economic impacts of yield, but also on agro-ecosystem responses such as soil organic matter levels. Management options explored in this chapter include planting dates, planting densities and application of both inorganic nitrogen fertiliser and manure.

For this study five Quaternary Catchments were selected with a range of mean annual precipitation (MAP) from 432 mm through to 903 mm. Details of the selected sites are shown in Table 6.1.1 and the location of the five QCs are shown in Figure 6.1.1.

Table 6.1.1 Details of Quaternary Catchments used in this study

	Christiana	Bothaville	Frankfort	Ermelo	Piet Retief
Description	Very Dry	Dry	Medium	Wet	Very Wet
Quaternary Catchment ID	C91B	C24J	C83M	C11F	W51C
MAP (mm)	432	552	639	704	903
Average Maize Yield (kg/ha)	2 169	3 178	3 801	3 792	6 299
Thickness A Horizon (m)	0.24	0.21	0.23	0.25	0.28
Thickness B Horizon (m)	0.33	0.30	0.31	0.42	0.50
Dominant Soil Texture Class	SaLm	SaClLm	Cl	SaClLm	SaClLm
Heat Units (°days) Oct-March	2078	2011	1713	1443	1872
Reference Potential Evaporation (mm), (A-pan equiv): Oct-March	1600	1493	1313	1124	1143

For this assessment a framework adapted from von Wiren-Lehr's (2001) goal orientated system, which was described in Chapter 4, was employed to gauge various sustainability pathways. This system has four stages, *viz.*

- Identifying the goal (Section 6.1)
- Sustainability modelling (Section 6.2)
- Evaluation (Section 6.3) and
- Management advice (Section 6.4).

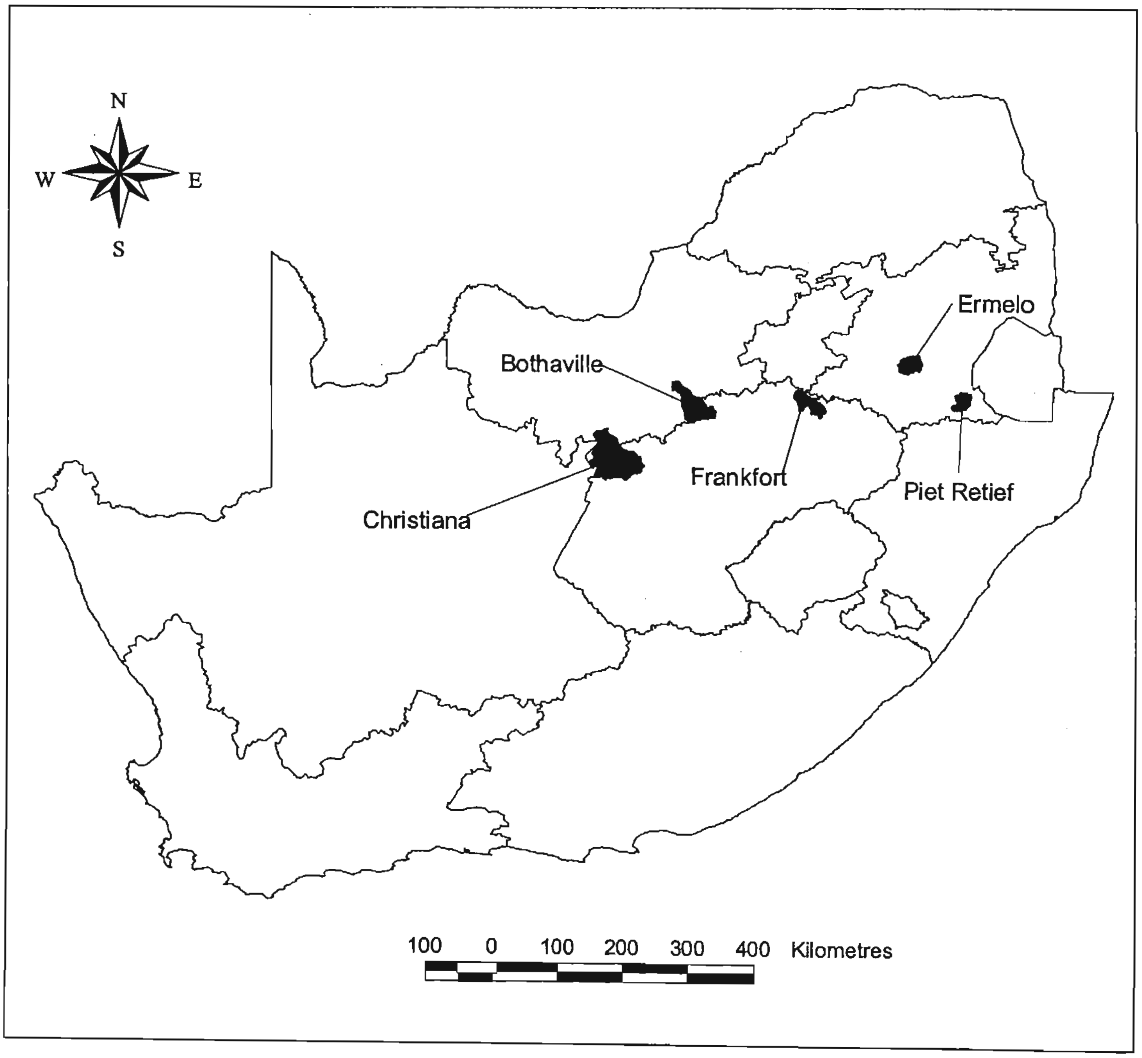


Figure 6.1.1 Location of five Quaternary Catchments selected for sustainability assessment

6.1 Goal Definition

Agriculture forms the economic base of the rural economy in South Africa. The importance of adequate food supply for human and animal consumption can not be overemphasised, as it influences farmer and community well-being and ecological integrity (Thornton *et al.,* 1997). The creation of employment opportunities both on and off the farm is important in preventing large scale migration to urban areas and in achieving sustainable agro-ecosystems. Vast areas in South Africa are planted under maize even though they could be classified as semi-arid (du Toit *et al*., 1999). Therefore, a sustainability framework is required (Section 4.2) so that different options can be explored and more informed decision making can take place.

The concept of agro-ecosystem integrity must recognise a human perspective such as the ability of an agro-ecosystem to continue to provide the goods and services that humans expect (De Leo and Levin, 1997). Examples of ecosystem services particularly important for agro-ecosystems are: continuation of the genetic diversity essential for successful crop breeding; recycling of nutrients; biological control of pests and diseases; erosion control and sediment retention; and regulation of local hydrological processes. The indicators used to assess sustainability are biophysical in nature and are based on the output from the CERES-Maize model (Section 6.2). There are no direct indicators for economic and social components of sustainability. However, inferences can be made regarding the socio-economic aspect of agro-ecosystems from the results of the biophysical indicators particular yield.

As was the case in Chapter 5, the goal, in this assessment, of the system in regard to sustainability is as follows:

> *'The goal is for the agro-ecosystems in the Highveld region to continue in the long term, providing quality well-being for farmers and local communities and to maintain ecological integrity.'* (Section 5.2)

Maize production in the five selected quaternary catchments will be assessed in relation to this goal.

6.2 Sustainability Modelling and Indicator Selection

The DSSAT suite of crop yield models can be used for long-term simulation of cropping sequences. A sequence refers to the growing of crops one season after the other for a stated duration (Thornton *et al.*, 1995). Using CERES-Maize in sequential mode, levels of variables such as soil water, soil organic carbon and nitrogen are passed on from the end of one season to the beginning of the next. Therefore, the appeal of sequential modelling is that trends in the end-of-season output such as yield, nitrogen uptake, or soil organic carbon level can be determined. The propensity of the output variables to change with time in a consistent direction will define the trend. Any trend can then be used to estimate the potential of biophysical sustainability for a given cropping sequence and management strategies (Bowen *et al.*, 1998).

The simulation of a cropping sequence entails the setting of initial conditions for the start of the run. The model then simulates crop growth and yields for a number of successive growing seasons with fallow periods when there is no planned crop cover (Thornton *et al.*, 1995).

The utilisation of indicators is useful in assessing the suitability of different management options in terms of sustainability and can also highlight the effects on an agro-ecosystem of climate variability.

Bio-physical indicators (described in Section 4.2.1) from output of CERES-Maize simulations that can be employed are:

- Grain yield
- Grain nitrogen content
- Soil organic nitrogen
- Soil organic carbon
- Extractable soil water
- Cumulative runoff
- Cumulative drainage and
- Nitrogen recovery (N used by crop/N applied *100).

A variety of scenarios can be modelled using the sequential approach. Various sustainability pathways were assessed by investigating the effect of different management practices on selected sustainability indicators. The results of these were used to create a sustainability index (Section 6.3). A DSSAT input file was created which included 54 treatments. These were run sequentially for 44 year with daily rainfall, daily temperatures and soils information from the School of BEEH Quaternary Catchments Database.

The 54 treatments consisted of three planting dates, three plant densities for each planting date, with six fertiliser/manure regimes for each plant density, and are summarised in the first five columns of Tables 6.3.1-6.3.3. The planting date, plant densities, and fertiliser/manure levels were:

- Planting dates: 15 October, 15 November, and 15 December
- Plant densities: plant population 1.5/m^2 with row space 1.5 m, plant population 2.0/m^2 with row space 1.2 m, plant population 3.0/m^2 with row space 0.90 m
- Fertiliser regimes: 80 kg N/ha, 120 kg N/ha, 160 kg N/ha
- Manure regimes: 22.6 kg N/ha, 45.2 kg N/ha, 67.8 kg N/ha (Lumsden and Schulze, 2004).

The use of crop rotations was not considered, as access to locally derived genetic coefficients of soya for use in the DSSAT models was limited. Also the SOYGRO model has not undergone the same extensive regional calibration in South Africa as CERES-Maize. Fallow periods could be beneficial particularly in terms of retaining soil organic matter and for the maintenance of ecological integrity. This is practised in the Highveld, but for analysis at the Quaternary Catchment scale this author decided that effects of sustained maize production alone should be assessed.

For the commercial farmer it becomes economically viable to produce maize when its production exceeds 2 200 kg/ha in western Highveld and exceeds 3 600 kg/ha in the eastern Highveld (Durand and du Toit, 1999). The yield levels were calculated assuming the maize price to be $95 per 1 000 kg and total production costs to be $200 per hectare.

In the modelling performed, a maize crop was assumed to be planted each year with no fallow seasons. The planting date and densities were the same that were used in Chapter 5, while manure levels were identical to those used by Lumsden and Schulze (2004) in a study of management strategies for small-scale farmers producing maize under conditions of climate variability.

6.3 Evaluation Strategy Using a Sustainability Index

A sustainability index was employed to assess the sustainability of maize production at the five selected QCs. This was the same index discussed in Chapter 4 with averages calculated for each indicator from values over 44 seasons of maize production. The average figure was compared against a critical limit, or threshold value, and was then scored accordingly. The scores for each agro-ecosystem function were summed for the treatment. The result of the above analysis gave a likelihood of sustainability for the agro-ecosystem under a particular management regime or climate regime. Four options are given for likelihood of sustainability: minimal, low, medium and high. The likelihood of sustainability for each of the 54 treatments at the five selected QCs is shown in Table 6.3.1, Table 6.3.2 and Table 6.3.3.

In the Christiana catchment (very dry, QC C91B) all management options with a planting date of 15 October return a minimal chance of sustainability (Table 6.3.1). This is due to the planting date being too early and the soil still being too parched from the dry winter months for development of the crop.

Treatments in the Christiana catchment that have a low chance of sustainability are 31-33 (Table 6.3.2), 44, 45 and 49 (Table 6.3.3). These are all treatments with organic nitrogen inputs. Although the treatments with manure inputs have a high nitrogen recovery, the yields are low. The break-even figure used is one for commercial farmers, so in reality maize could still be produced by the emerging farmers who currently do not have the same capital input costs. The low yields might be acceptable if the maize production forms part of a broader sustainable livelihoods strategy, i.e. if the farmer or members of the farmer's family have off-farm employment. At Christiana (QC C91B) Treatments 50 and 51 (Table 6.3.3) receive a high rating for sustainability. This is due in part to Treatment 50 being used to calculate baseline values for the water related thresholds. However, it is the optimum management strategy according to the seasonal modelling performed in Chapter 5.

Table 6.3.1 Likelihood of sustainability for five selected Quaternary Catchments, Treatments 1-18

Treatment Number	Planting Date	Plant Density (plants/m^2)	Nitrogen Application Type	Nitrogen Applied (kg/ha)	Christiana QC C91B (Very Dry)	Bothaville QC C24J (Dry)	Frankfort QC C83M (Medium)	Ermelo QC C11F (Wet)	Piet Retief QC W51C (Very Wet)
1	15 Oct	1.5	Inorganic	80.0	Minimal	Low	Medium	Low	Medium
2	15 Oct	1.5	Inorganic	120.0	Minimal	Low	Medium	Low	Medium
3	15 Oct	1.5	Inorganic	160.0	Minimal	Minimal	Medium	Low	Medium
4	15 Oct	1.5	Manure	22.6	Minimal	Minimal	Minimal	Minimal	Low
5	15 Oct	1.5	Manure	45.2	Minimal	Minimal	Minimal	Minimal	Low
6	15 Oct	1.5	Manure	67.8	Minimal	Minimal	Minimal	Minimal	Minimal
7	15 Oct	2.0	Inorganic	80.0	Minimal	Medium	Medium	High	Medium
8	15 Oct	2.0	Inorganic	120.0	Minimal	Medium	Medium	High	Medium
9	15 Oct	2.0	Inorganic	160.0	Minimal	Low	Medium	High	Medium
10	15 Oct	2.0	Manure	22.6	Minimal	Minimal	Minimal	Low	Minimal
11	15 Oct	2.0	Manure	45.2	Minimal	Minimal	Minimal	Low	Minimal
12	15 Oct	2.0	Manure	67.8	Minimal	Minimal	Minimal	Minimal	Minimal
13	15 Oct	3.0	Inorganic	80.0	Minimal	Medium	High	High	Medium
14	15 Oct	3.0	Inorganic	120.0	Minimal	Medium	High	High	Medium
15	15 Oct	3.0	Inorganic	160.0	Minimal	Medium	High	Medium	Medium
16	15 Oct	3.0	Manure	22.6	Minimal	Minimal	Low	Low	Low
17	15 Oct	3.0	Manure	45.2	Minimal	Low	Low	Low	Low
18	15 Oct	3.0	Manure	67.8	Minimal	Minimal	Minimal	Minimal	Minimal

Table 6.3.2 Likelihood of sustainability for five selected Quaternary Catchments, Treatments 19-36

Treatment Number	**Planting Date**	**Plant Density (plants/m^2)**	**Nitrogen Application Type**	**Nitrogen Applied (kg/ha)**	**Christiana QC C91B (Very Dry)**	**Bothaville QC C24J (Dry)**	**Frankfort QC C83M (Medium)**	**Ermelo QC C11F (Wet)**	**Piet Retief QC W51C (Very Wet)**
19	15 Nov	1.5	Inorganic	80.0	Minimal	Medium	Medium	Minimal	Medium
20	15 Nov	1.5	Inorganic	120.0	Minimal	Medium	Medium	Minimal	Medium
21	15 Nov	1.5	Inorganic	160.0	Minimal	Medium	Low	Minimal	Medium
22	15 Nov	1.5	Manure	22.6	Minimal	Minimal	Minimal	Minimal	Minimal
23	15 Nov	1.5	Manure	45.2	Minimal	Minimal	Minimal	Minimal	Minimal
24	15 Nov	1.5	Manure	67.8	Minimal	Minimal	Minimal	Minimal	Minimal
25	15 Nov	2.0	Inorganic	80.0	Minimal	Medium	Medium	Low	Medium
26	15 Nov	2.0	Inorganic	120.0	Minimal	Medium	Medium	Low	Medium
27	15 Nov	2.0	Inorganic	160.0	Minimal	Medium	Medium	Minimal	Medium
28	15 Nov	2.0	Manure	22.6	Minimal	Minimal	Minimal	Minimal	Minimal
29	15 Nov	2.0	Manure	45.2	Minimal	Minimal	Minimal	Minimal	Minimal
30	15 Nov	2.0	Manure	67.8	Minimal	Minimal	Minimal	Minimal	Minimal
31	15 Nov	3.0	Inorganic	80.0	Low	Medium	Medium	Low	Medium
32	15 Nov	3.0	Inorganic	120.0	Low	High	Medium	Low	Medium
33	15 Nov	3.0	Inorganic	160.0	Low	Medium	Medium	Low	Medium
34	15 Nov	3.0	Manure	22.6	Minimal	Low	Minimal	Minimal	Minimal
35	15 Nov	3.0	Manure	45.2	Minimal	Low	Minimal	Minimal	Minimal
36	15 Nov	3.0	Manure	67.8	Minimal	Minimal	Minimal	Minimal	Minimal

Table 6.3.3 Likelihood of sustainability for 5 selected Quaternary Catchments, Treatments 37-54

Treatment Number	**Planting Date**	**Plant Density (plants/m^2)**	**Nitrogen Application Type**	**Nitrogen Applied (Kg/ha)**	**Christiana QC C91B (Very Dry)**	**Bothaville QC C24J (Dry)**	**Frankfort QC C83M (Medium)**	**Ermelo QC C11F (Wet)**	**Piet Retief QC W51C (Very Wet)**
37	15 Dec	1.5	Inorganic	80.0	Minimal	Medium	Minimal	Minimal	Low
38	15 Dec	1.5	Inorganic	120.0	Minimal	Low	Minimal	Minimal	Low
39	15 Dec	1.5	Inorganic	160.0	Minimal	Low	Minimal	Minimal	Low
40	15 Dec	1.5	Manure	22.6	Minimal	Minimal	Minimal	Minimal	Minimal
41	15 Dec	1.5	Manure	45.2	Minimal	Minimal	Minimal	Minimal	Minimal
42	15 Dec	1.5	Manure	67.8	Minimal	Minimal	Minimal	Minimal	Minimal
43	15 Dec	2.0	Inorganic	80.0	Minimal	Medium	Minimal	Minimal	Low
44	15 Dec	2.0	Inorganic	120.0	Low	Medium	Minimal	Minimal	Low
45	15 Dec	2.0	Inorganic	160.0	Low	Low	Minimal	Minimal	Low
46	15 Dec	2.0	Manure	22.6	Minimal	Minimal	Minimal	Minimal	Minimal
47	15 Dec	2.0	Manure	45.2	Minimal	Minimal	Minimal	Minimal	Minimal
48	15 Dec	2.0	Manure	67.8	Minimal	Minimal	Minimal	Minimal	Minimal
49	15 Dec	3.0	Inorganic	80.0	Low	Medium	Low	Minimal	Low
50	15 Dec	3.0	Inorganic	120.0	High	Medium	Minimal	Minimal	Low
51	15 Dec	3.0	Inorganic	160.0	High	Medium	Minimal	Minimal	Low
52	15 Dec	3.0	Manure	22.6	Minimal	Minimal	Minimal	Minimal	Minimal
53	15 Dec	3.0	Manure	45.2	Minimal	Minimal	Minimal	Minimal	Minimal
54	15 Dec	3.0	Manure	67.8	Minimal	Minimal	Minimal	Minimal	Minimal

At Bothaville (dry, QC C24J) treatments using manure that achieve higher than minimal rating are numbers 17, 34 and 35. The result of Treatment 17 (Table 6.3.1) is surprising, as the planting date of 15 October is very early for this area, but the output from the runoff and drainage variables fall within the threshold values, there is high nitrogen recovery and adequate nitrogen in the grain for protein formation. Treatment 32 (Table 6.3.2) has a high sustainability rating and it is the optimum planting strategy for QC C24J. Treatments 31 and 33 achieve good yields along with higher than 60% nitrogen recovery.

The optimum planting date for Frankfort (medium rainfall, QC C83M) is 15 October, and by using this planting date the highest sustainability ratings are achieved in this QC. When using manure the best results are for Treatments 16 and 17 (Table 6.3.1). These treatments have a high plant density and their likelihood of sustainability is low when using commercial break-even figures.

At Ermelo (wet, QC C11F) the high sustainability ratings are achieved for Treatments 7-9, 13 and 14 (Table 6.3.1). These treatments have a planting date of 15 October, a high plant density and either 80 or 120 kg/ha of inorganic nitrogen applied. Planting later in the season will result in reduced yields and higher yield variability, and as a consequence, a lower sustainability likelihood rating. Management strategies with manure applications at Ermelo require a planting date of 15 October and either a plant density of low or high and a manure nitrogen input of either 22.6 or 44.2 kg/ha.

All treatments with inorganic nitrogen inputs used in the Piet Retief QC (very wet, QC W51C) achieve a least a medium sustainability rating. The optimum management strategy would be a 15 October planting date with a high plant density and either 80 or 120 kg/ha application of inorganic nitrogen fertiliser. The favourable sustainability ratings in this QC are due mainly to the high rainfall. The high MAP also appears to be the reason for the high organic matter loss, which is the highest for any of the five QCs investigated. The highest scores on the sustainability index for treatments with manure as inputs into the system are for numbers 4, 5, 15 and 16 (Table 6.3.1).

In Tables 6.3.1, 6.3.2, and 6.3.3 the threshold for grain yield was set at a break-even level for commercial farmers (Table 4.2.3). This varied according to which region the QC was in, i.e.

the break-even level was higher is the eastern Highveld than the western Highveld. In Tables 6.3.4 and 6.3.5 the grain yield threshold for those treatments using manure as a nitrogen input has been set at 900 kg/ha. This is a famine threshold (Durand and du Toit, 1999) and is the amount of maize a family of four can survive on until the next harvest. If yields fall below this level, the smallholder farmers will not be producing enough maize to live on.

Table 6.3.4 Comparison of sustainability likelihood outcome for Christiana (QC C91B)

Treatment Number	Planting Date	Plant Density (plants/m^2)	Nitrogen Application Type	Nitrogen Applied (kg/ha)	Christiana Yield Threshold Commercial	Christiana Yield Threshold Famine Level
37	15 Dec	1.5	Inorganic	80.0	Minimal	Minimal
38	15 Dec	1.5	Inorganic	120.0	Minimal	Minimal
39	15 Dec	1.5	Inorganic	160.0	Minimal	Minimal
40	15 Dec	1.5	Manure	22.6	Minimal	Low
41	15 Dec	1.5	Manure	45.2	Minimal	Low
42	15 Dec	1.5	Manure	67.8	Minimal	Low
43	15 Dec	2.0	Inorganic	80.0	Minimal	Minimal
44	15 Dec	2.0	Inorganic	120.0	Low	Low
45	15 Dec	2.0	Inorganic	160.0	Low	Low
46	15 Dec	2.0	Manure	22.6	Minimal	Low
47	15 Dec	2.0	Manure	45.2	Minimal	Low
48	15 Dec	2.0	Manure	67.8	Minimal	Low
49	15 Dec	3.0	Inorganic	80.0	Low	Low
50	15 Dec	3.0	Inorganic	120.0	High	High
51	15 Dec	3.0	Inorganic	160.0	High	High
52	15 Dec	3.0	Manure	22.6	Minimal	Minimal
53	15 Dec	3.0	Manure	45.2	Minimal	Minimal
54	15 Dec	3.0	Manure	67.8	Minimal	Minimal

A comparison between using a commercial threshold and the famine threshold figure for yield for those treatments using manure is shown for Christiana (QC C91B) in Table 6.3.4. The planting dates are for mid-December, which is the optimum planting time for this QC. For those treatments which have a low or medium planting density, the sustainability likelihood has increased from minimal to low.

Table 6.3.5 gives a comparison of the sustainability indices at Bothaville (QC C24J). The comparison has been made for those treatments using the optimum planting date for this catchment, which is mid-November. For those treatments using a low or medium plant density the sustainability likelihood has increased from minimal to low. Treatments 34 and 35 have moved from minimal sustainability likelihood to medium and Treatment 36 from minimal to low.

Table 6.3.5 Comparison of sustainability likelihood outcome for Bothaville (C24J)

Treatment Number	Planting Date	Plant Density (plants/m^2)	Nitrogen Application Type	Nitrogen Applied (kg/ha)	Bothaville Yield Threshold Commercial	Bothaville Yield Threshold Famine Level
19	15 Nov	1.5	Inorganic	80.0	Medium	Medium
20	15 Nov	1.5	Inorganic	120.0	Medium	Medium
21	15 Nov	1.5	Inorganic	160.0	Medium	Medium
22	15 Nov	1.5	Manure	22.6	Minimal	Low
23	15 Nov	1.5	Manure	45.2	Minimal	Low
24	15 Nov	1.5	Manure	67.8	Minimal	Low
25	15 Nov	2.0	Inorganic	80.0	Medium	Medium
26	15 Nov	2.0	Inorganic	120.0	Medium	Medium
27	15 Nov	2.0	Inorganic	160.0	Medium	Medium
28	15 Nov	2.0	Manure	22.6	Minimal	Low
29	15 Nov	2.0	Manure	45.2	Minimal	Low
30	15 Nov	2.0	Manure	67.8	Minimal	Low
31	15 Nov	3.0	Inorganic	80.0	Medium	Medium
32	15 Nov	3.0	Inorganic	120.0	High	High
33	15 Nov	3.0	Inorganic	160.0	Medium	Medium
34	15 Nov	3.0	Manure	22.6	Low	Medium
35	15 Nov	3.0	Manure	45.2	Low	Medium
36	15 Nov	3.0	Manure	67.8	Minimal	Low

Optimum planting strategies can also be determined by investigation of yield and standard deviation of yields at each Quaternary Catchment. Table 6.3.6 shows the average yield from seasonal modelling along with standard deviations for the five selected Quaternary Catchments. At the Christiana QC the optimum planting date from the range which was modelled is either 1 or 15 December, along with a high plant density. The results from the modelling differ slightly from practice, where normally in this area a medium plant density would be favoured (Durand and du Toit, 1999).

Table 6.3.6 Mean yields and coefficient of variation of seasonal modelling using a range of planting dates and plant densities with CERES-Maize, with fixed inorganic nitrogen application of 120 kg/ha

Planting Date and Plant Densities		QC C91B	QC C24J	QC C83M	QC C11F	QC W51C
		Christiana	**Bothaville**	**Frankfort**	**Ermelo**	**Piet Retief**
		Very dry	Dry	Medium	Wet	Very wet
15 Oct Low	Yield (kg/ha)	1052	2219	3633	3426	5290
	CV (%)	109	52	44	43	24
15 Oct Medium	Yield (kg/ha)	1159	2179	3740	3703	5893
	CV (%)	99	71	51	46	28
15 Oct High	Yield (kg/ha)	1654	2230	3801	3792	6299
	CV (%)	79	62	59	45	32
1 Nov Low	Yield (kg/ha)	1182	2208	3442	2978	4920
	CV (%)	90	69	47	51	26
1 Nov Medium	Yield (kg/ha)	1352	2277	3544	3141	5448
	CV (%)	84	73	54	56	30
1 Nov High	Yield (kg/ha)	1870	2570	3662	3297	6022
	CV (%)	61	67	56	62	35
15 Nov Low	Yield (kg/ha)	1509	2577	3367	2431	4688
	CV (%)	109	65	46	55	27
15 Nov Medium	Yield (kg/ha)	1450	2732	3344	2559	5136
	CV (%)	93	65	52	62	31
15 Nov High	Yield (kg/ha)	2000	3178	3527	2622	5786
	CV (%)	69	63	60	68	34
1 Dec Low	Yield (kg/ha)	1658	2757	2839	2182	3822
	CV (%)	83	56	50	61	36
1 Dec Medium	Yield (kg/ha)	1816	2802	2787	2254	4029
	CV (%)	80	65	55	69	42
1 Dec High	Yield (kg/ha)	2217	3129	2898	2265	4239
	CV (%)	61	63	65	76	47
15 Dec Low	Yield (kg/ha)	1743	2467	2485	2259	3800
	CV (%)	85	70	46	51	36
15 Dec Medium	Yield (kg/ha)	1897	2547	2480	2331	4123
	CV (%)	86	76	53	62	43
15 Dec High	Yield (kg/ha)	2169	2791	2608	2279	4233
	CV (%)	78	75	62	69	50

The coefficient of variation at the Christiana QC (very dry) decreases for each of the 5 planting dates when the plant density is increased. The highest yields at the Bothaville catchment are with a 15 November or 1 December planting date, along with a high plant density. The coefficient of variation increases for each of the five planting dates when the plant density is increased.

The remaining three QCs, *viz.* at Frankfort, Ermelo and Piet Retief, all favour a 15 October planting date with a high plant density. The coefficient of variation increases for each of the five planting dates when the plant density is increased.

The sustainability likelihood is based on the results from a number of indicators of simulated agro-ecosystem functions, pointing to the possibility of a particular management option being sustainable or not. This analysis gives a general perspective of what is happening in the agro-ecosystem at a particular location. In the section which follows two indicators, *viz.* soil organic carbon and nitrogen, are evaluated in detail at each of the five selected QCs. Using the sequential method of modelling with CERES-Maize permits the responses of soil organic carbon and nitrogen under different management options to be analysed.

6.3.1 Christiana (very dry, QC C91B)

The Christiana QC has a MAP of 432mm and is situated in the western edge of the Highveld (Figure 6.1.1). The mean grain yield simulated using the seasonal method (Chapter 5) with CERES-Maize is 2 169 kg/ha. For a given planting date and plant density the loss of organic nitrogen is higher for manure than for fertilisers (Figure 6.3.1). This could be due to the low amount of nitrogen added in the manure. The crop, therefore, uses the existing supply of nitrogen in the soil. When the planting date is moved from 15 October to a later one the rate of organic nitrogen depletion is reduced.

For a range of fertiliser regimes (80 kg N/ha, 120 kg N/ha, 160 kg N/ha) and all else being held equal, there is no significant difference in the loss of organic nitrogen. For a range of manure regimes (22.6kg N/ha, 45.2 kg N/ha, 67.8 kg N/ha), and all else being held equal, there is no significant difference in the loss of organic nitrogen. There is a significant difference between the October and December planting dates for both inorganic and manure nitrogen inputs into the system, with the loss being between 5-9% higher in October. Those treatments with planting date in October and November are exposed to early summer rains should they occur and, therefore, experience a higher percentage loss of soil organic nitrogen over 44 seasons.

Soil organic carbon losses at the Christiana catchment are the lowest when the planting date is in December (Figure 6.3.2). There are losses of soil organic carbon of over 30% with planting dates of 15 October or 15 November when using manure as the source of added nitrogen to the system. The highest losses occur with Treatments 22-24, which have a planting date of 15 November, a low plant density and manure as the nitrogen input into the system.

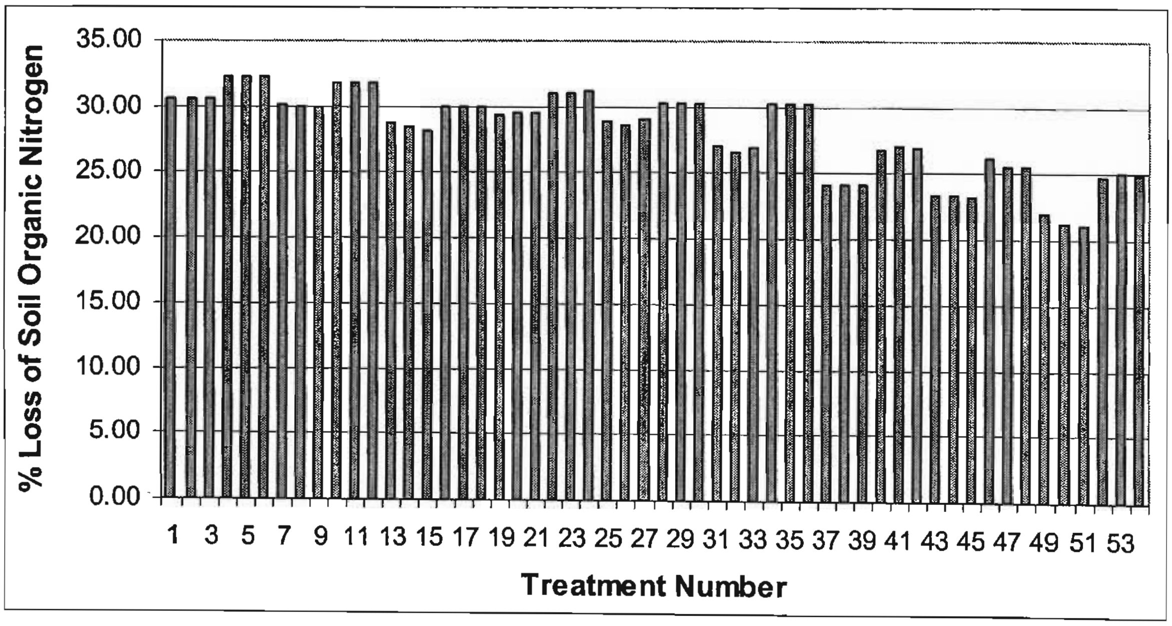


Figure 6.3.1 Percentage loss of soil organic nitrogen at Christiana over 44 seasons

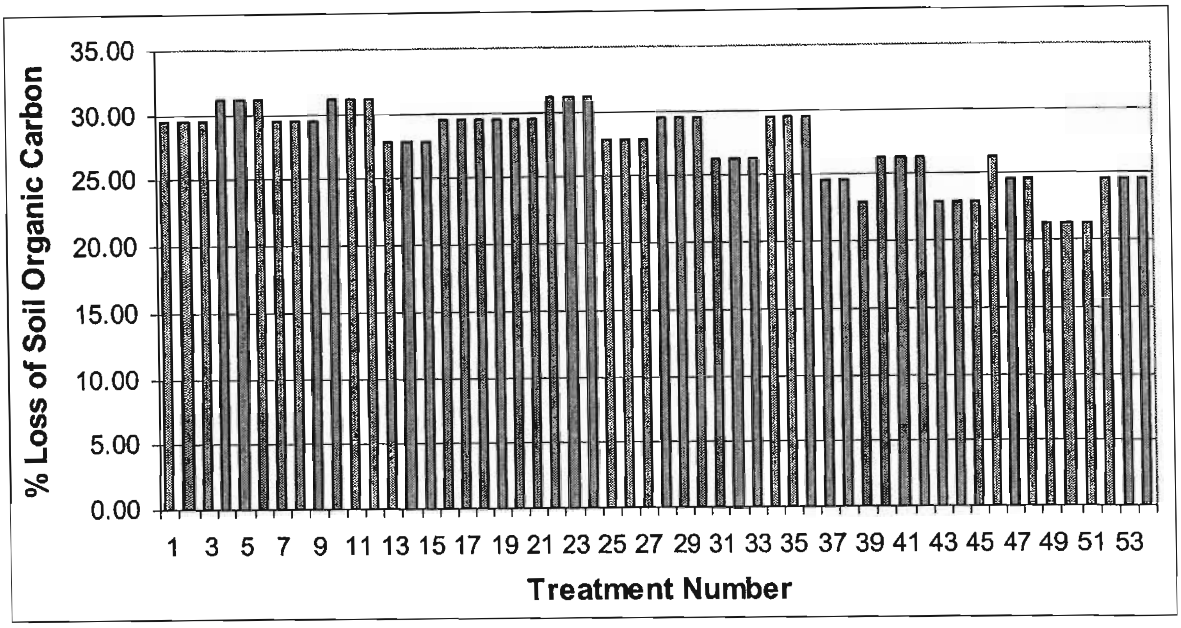


Figure 6.3.2 Percentage loss of soil organic carbon at Christiana over 44 seasons

6.3.2 Bothaville (dry, QC C24J)

The selected dry QC, *viz.* Bothaville, has a MAP of 552 mm and simulated mean grain yield is 3 178 kg/ha when using a suitable planting date. The MAP in this QC is higher than Christiana and the result is that the depletion rates of soil organic carbon and nitrogen are, in general, higher at Bothaville than at Christiana.

The depletion rate of nitrogen for a December planting date is significantly less than when planting in October and November (Figure 6.3.3). The highest soil organic nitrogen losses, at over 32%, are for Treatments 4-6 (planting date 15 October, manure input, low plant density), Treatments 22-24 (planting date 15 November, manure input, low plant density) and Treatments 34-36 (planting date 15 November, manure input, high plant density). Those treatments with planting date in October and November are exposed to early summer rains should they occur and, therefore, experience a higher percentage loss of soil organic nitrogen over 44 seasons.

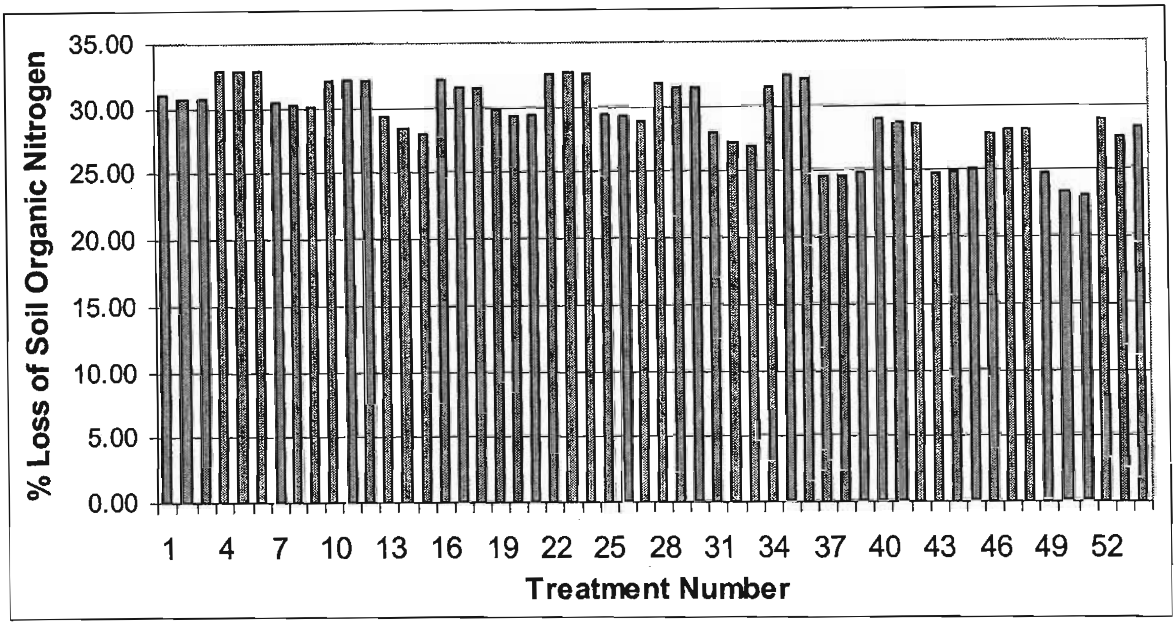


Figure 6.3.3 Percentage loss of soil organic nitrogen at Bothaville over 44 seasons

Treatments 49-51 (planting date 15 December, high plant density) show the lowest reduction in soil organic carbon with Treatment 51 having a 23% reduction over 44 seasons when the inorganic nitrogen input is 160 kg/ha/season. The low reduction rate could be due to much of the early rains having been missed with this plant date and also the readily available high inorganic nitrogen input implying that less of the organic soil nitrogen is utilised.

At the Bothaville site the highest losses of organic carbon occur with Treatment 6 (planting date 15 October, 6 kg/N/ha, low plant density), at over 33 % loss over 44 seasons from the starting value (Figure 6.3.4). Again the lowest depletion rate occurs with a December planting date, with Treatment 49 having the least amount of carbon loss.

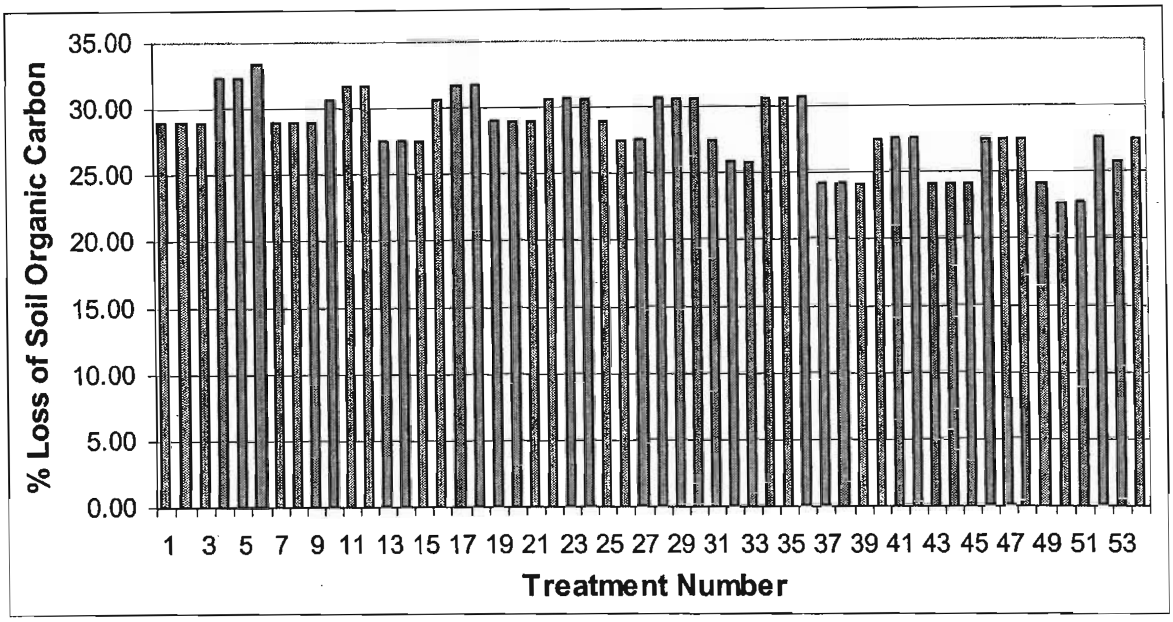


Figure 6.3.4 Percentage loss of soil organic carbon at Bothaville over 44 seasons

6.3.3 Frankfort (medium rainfall, QC C83M)

This QC has a MAP of 639 mm and a mean grain yield over 44 seasons of 3 801 kg/ha (Chapter 5) with a favourable planting date. The MAP is higher than at both Christiana and Bothaville and results in higher yields as well as slightly higher depletion rates of soil organic carbon and nitrogen.

When depletion rates of nitrogen were compared for those treatments using inorganic nitrogen, the highest levels of depletion were recorded for those with 15 October planting dates (Figure 6.3.5), with no significant differences in depletion apparent between the 15 November and 15 December planting dates.

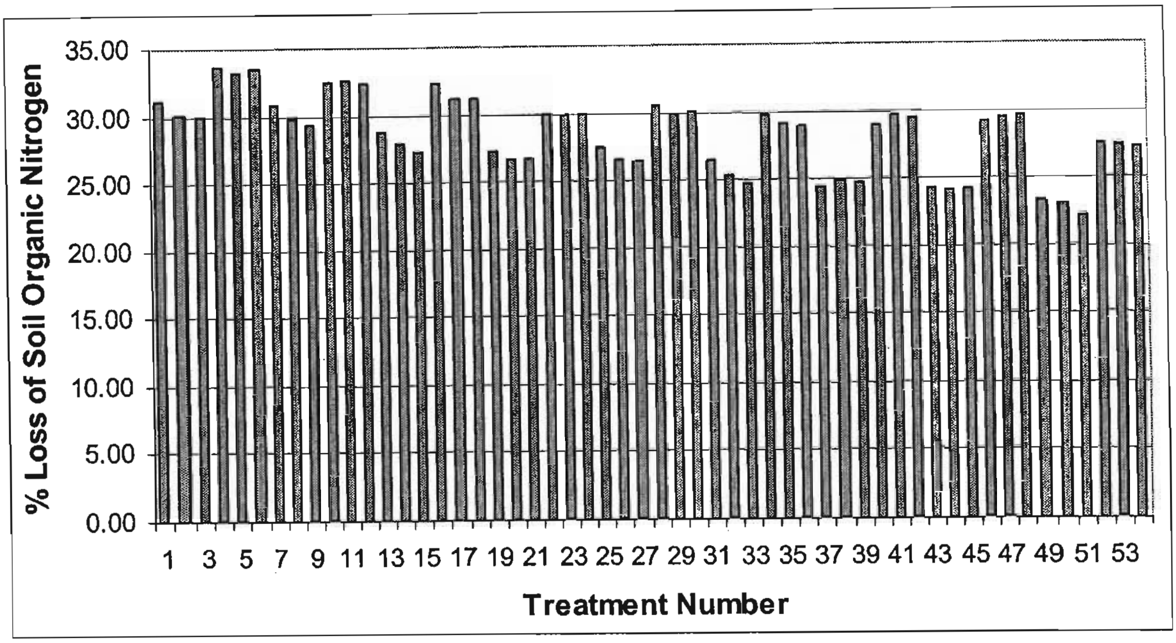


Figure 6.3.5 Percentage loss of soil organic nitrogen at Frankfort over 44 Seasons

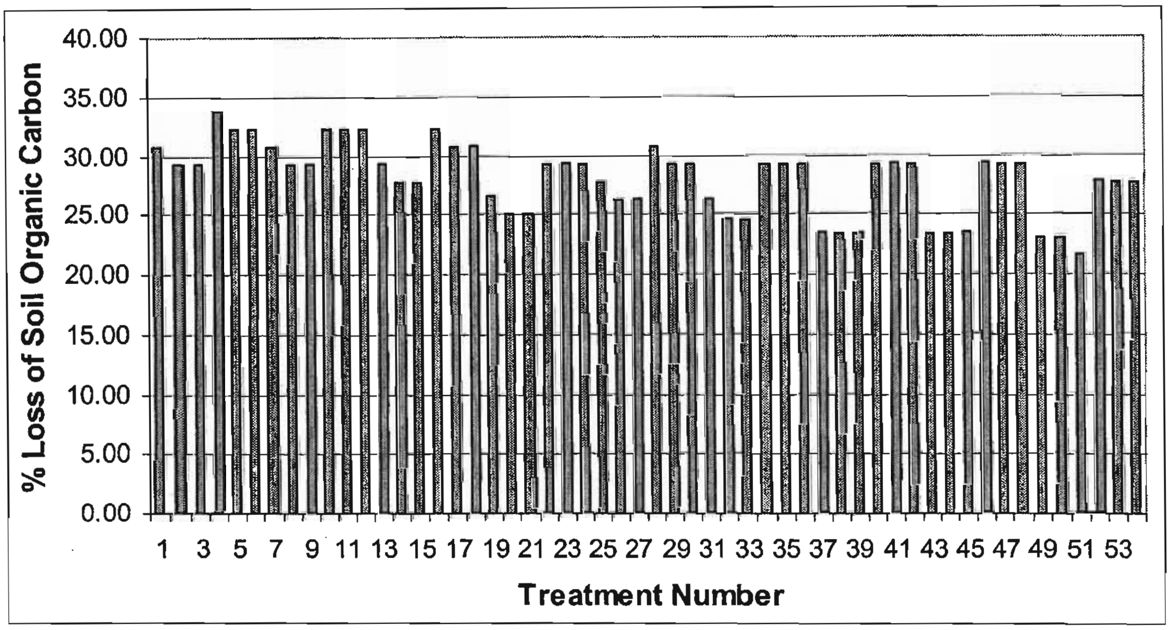


Figure 6.3.6 Percentage loss of soil organic carbon at Frankfort over 44 seasons

The smallest decrease occurs for those treatments with a December planting date and inorganic nitrogen inputs.

The highest depletion rates of soil organic carbon (Figure 6.3.6) occur with an October 15 planting date for both inorganic nitrogen and manure inputs. Treatment 4 (15 October, 22.6 kg/N/ha and low plant density) has the highest loss, at almost 34% reduction from the starting value over 44 seasons.

6.3.4 Ermelo (wet, QC C11F)

This QC has a MAP of 704 mm and a simulated mean grain yield of 3 792 kg/ha when using a suitable planting date. Although Ermelo has a higher MAP than Frankfort, it has not resulted in higher average yields and in general Ermelo displays a lower soil organic nitrogen and carbon depletion over 44 seasons than does Frankfort.

The highest rate of depletion of soil organic nitrogen in the Ermelo QC over 44 seasons is for Treatment 16 (plating date 15 October, manure input 22.6 kg/N/ha), with a 32% reduction in soil organic nitrogen from the starting value (Figure 6.3.7). The lowest organic nitrogen loss is for Treatments 31-33, which have a November planting date, high plant density and inorganic nitrogen inputs.

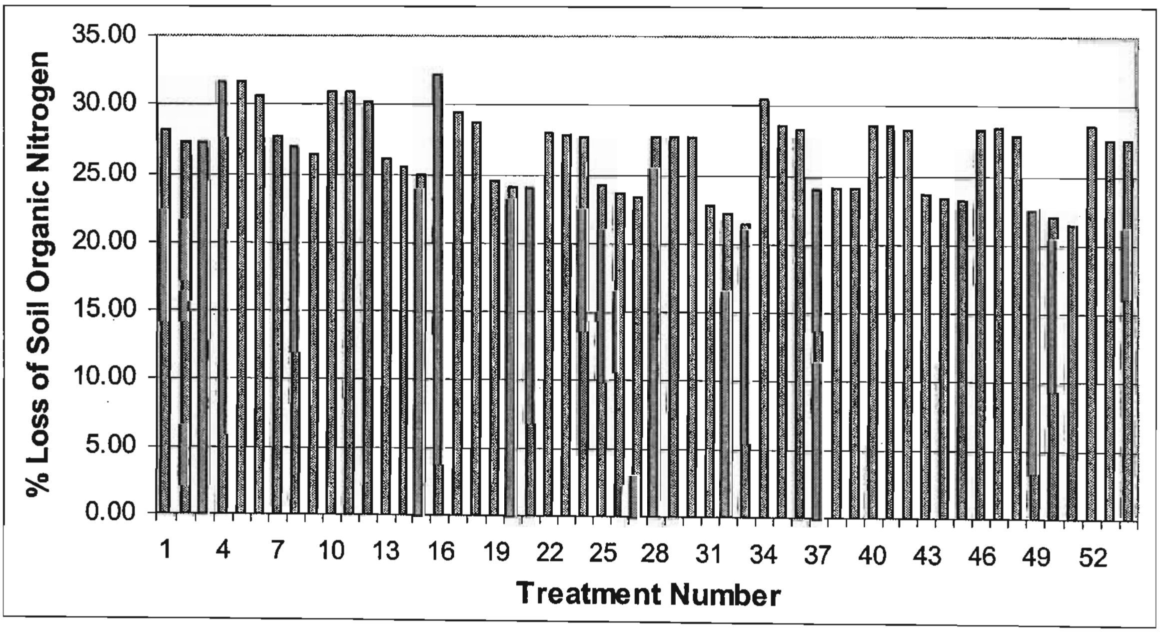


Figure 6.3.7 Percentage loss of soil organic nitrogen at Ermelo over 44 seasons

For soil organic carbon loss (Figure 6.3.8) both Treatment 5 (15 October, 45.2 kg/N/ha, low plant density) and Treatment 16 (15 October, 22.6 kg/N/ha, with high plant density) incur losses of 33% over 44 seasons. The higher losses occur with an October planting date and the least organic carbon loss is simulated with a planting date in November.

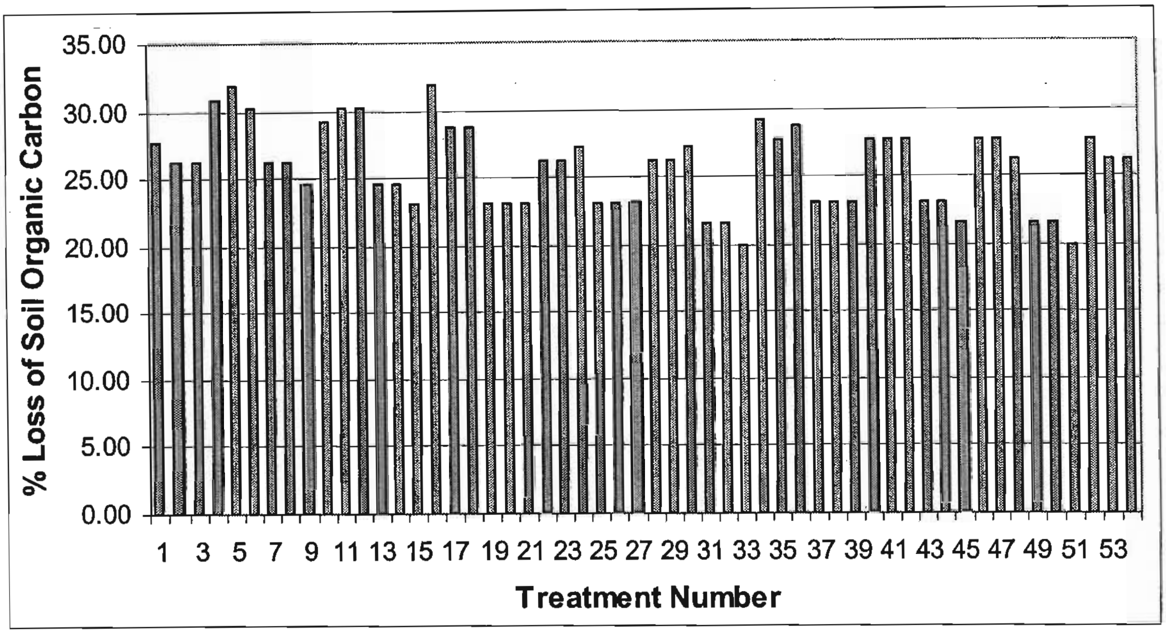


Figure 6.3.8 Percentage loss of soil organic carbon at Ermelo over 44 seasons

6.3.5 Piet Retief (very wet, QC W51C)

The very wet QC, Piet Retief, has a MAP of 903 mm and a simulated average grain yield over 44 seasons with an October planting date of 6 299 kg/ha. The MAP of Piet Retief is considerably higher than that at Ermelo and the resulting potential rainfed maize yields are also significantly higher.

There is no marked difference between the soil organic nitrogen losses with a November and December planting date when using inorganic nitrogen inputs (Figure 6.3.9). The highest rate of depletion of soil organic nitrogen is for Treatment 4 (planting date 15 October, manure input of 22.6 kg/N/ha).

All things being equal there is no marked difference in losses of soil carbon when the planting date is in November or December (Figure 6.3.10). The highest loss occurs with use of Treatment 4 (15 October, 22.6 kg/N/ha, with a low plant density), the loss sustained being 35.3% over 44 seasons. The lowest losses transpire with a November planting date using inorganic nitrogen as an input to the agro-ecosystem.

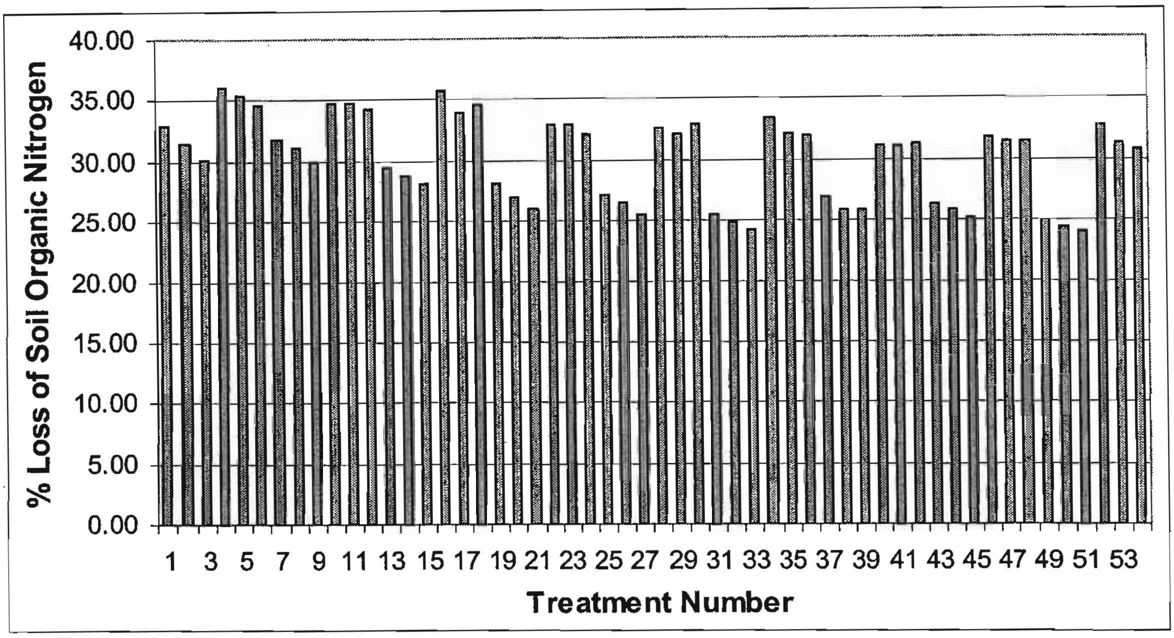


Figure 6.3.9 Percentage loss of soil organic nitrogen at Piet Retief over 44 seasons

In all the five selected QCs losses for soil organic nitrogen was less when inorganic nitrogen was added to the agro-ecosystem. This could be due to there being more readily available nitrogen for the crop to utilise when compared with using manure as the nitrogen input, as it takes time for the manure to break down and for the nitrogen to be available to plant processes in the agro-ecosystem.

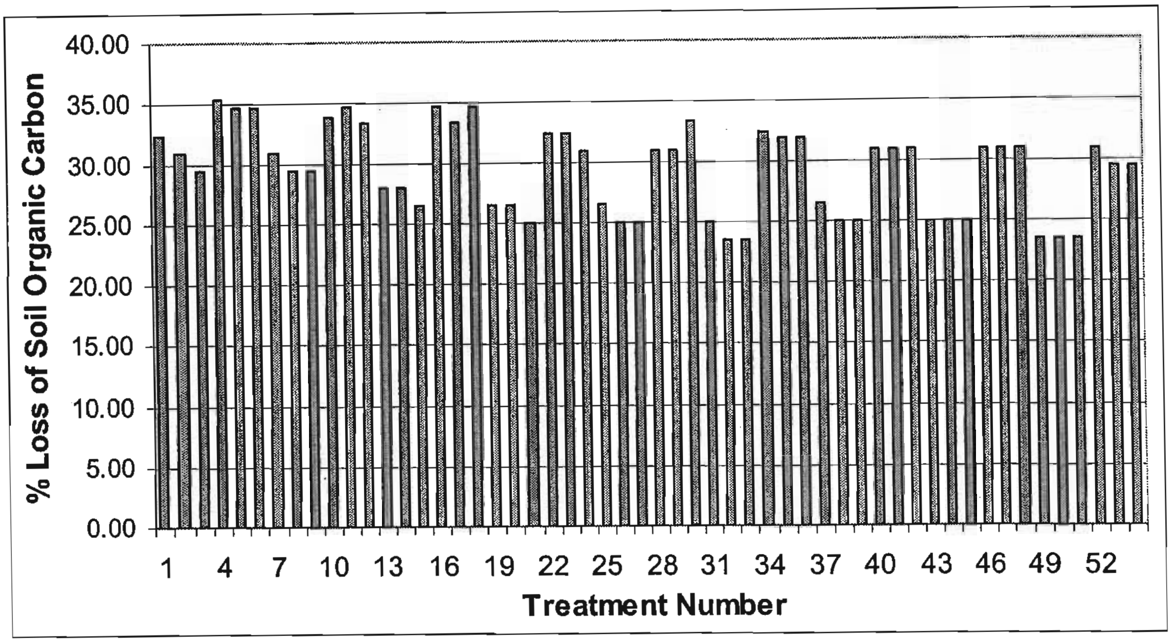


Figure 6.3.10 Percentage loss of soil organic carbon at Piet Retief over 44 seasons

In general the higher the MAP of a catchment the higher the yields, but also the depletion rate of both soil organic carbon and nitrogen. The exception to this is at Ermelo (wet QC, MAP 704mm) with its slightly lower yields and nitrogen and carbon losses than Frankfort (medium rainfall, MAP 639mm). Continued depletion of soil organic carbon and nitrogen will have impacts on the quality of the soil while the leaching of inorganic nitrogen has consequences for water quality.

6.4 Management Advice

Soil organic carbon and nitrogen losses were highlighted in Section 6.3 and they affected all five QCs. The losses were higher in those QCs that had a higher MAP. If the quality of the soil decreases it will eventually have negative effects on the yield and thus threaten the long-term economic and social sustainability of the agro-ecosystem. Possible solutions to this would be to increase the amount of external inputs into the system, which itself is not a sustainable pathway if external inputs continue to increase, or adopt some form of conservation tillage to maintain soil quality. The losses were generally higher with an earlier planting date and were also higher with treatments that used manure as the nitrogen input into the system.

The management strategies that are considered to cope best with the Highveld region's biophysical constraints are the ones that will produce environmental and economic sustainability for the agro-ecosystem. Once again, the goal of the system used to assess agro-ecosystems in the five selected QCs in the Highveld is:

> *'The goal is for the agro-ecosystems in the Highveld region to continue in the long term, providing quality well-being for farmers and local communities and to maintain ecological integrity.'* (Section 6.1)

The management strategies from the sustainability assessment that are considered the most likely sustainable pathway for the each of the five QCs' agro-ecosystems are summarised in Table 6.4.1. The management strategies are based on the sustainability likelihood analysis (Tables 6.3.1, 6.3.2, 6.3.3) and the analyses of yield and CV of yield (Table 6.3.6).

The amount of nitrogen applied can be considered high by world standards in terms of the plant density used, which is lower than in other major maize producing areas of the world. The figures given in Table 6.4.1 were the climatically optimum results from the sustainability modelling in Chapter 6. The amount of nitrogen applied, however, is not unusually high for the Highveld region of South Africa (Schmidt and Smalberger, 1999). There are several reasons why the optimum nitrogen level is higher in the Highveld than for agriculture in other parts of the world. Most of the soils in the Highveld, especially those in the drier western parts, are very low in organic matter content and over decades of intensive use the tillage methods employed have depleted the soils to a large extent of organic matter, as illustrated in Section 6.3. This could be attributed to the regular turnover of the soil, which exposes accumulated organic matter to high temperatures, and to frequent wetting and drying spells that increase the rate of decomposition by micro-organisms. Also many soils in the Highveld are of sandstone origin, and as a result have very low levels of useable nutrients. The soil types also contribute to loss of nutrients through leaching (Prinsloo, 2005).

The difference between the simulated optimum levels of nitrogen applied to that in practice could be due to the way nitrogen use is simulated in CERES-Maize, particularly in semi-arid areas. Alternatively, the difference could be in the way the optimum management strategies are calculated. The indicators involving nitrogen are grain nitrogen content, nitrogen recovery and soil organic nitrogen levels and yield (Section 4.2.1). There is not an indicator for nitrogen levels in runoff or in the groundwater. Therefore, a high level of nitrogen application could produce a high yield, acceptable grain nitrogen content and prevent inorganic soil loss and give a result of a medium or high likelihood of sustainability. This could still have a negative effect on the agro-ecosystem due to high nitrogen levels in the ground and surface water. This negative effect would then be masked, as there is no indicator to advise otherwise with the overall result being that too high a nitrogen level is recommended for application.

Table 6.4.1 Optimum management strategies for maize production under present climate conditions at five selected locations in the Highveld

Quaternary Catchment	**Treatment Number**	**Planting Date**	**Plant Density (plants/m^2)**	**Nitrogen Application Type**	**Amount of Nitrogen Applied (kg/ha)**
Christiana	50	15 Dec	3.0	Inorganic	120
Bothaville	32	15 Nov	3.0	Inorganic	120
Frankfort	14	15 Oct	3.0	Inorganic	120
Ermelo	14	15 Oct	3.0	Inorganic	120
Piet Retief	14	15 Oct	3.0	Inorganic	120

Although the sustainability framework and methods were not formulated with up-scaling as an aim, it is still valuable to consider upscaling so that possible lessons can be drawn. With the Quaternary Catchment scale assessment there appears to be limited scope for up-scaling to the regional level. This is particularly pertinent in regard to up-scaling results from the surface and subsurface hydrology routines contained in CERES-Maize. These routines were not designed for modelling hydrological responses at such a large scale especially for South African conditions. A possible solution would be to link CERES-Maize to the *ACRU* hydrological modelling system, as was done in the research by Schulze *et al.* (1996). This would be of interest, as CERES-Maize has undergone extensive regional calibration in South Africa since that work was performed.

The strategies summarised in Table 6.4.1 are used in Chapter 7 to investigate the impacts on agro-ecosystems under different climatic regimes. The optimum strategies are based on averages over 44 seasons. In practice a range of strategies may be utilised to counteract the effects of, for example, El Niño years and extended periods of drought.

7 AGRICULTURAL SUSTAINABILITY AT A QUATERNARY CATCHMENT SCALE: ASSESSING AGRO-ECOSYSTEM SUSTAINABILITY UNDER DIFFERENT CLIMATE REGIMES

A change in means of climate parameters, or an increase in climate variability, will have complex impacts on agro-ecosystems. Climate comprises of complex relationships between variables such as temperature, precipitation, evaporation, wind and cloud. Such relationships are generally independent of atmospheric carbon dioxide (CO_2) concentrations, but CO_2 and other greenhouse gases contribute largely to climates changing through their effect on the radiation balance of the atmosphere. An increased level of CO_2 in the atmosphere has a positive influence on plant photosynthesis (Sombroek and Gommes, 1996).

The risk and uncertainty associated with agriculture affects decision-making. As a direct consequence, uncertainty can result in inefficiencies to occur in the agricultural sector, along with concerns over food security. Informed decision making under risk involves combining decision makers' expectations about what is likely to happen in the future with their management preferences (Thornton and Wilkens, 1998).

For this assessment the five QCs used in the evaluation in Chapter 6 were again selected. These QCs have a range of mean annual precipitation (MAP) from 432 mm through to 903 mm. In order to investigate sustainability on a Quaternary Catchment scale under different climate regimes, an adapted goal orientated system of von Wiren-Lehr's (2001) described in Chapter 4, was applied. This system has four stages:

- Identifying the goal (Section 7.1)
- Sustainability modelling (Section 7.2)
- Evaluation (Section 7.3) and
- Management advice (Section 7.4).

7.1 Goal Definition

The question as to whether an agro-ecosystem is sustainable for maize production, for example, encompasses a wide range of considerations including climate variability and change, management practices, government policy, equity goals, food security, livelihoods and biodiversity. What is certain is that there is a lack of knowledge on how specific agro-ecosystem functions may change should the agro-ecosystem be transformed (O'Riordan, 2002). This lack of knowledge is related to being able to maintain the ecological integrity of an agro-ecosystem. This is the integrity of both system structure and function, maintenance of which is uncertain under climatic changes.

The intention of this assessment was to investigate how the agro-ecosystem functions may be affected by modifications to the environment, and in particular to climate change. Any major climate changes, be they positive or negative, are likely to have significant bearing on the long-term sustainability of the agro-ecosystem. The goal of the system assessment must therefore incorporate this.

The sustainability goal used for this particular assessment is given below:

> *'The goal is for the agro-ecosystems in the Highveld region to continue in the long term, providing quality well-being for farmers and local communities and to maintain ecological integrity.'* (Sections 2.7, 5.2 and 6.1)

The objective of this assessment is to be able to summarise findings by simulating agro-ecosystems at a QC scale under different climate scenarios. This information will then be assessed in regard to agro-ecosystem sustainability.

7.2 Sustainability Modelling

The purpose of modelling in this particular assessment is to assess how different agro-ecosystem functions respond to anticipated changes in climate. The five QCs used for the sustainability assessment in Chapter 6 were again used in this study. The optimum management strategies determined in Chapter 6, which include planting date, plant density and nitrogen application level, were modelled for a variety of climate scenarios. A summary of the five QCs used in Chapter 6 is given in Table 7.2.1, along with the optimum planting strategies for each QC under present climatic conditions.

Table 7.2.1 Summary of selected QC details and optimum management strategies under present climatic conditions

	Christiana	Bothaville	Frankfort	Ermelo	Piet Retief
General Description of Rainfall Regime	Very dry	Dry	Medium	Wet	Very wet
Quaternary Catchment ID	C91B	C24J	C83M	C11F	W51C
MAP (mm)	432	552	639	704	903
Mean yield (kg/ha)	2169	3178	3801	3792	6299
Planting date	15 Dec	15 Nov	15 Oct	15 Oct	15 Oct
Plant density (plants/m^2)	3.0	3.0	3.0	3.0	3.0
Nitrogen source	Inorganic	Inorganic	Inorganic	Inorganic	Inorganic
N applied (kg/ha)	120	120	120	120	120

With the uncertainties still surrounding the magnitudes and timing of climate changes, as generated by General Circulation Models (IPCC, 2001), one approach is for plausible climate scenarios to be utilised to estimate the impacts of climate change on a system (Rosenzweig and Iglesias, 1998). In this study eleven climate scenarios were regarded as plausible for southern Africa based on output from GCMs (Schulze and Perks, 2000). These scenarios were considered so that a range of effects could be identified. A present climate data set from 1950-1994 was used, with environmental modifications made to the input files of CERES-Maize so that the following scenarios could be modelled:

- a doubling of present CO_2 atmospheric concentrations to 555 ppmv (2xCO_2)
- increasing both minimum and maximum daily temperatures by 2°C
- 2xCO_2 + 1°C minimum/maximum daily temperature increase
- 2xCO_2 + 2°C minimum/maximum daily temperature increase
- 2xCO_2 + 3°C minimum/maximum daily temperature increase
- 10% reduction in rainfall
- 10% increase in rainfall
- 2xCO_2 with 10% reduction in rainfall
- 2xCO_2 with 10% increase in rainfall
- 2xCO_2 +2°C minimum/maximum daily temperature increase with 10% reduction in rainfall and

- $2xCO_2$ +2°C minimum/maximum daily temperature increase with 10% increase in rainfall.

The climate scenarios listed above will have a range of effects on the agro-ecosystem in regard to sustainability. The various scenarios and their possible effects are as follows:

- The enhancement of atmospheric CO_2 concentrations from present levels around 360 ppmv to 555 ppmv, abbreviated to the '2x CO_2' scenario: $2xCO_2$ results in enhanced photosynthetic rates plus stomatal closure, with the latter implying reduced transpiration rates. The hypothesis is that this scenario will increase yield, more so with higher plant densities.
- An increase in both maximum and minimum daily temperatures by 2°C is designated the '+2°C' scenario. An increase temperature promotes rate of crop development, but simultaneously, through increased evaporative demand, can dry out soil more rapidly. An increase in the rate of development would reduce the time available for the crop to capture solar radiation and convert CO_2 to biomass. The hypothesis, in a southern African context in which climates are rainfall limited but not radiation limited, is that yields would generally decrease with an increase in temperature by itself.
- A 10% increase in rainfall scenario: In the Highveld, particularly in the western parts, rainfall is the major limiting factor to crop development. The hypothesis is that this scenario would increase yields.
- A 10% reduction in rainfall scenario: A reduction in rainfall, particularly in the Quaternary Catchments that have a low MAP, will lead to the maize crop's becoming stressed more frequently and crop development will be inhibited. The hypothesis is that this scenario will reduce yields.
- The combination of an effective doubling of atmospheric CO_2 plus increased temperatures (the '2x CO_2 with +1°C, +2°C, and +3°C' increases): The hypothesis is that the "drivers" in this climate scenario are self cancelling up to a point, with the climate scenario '2x CO_2 +3°C' seeing reduced yields, particularly in the drier areas of the Highveld.
- The combination of effective doubling of atmospheric CO_2 and a 10% decrease in rainfall (the '$2xCO_2$ with 10% rainfall reduction' scenario): In this case the hypothesis is that the drivers in will result in self cancelling of impacts up to a point, but in the western

drier areas of the Highveld the reduced rainfall will affect yields negatively even with $2xCO_2$.

- The combination of effective doubling of atmospheric CO_2 and a 10% increase in rainfall (the '$2xCO_2$ with 10% rainfall increase' scenario): The hypothesis is that the drivers in this climate scenario would increase yields.
- The combination of an effective $2xCO_2$ +2°C minimum/maximum daily temperature increase with a 10% reduction in rainfall: In this case the hypothesis is that in the drier areas the reduced rainfall and increased temperatures will inhibit crop development and reduce yields, while in regard to soil organic nitrogen and carbon the combination of drivers will result in higher losses.
- The combination of $2xCO_2$ +2°C minimum/maximum daily temperature increase with a 10% increase in rainfall: The hypothesis is that yields would increase and in regard to soil organic nitrogen and carbon the combination of drivers would cause higher losses in yields.

CERES-Maize was operated in sequential mode so that values of soil water, soil organic carbon and nitrogen would be passed on from the end of one season to the beginning of the next. Any trend identified could then be used to estimate the potential of biophysical sustainability for a given management strategy for different climate scenarios. From the results of the modelling, an index was created that provides an indication of the impacts on the agro-ecosystem sustainability for each QC.

7.3 Evaluation Strategy

The likelihood of sustainability for an agro-ecosystem under different climate scenarios was ascertained by the use of the weighted index described previously in Chapter 4. This index gives four options for the likelihood of sustainability: minimal, low, medium and high. The mean figure of a selected indicator was compared against a critical limit and was then scored accordingly. The scores for each agro-ecosystem function were summed for the climate scenario. The sustainability likelihoods for each of the five QCs are shown in Table 7.3.1. The indicators used for the sustainability modelling are:

- mean grain yield
- grain nitrogen content

- soil organic carbon
- soil organic nitrogen
- nitrogen recovery
- extractable water
- cumulative runoff and
- drainage.

Table 7.3.1 Agro-ecosystem sustainability likelihoods in five selected QCs under different climate regimes

Climate Scenario	**Christiana**	**Bothaville**	**Frankfort**	**Ermelo**	**Piet Retief**
Present climate	Medium	Medium	Medium	Medium	High
2x CO_2	Medium	Low	Medium	Medium	Medium
Temperature + 2°C	Low	Low	Low	Low	Medium
2x CO_2 +1°C	Medium	Low	Low	Medium	Medium
2x CO_2 +2°C	Low	Low	Low	Medium	Medium
2x CO_2 +3°C	Low	Low	Low	Low	Low
+10% Rainfall	Low	Medium	Low	Low	Medium
-10% Rainfall	Low	Low	Low	Low	Low
2xCO_2 +10% Rainfall	Low	Medium	Medium	Medium	Medium
2xCO_2 -10% Rainfall	Low	Low	Low	Medium	Medium
2xCO_2 +10% Rainfall +2°C	Low	Medium	Low	Medium	Medium
2xCO_2 -10% Rainfall +2°C	Low	Low	Low	Medium	Medium

Under the present climate the sustainability likelihoods of the five QCs are medium or high when optimum management strategies of planting date, plant density and fertiliser application are chosen. The likelihood of sustainability is uncertain under different climate regimes. The results from the sustainability modelling, summarised in Table 7.3.1, show that a maize crop will benefit especially in terms of mean grain yields from an effective doubling of atmospheric CO_2. However, this benefit can be counteracted when there is an increase in temperature, particularly of 2°C or more. Rising air temperatures are likely to increase water vapour deficits which will increase the potential crop evapotranspiration (Rosenzwig and Hillel, 1998). It is noteworthy that a very dry QC such as Christiana does not have an improved sustainability likelihood with a scenario of a doubling of CO_2 and a 10% increase in rainfall. Although there is an increase in the mean grain yield, the runoff and soil organic nitrogen and carbon also increase, giving the Christiana QC reduced sustainability likelihood. In reality this climate scenario should generally be highly beneficial to an agro-ecosystem, therefore management changes could be made to take advantage of such favourable climate conditions.

In all QCs an increase in temperature of 3°C with a doubling of CO_2 leads to the likelihood of sustainability being reduced. Conversely, with a doubling CO_2 and a 10% increase in rainfall the likelihood of sustainability is increased in all QCs except Christiana. The two QCs with the higher MAP, Ermelo and Piet Retief, are able to absorb a temperature increase with lower adverse effects than the other QCs with lower rainfalls. A decrease in rainfall by itself results in a low sustainability likelihood in 5 of the QCs. However, an increase in rainfall by itself only increases the sustainability rating at the Bothaville and Piet Retief QCs. The reasons for this vary for each QC. At Christiana the increase in rainfall only increases mean grain yield over 44 seasons by 100 kg/ha, which is not enough to improve the sustainability likelihood. At Frankfort and Ermelo QCs the increase in rainfall increases the soil organic carbon and nitrogen loss and produces a higher amount of runoff. A weighted index resulting in a given sustainability likelihood allows general agro-ecosystem health to be assessed. In the sections which follow key indicators from the output of CERES-Maize are analysed for each QC to identify impacts of climate change scenarios.

7.3.1 Christiana (very dry, QC C91B)

Christiana is the driest of the five QCs selected and has a mean grain yield of 2 218 kg/ha under present climate conditions With a doubling of CO_2 the mean grain yield increases to 2 746 kg/ha because of the fertilisation effect of CO_2 and reduction in transpiration rates. Even though the mean grain yield is above the general break-even figure for maize production in the area, the mean yield masks a marked inter-seasonal variability in the yield.

The variability of yields under different climate scenarios at the Christiana QC is shown in Table 7.3.2. Under current conditions the inter-seasonal yields are highly variable at this very dry Quaternary Catchment. For different climate scenarios the variability of yields was found to generally decrease. An increase in temperature results in a reduction in variability. An increase in temperature will induce an acceleration of crop growth and development, but reduce soil moisture. The increase in temperature seems to reduce the number of 'extreme' good harvests, and therefore reduce variability. The reduction in variability in this case is not a benefit to the farmer as it is the crop failures which need to be minimised. Furthermore, the climate scenarios which include temperature increases appear to reduce the benefits to the crop in higher rainfall years. It was hypothesised that with the scenario of '2x CO_2 -10% rainfall' that in a dry QC such as Christiana, a reduction in yields would occur. In fact the CO_2 enrichment in the atmosphere was still able to result in an increase in yield of 200 kg/ha even with a 10% reduction in rainfall. The reduction in rainfall with this scenario meant that soil organic nitrogen loss was the lowest of the scenarios simulated.

Table 7.3.2 Mean yields and coefficients of variation of yields over 44 seasons for the Christiana QC

Christiana QC		
Climate Scenario	Mean Yields (kg/ha)	CV of Yields (%)
Present Climate	2 216.6	86.8
2xCO_2	2 730.7	79.8
Temperature + 2°C	1 983.6	56.2
2x CO_2 +1°C	2 735.9	71.9
2x CO_2 +2°C	2 561.4	69.5
2x CO_2 +3°C	2 382.8	63.7
2x CO_2-10% rainfall	2 423.8	84.8
2x CO_2 +10% rainfall	2 967.3	73.4
Plus 10% rainfall	2 345.9	77.7
Minus 10% rainfall	1 904.0	73.8
2x CO_2+ 2°C +10% rainfall	2 721.5	68.5
2x CO_2+ 2°C -10% rainfall	2 174.9	69.1

For 39 out of 44 seasons a doubling of CO_2 will result in an increase of grain yield (Figure 7.3.1), the increase being particularly marked when the yields for present climate are around 3 000 kg/ha. From season 7-16 present yields fall below the break-even figure of 2 200 kg/ha, and over 44 seasons falls below this value 14 times with present climate and 9 times when the CO_2 level is increased. During extended periods of low rains, farmers would have to look at other strategies with which to survive this climatic phenomenon. Even the fertilisation effect of a doubling of CO_2 has only a marginal positive effect when the rainfall is low.

With a doubling of CO_2 and a temperature increase of 2°C the maize yield increases for 27 out of 44 seasons modelled (Figure 7.3.2). However, in 19 of the seasons the yield under both present conditions and under $2xCO_2+2°C$ climate scenario falls below 2 000 kg/ha. For this particular comparison there are some pronounced differences in yield in some seasons. For example, in Season 6 the yield is much higher under present conditions and in Season 25 the yield is considerably higher for the $2xCO_2+2°C$. In some years the increase in temperatures inhibits crop development and as a consequence the maize is unable to take advantage of possible CO_2 enhancement of plant growth. In higher rainfall years, such as Season 25, the negative impacts of the temperature increase in this QC are lessened and the crop is benefits from CO_2 fertilisation.

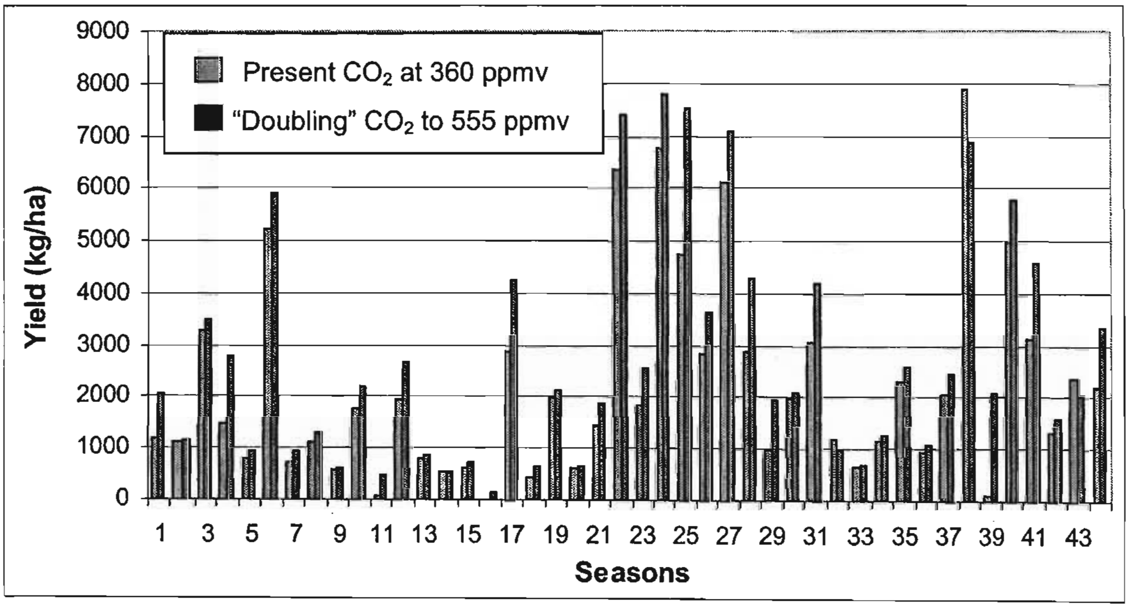


Figure 7.3.1 The influence on maize yield of an effective doubling of atmospheric CO_2 concentration for the Christiana Quaternary Catchment

Soil organic nitrogen loss from the system is shown in Figure 7.3.3. The climate scenario under which most organic nitrogen is removed from the soil is an effective doubling of CO_2 concentrations in combination with a temperature increase of 3°C.

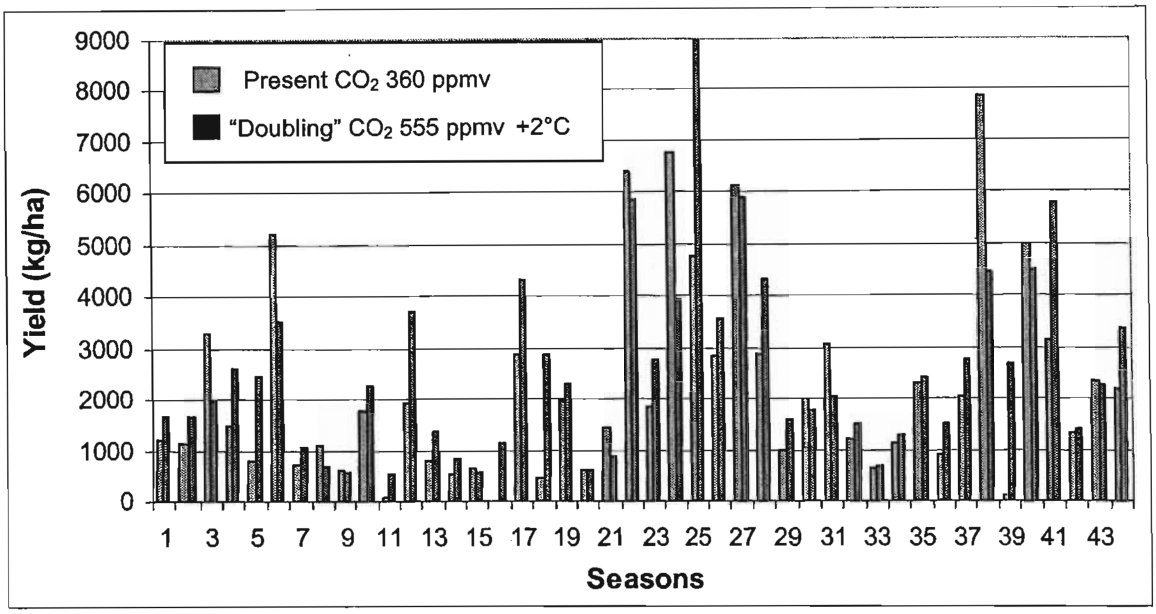


Figure 7.3.2 The influence on maize yield of an effective doubling of atmospheric CO_2 concentration and a 2°C increase in minimum and maximum temperatures for the Christiana Quaternary Catchment

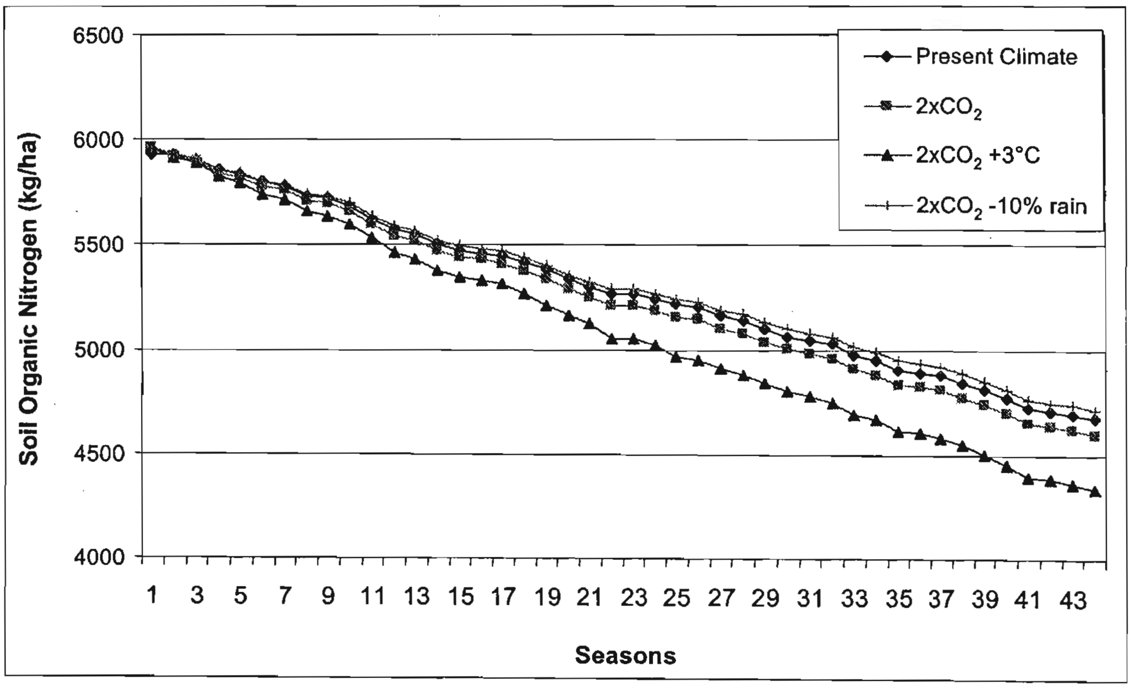


Figure 7.3.3 Decreases in soil organic nitrogen levels over 44 seasons at the Christiana QC for selected climate scenarios

A reduction in rainfall (Figure 7.3.3) will lead to less organic nitrogen being lost. However, this is probably due to lower crop yields associated with less plant growth and, therefore, less nitrogen being required by the crop. The general efficiency with which the maize crop uses added nitrogen is shown in Figure 7.3.4. The mean nitrogen recovery under present climatic conditions is 85%, while it is 78% with an effective doubling of atmospheric CO_2. The figures are high compared with the world-wide average of 50% (Craswell and Godwin, 1984). The reasons for such high efficiency within this particular agro-ecosystem could be because the optimum planting strategy is being utilised or that this QC had a low MAP so a smaller percentage of added nitrogen is leached from the soil.

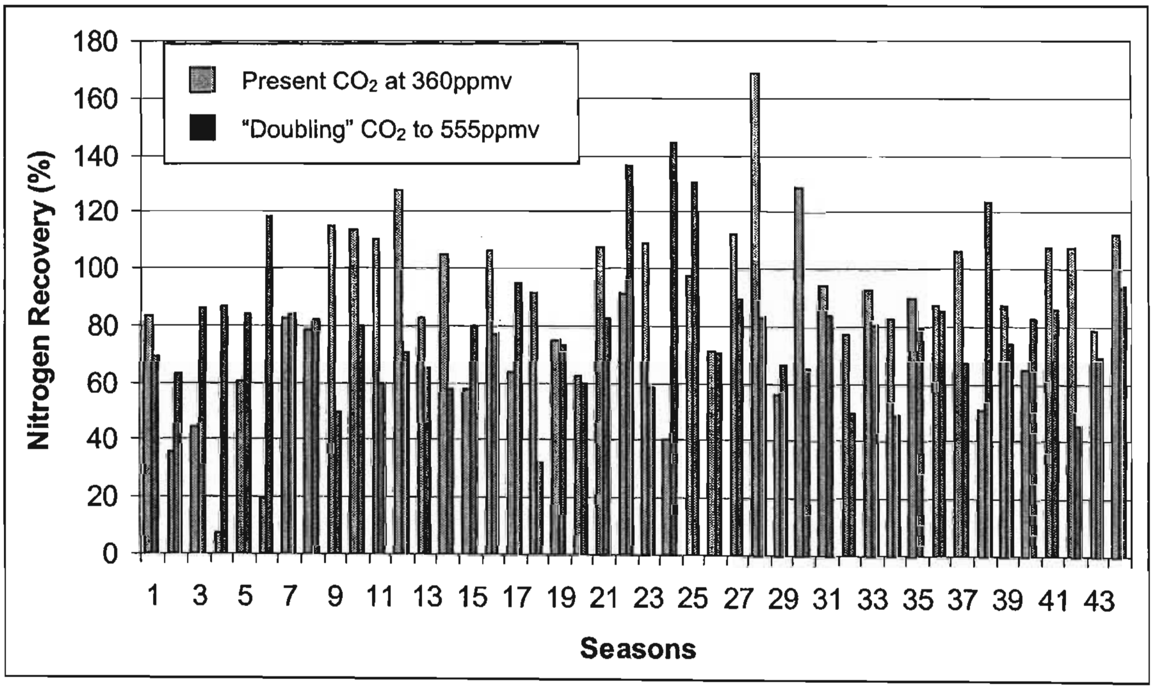


Figure 7.3.4 Comparison of nitrogen recovery over 44 seasons at the Christiana QC for present CO_2 levels and an effective doubling of atmospheric CO_2 concentration

The drier areas of the western Highveld are particularly vulnerable to rainfall changes. A reduction in rainfall of 10% is a plausible future scenario for this area (Engelbrecht, 2005). This scenario was modelled in CERES-Maize in a linear manner i.e. by simply reducing the rainfall of each day in the present climate data file by 10%. However, future work could investigate the changes in distribution and magnitude of daily rainfalls under future climates to assess their impacts on the agro-ecosystem goods and services.

7.3.2 Bothaville (dry, QC C24J)

The selected dry QC, Bothaville, with a MAP of 552mm has a simulated mean grain yield of 3 178 kg/ha under present climatic conditions when using a planting date of 15 October with a high plant density and 120 kg/ha of inorganic fertiliser. The inter-annual coefficient of variation of yields in this part for the Highveld region is high (65%) and this is illustrated in Figure 7.3.5. The average yields over 44 seasons with an effective doubling of atmospheric CO_2 increases to 4 281 kg/ha. For 38 out of 44 seasons the yields are higher with a doubling of CO_2 (Figure 7.3.5). There are 14 seasons under present climate conditions where the yield is below 2 200 kg/ha, which is the break-even figure, with this reducing to 9 seasons out of 44 with a doubling of CO_2. The yields fall below the 900 kg/ha on three occasions with present climate and only once with the CO_2 increase. The yield variability is lower with a 2x CO_2 scenario compared to present climatic conditions (Table 7.3.3). In some seasons such as 5, 17 and 39 the increase in yield with this scenario is quite marked. The reason for this could be the temperature, rainfall and solar radiation in these years enables the crop to benefit from CO_2 fertilisation, while in other years such as Seasons 24 and 25 this might not be the case.

Table 7.3.3 Mean yields and coefficients of variation of yields over 44 seasons for the Bothaville QC

Bothaville QC		
Climate Scenario	Mean Yields	CV of Yields
Present Climate	3 393.5	54.3
2xCO_2	4 280.7	42.7
Temperature + 2°C	2 435.3	54.3
2xCO_2 +1°C	3 700.4	46.9
2xCO_2 +2°C	3 325.5	49.0
2xCO_2 +3°C	2 986.1	52.2
2xCO_2 -10% rainfall	3 797.2	48.7
2xCO_2 +10% rainfall	4 325.2	35.3
Plus 10% rainfall	2 983.3	49.2
Minus 10% rainfall	2 552.5	63.6
2xCO_2+ 2°C +10% rainfall	3 799.2	42.7
2xCO_2+ 2°C -10% rainfall	3 061.2	59.8

With an effective doubling of CO_2 plus a temperature increase of 2°C the maize yield increases in 26 out of 44 seasons (Figure 7.3.6). The increase in temperature of 2°C counteracts the photosynthetic benefit to the plant of an effective doubling of CO_2. The yields are still highly variable with this climate scenario due to the variability of rainfall.

The yield variability is affected in a negative manner when there is a 10% reduction in the rainfall by itself (Table 7.3.3). This effect is reduced when in combination with $2xCO_2$, but when a temperature rise of 2°C is added to this, the variability again increases to a higher percentage than under present conditions. The lowest yield variability occurs with those climate scenarios that have a 10% increase in rainfall.

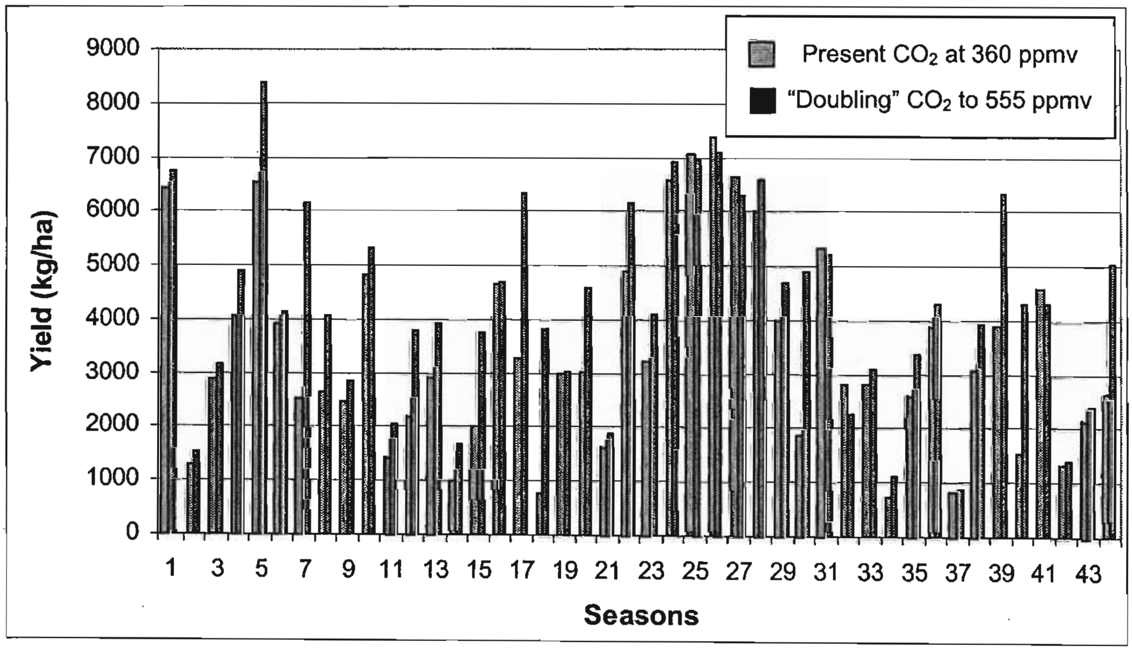


Figure 7.3.5 The influence on maize yield of an effective doubling of atmospheric CO_2 concentrations for the Bothaville QC

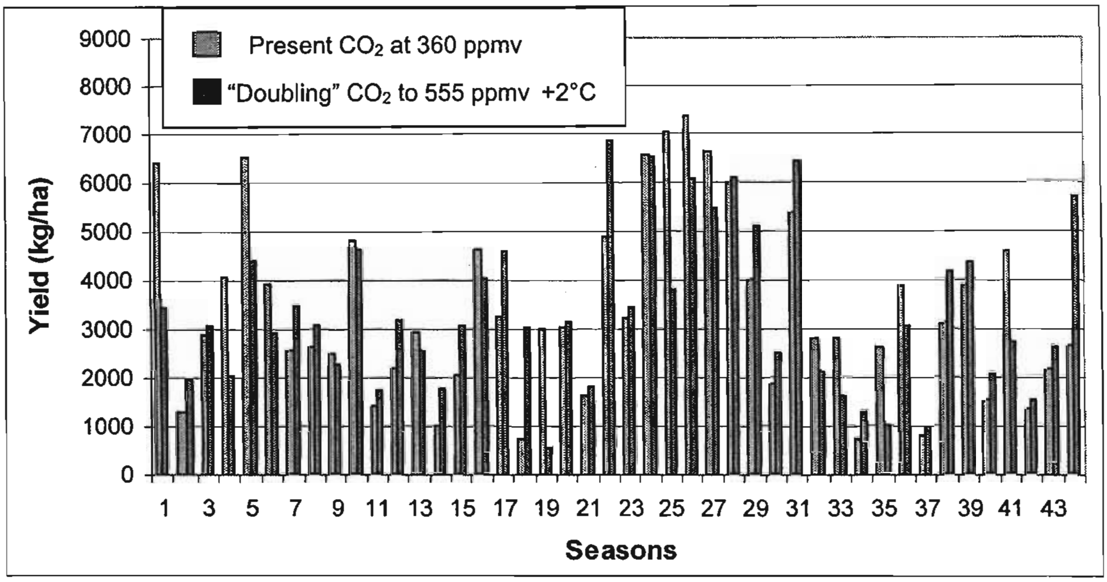


Figure 7.3.6 The influence on maize yield of an effective doubling atmospheric CO_2 concentration plus a 2°C increase in minimum and maximum temperatures for the Bothaville QC

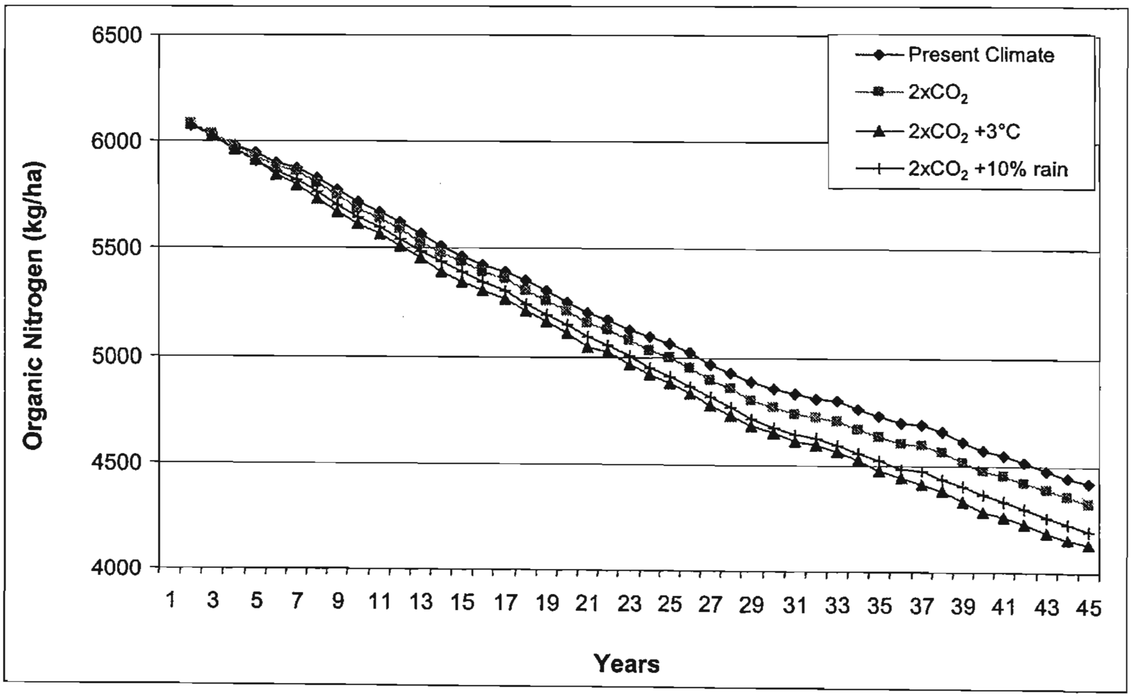


Figure 7.3.7 Decreases in soil organic nitrogen levels over 44 seasons at the Bothaville QC for selected climate scenarios

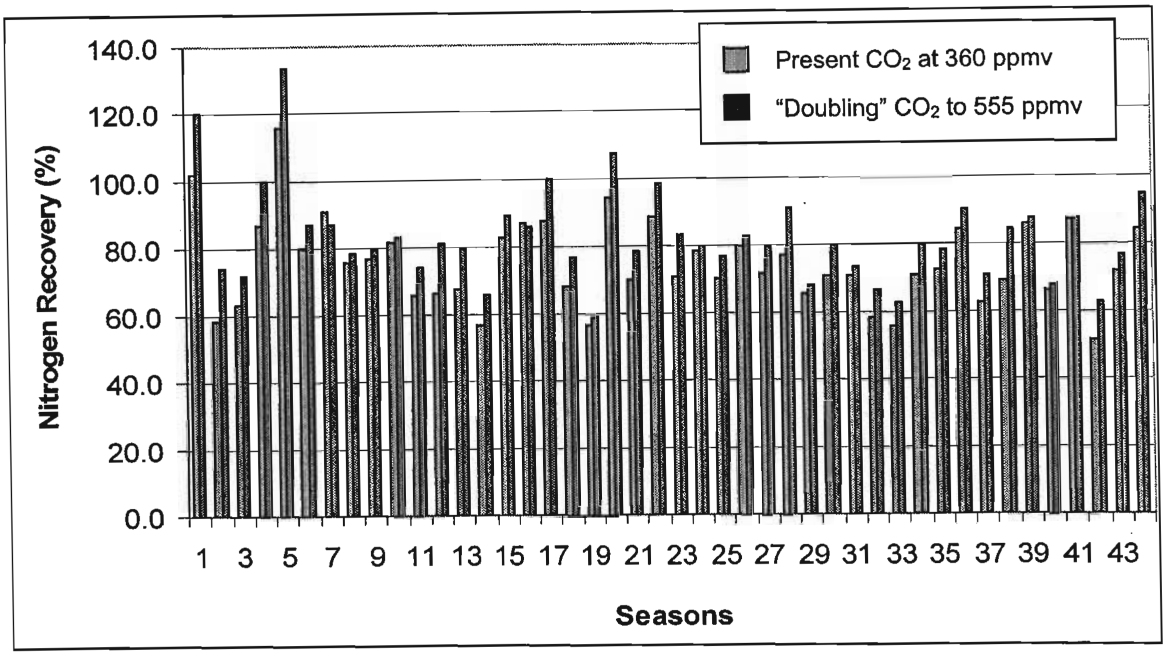


Figure 7.3.8 Comparison of nitrogen recovery over 44 seasons at the Bothaville QC for present CO_2 levels and an effective doubling of atmospheric CO_2 concentrations

The highest soil organic nitrogen loss occurs with a doubling of CO_2 concentrations in combination with either a 3°C increase in temperature or a 10% increase in rainfall (Figure 7.3.7). Higher temperatures and increased rainfall leads to an increase in microbial activity in the soil and accelerates the breakdown of organic matter, and thereby increasing the readily available nitrogen in the soil to the plant. The effective doubling of CO_2 will increase plant growth and increase the use of nitrogen from the soil. The nitrogen recovery level, i.e. how much nitrogen is being used compared with that added to the system, is high (Figure 3.7.8). In 41 out of 44 seasons a doubling of CO_2 leads to a higher percentage of nitrogen being used. In some years the figure is above 100%, implying that more nitrogen is being used by the crop than is added into the system for that particular year.

7.3.3 Frankfort (medium rainfall, QC C83M)

Mean grain yield over 44 seasons for the Frankfort QC is 4 274 kg/ha for present climate and 5 170 kg/ha with an effective doubling of atmospheric CO_2 concentrations. A doubling of CO_2 resulted in increased grain yield, in 35 out of 44 of the seasons simulated (Figure 7.3.9). For both climate scenarios the yield was below 1 000 kg/ha in one year and below the break-even value of 3 000 kg/ha in 9 seasons out of the 44. The mean grain yield is below the break-even value for seasons 1-3 even with an increase in CO_2, while the biggest differences in yield for the two climate scenarios occur when the present yield is between 2 500-3 500 kg/ha. In these seasons favourable environmental conditions in terms of rainfall and temperature exist, which enable the plant to be responsive to CO_2 enrichment. In higher rainfall years the crop appears to be less receptive to increases in CO_2 levels.

In this catchment a doubling of CO_2 and a temperature increase of 2°C causes the maize yield to increase 18 out of 44 seasons (Figure 7.3.10). An increase in temperature negatively affects the mean grain yield results in the Frankfort QC. If the temperature increases by 1°C coupled with a CO_2 doubling, then the yield is higher than for the present climate. If the temperature increase is higher than that, then it counteracts the benefit to the crop of the CO_2 increase.

The yield variability at Frankfort increases with the +2°C scenario and also with a reduction in rainfall of 10% (Table 7.3.4). Yield variability reduces with those scenarios that have $2xCO_2$ or an increase in rainfall of 10%. The scenario which combines an effective doubling of CO_2 with a temperature rise and a reduction in rainfall ($2xCO_2$+2°C -10% rainfall), sees the positive physiological effects of CO_2 enrichment reduced due to less rainfall and an increase in temperatures. At higher temperatures the crop could be experiencing higher rates of respiration which negate the benefit of an enhanced rate of photosynthesis that is a characteristic of higher levels of CO_2 in the atmosphere (Rosenzweig and Hillel, 1993).

A 10% reduction in rainfall would result in a smaller loss in soil organic nitrogen than a 10% increase (Figure 7.3.11). An increase in temperature by 3°C in addition to an effective doubling of CO_2 causes the greatest simulated loss of organic matter when compared with losses under present climate conditions. The use of an optimum planting strategy has resulted in high nitrogen recovery for the system (Figure 7.3.12). In 26 out of 44 seasons simulated an effective doubling of CO_2 produces a high nitrogen recovery figure for the agro-ecosystem.

Table 7.3.4 Mean yields and coefficients of variation of yields over 44 seasons for the Frankfort QC

Frankfort QC		
Climate Scenario	Mean Yields (kg/ha)	CV of yields (%)
Present Climate	4 274.3	46.8
2xCO_2	5 170.1	34.7
Temperature + 2°C	2 966.8	58.5
2xCO_2 +1°C	4 641.5	42.7
2xCO_2 +2°C	3 996.2	45.3
2xCO_2 +3°C	3 492.3	42.8
2xCO_2-10% rainfall	4 794.5	39.0
2xCO_2 +10% rainfall	5 377.6	31.2
Plus 10% rainfall	4 127.0	44.2
Minus 10% rainfall	3 347.5	53.5
2xCO_2 + 2°C +10% rainfall	4 172.3	41.0
2xCO_2 + 2°C -10% rainfall	3 714.0	51.6

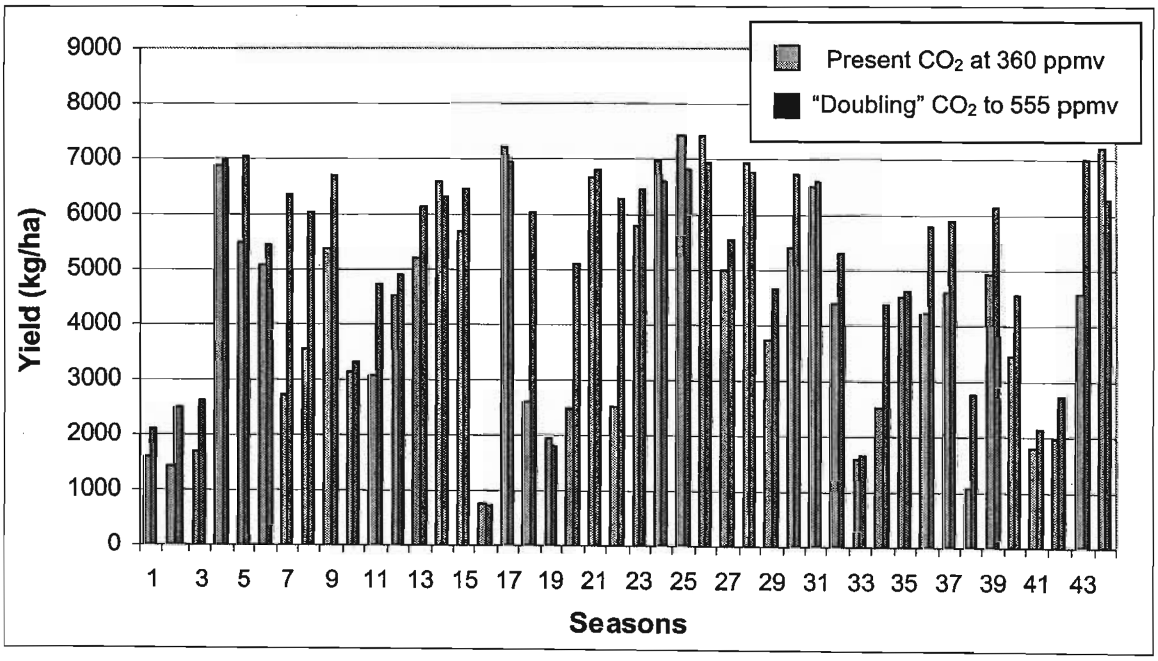


Figure 7.3.9 The influence on maize yield of an effective doubling of atmospheric CO_2 concentrations for the Frankfort QC

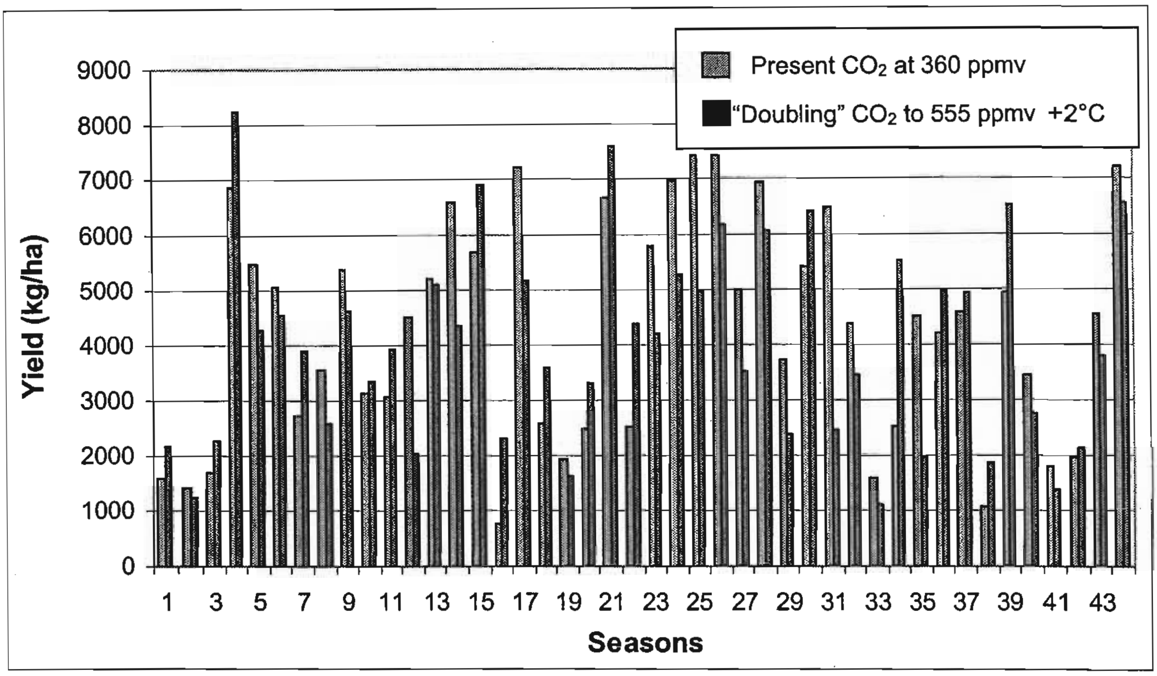


Figure 7.3.10 The influence on maize yield of an effective doubling of atmospheric CO_2 concentrations and a 2°C increase in minimum and maximum temperatures for the Frankfort QC

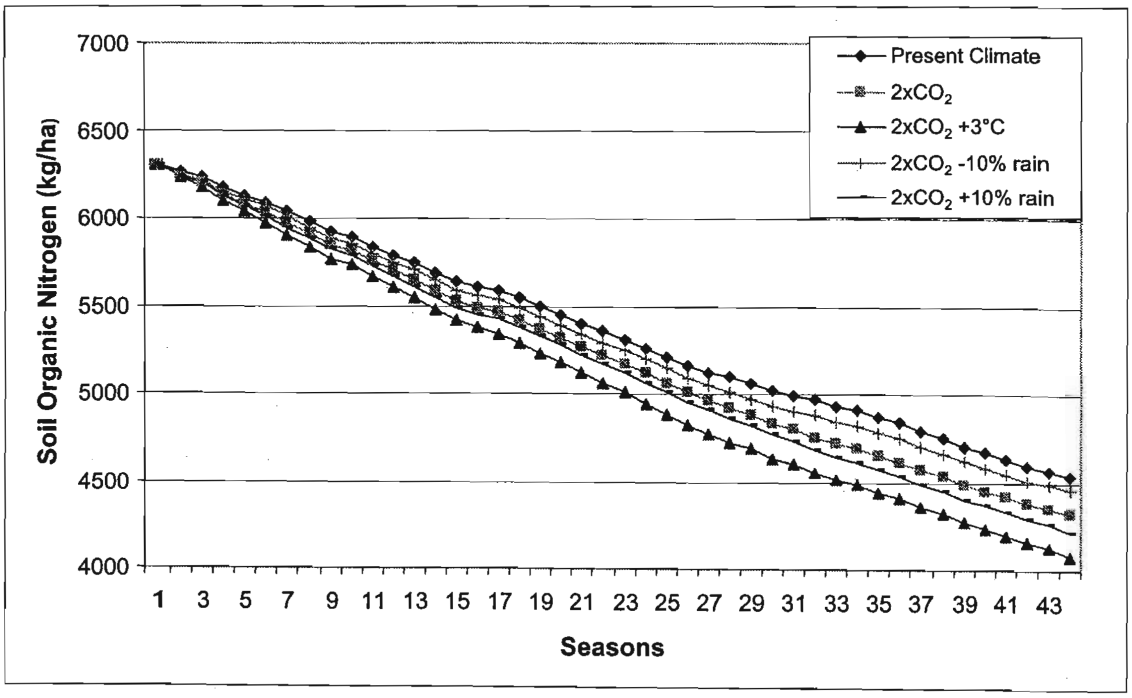


Figure 7.3.11 Decreases in soil organic nitrogen levels over 44 seasons at the Frankfort QC for selected climate scenarios

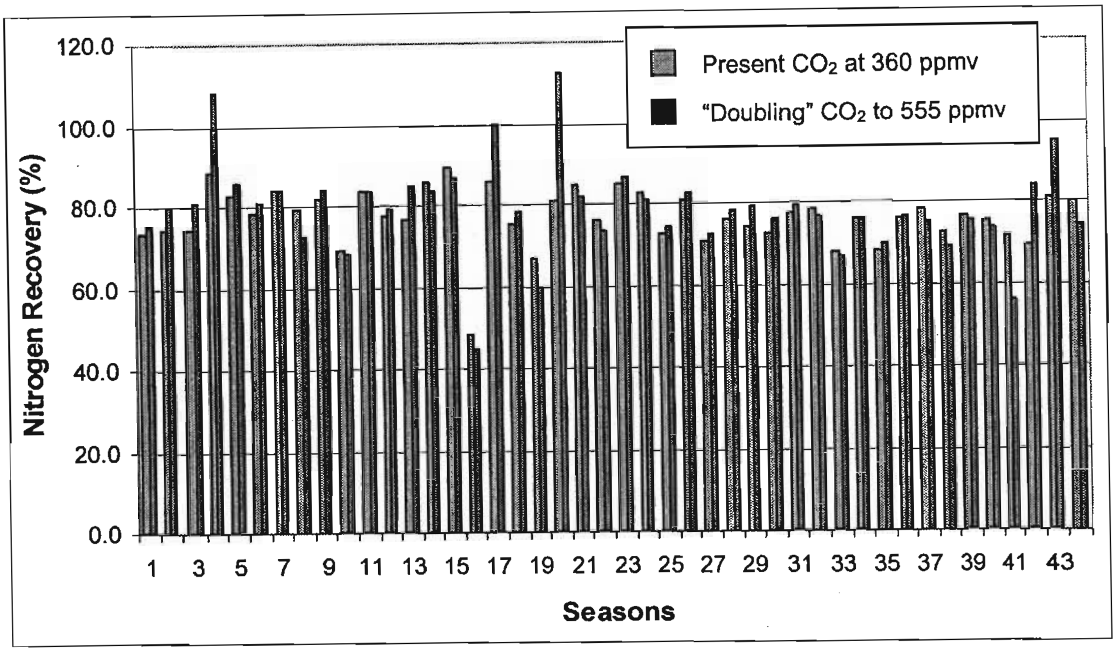


Figure 7.3.12 Comparison of nitrogen recovery over 44 seasons at the Frankfort QC for present CO_2 levels and an effective doubling of atmospheric CO_2 concentrations

7.3.4 Ermelo (wet, QC C11F)

The average yields over 44 seasons at the Ermelo QC are 3 970 kg/ha for present climate and with an effective doubling of atmospheric CO_2 concentrations the yield increases to 5 317 kg/ha. An increase in yield was recorded in 40 out of 44 seasons simulated with a CO_2 increase (Figure 7.3.13). The grain yield falls below the break-even threshold in 19 seasons out of 44 with the present climate compared with only 10 times when atmospheric CO_2 is increased to 555 ppmv. In seasons 8-10 the yield is below 3 000 kg/ha, with the yield falling below 2 000 kg/ha on a further five occasions. The largest variation in yield between the two scenarios occurs when yield under present climate conditions is around 4 000 kg/ha particularly in Seasons 5, 17, 25 and 30. The environmental conditions exist in these years that permit the crop to increase biomass accumulation, as the transpiration feedback is effective. In drier years, typified by low yields, the soil moisture is low and the transpiration feedback is ineffective; so the crop is unable to take advantage of the CO_2 enriched atmosphere. In high rainfall years such as Seasons 10 and 31, when yields are over 6 000 kg/ha under present conditions, the benefits of a doubling of CO_2 are not as striking.

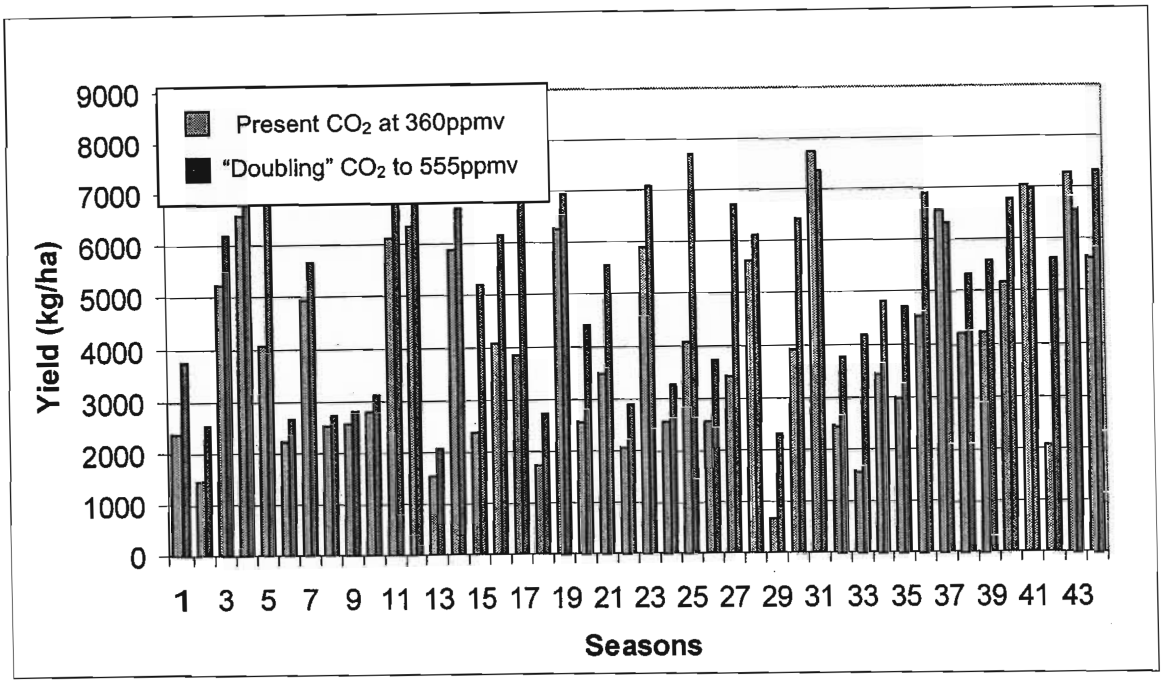


Figure 7.3.13 The influence on maize yield of an effective doubling of atmospheric CO_2 concentration for the Ermelo QC

With a doubling of CO_2 plus a temperature increase of 2°C the maize yield increases 33 out of 44 seasons (Figure 7.3.14). Although the grain yield increases in most seasons, the mean grain yield is lower with the present climate. If a temperature increase is coupled with a doubling of CO_2 the negative impact of the temperature increase is outweighed by the benefit of the CO_2 increase to the plant.

It is noteworthy that the yield variability is reduced at the Ermelo QC with those scenarios that have an effective doubling of CO_2, whether by itself or in combination with other drivers (Table 7.3.5). The only climate scenario modelled that increases yield variability is a reduction in rainfall of 10%. However, a temperature increase does result in an increase in soil organic nitrogen loss in this wet QC, as illustrated in Figure 7.3.15.

Table 7.3.5 Mean yields and coefficients of variation of yields over 44 seasons for the Ermelo QC

Ermelo QC		
Climate Scenario	Mean Yields (kg/ha)	CV of yields (%)
Present Climate	3 970.9	46.5
$2xCO_2$	5 317.9	33.5
Temperature + 2°C	3 880.7	40.6
$2xCO_2$ +1°C	5 410.8	27.5
$2xCO_2$ +2°C	5 332.4	26.4
$2xCO_2$ +3°C	4 845.2	30.3
$2xCO_2$ -10% rainfall	4 853.3	36.0
$2xCO_2$ +10% rainfall	5 874.0	28.2
Plus 10% rainfall	4 104.5	43.2
Minus 10% rainfall	3 123.6	49.7
$2xCO_2$ + 2°C +10% rainfall	5 494.8	23.0
$2xCO_2$ + 2°C -10% rainfall	4 979.1	30.4

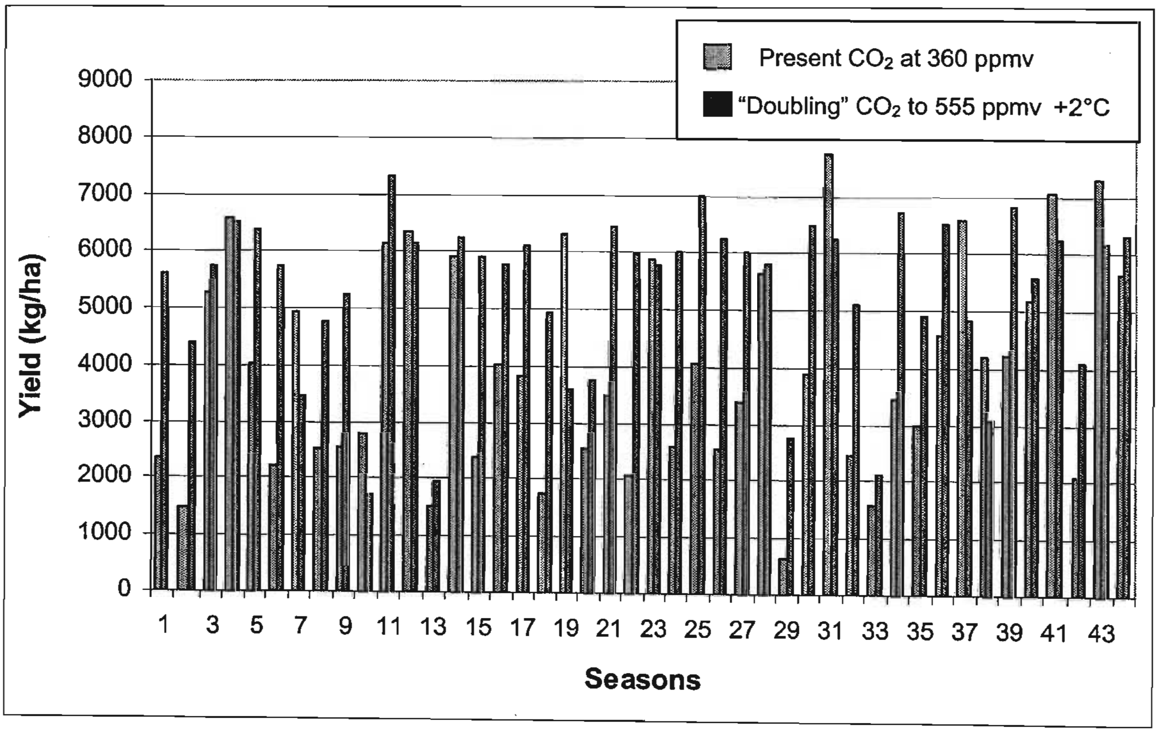


Figure 7.3.14 The influence on maize yield of an effective CO_2 doubling of atmospheric CO_2 concentrations and a 2°C increase in minimum and maximum temperature for the Ermelo QC

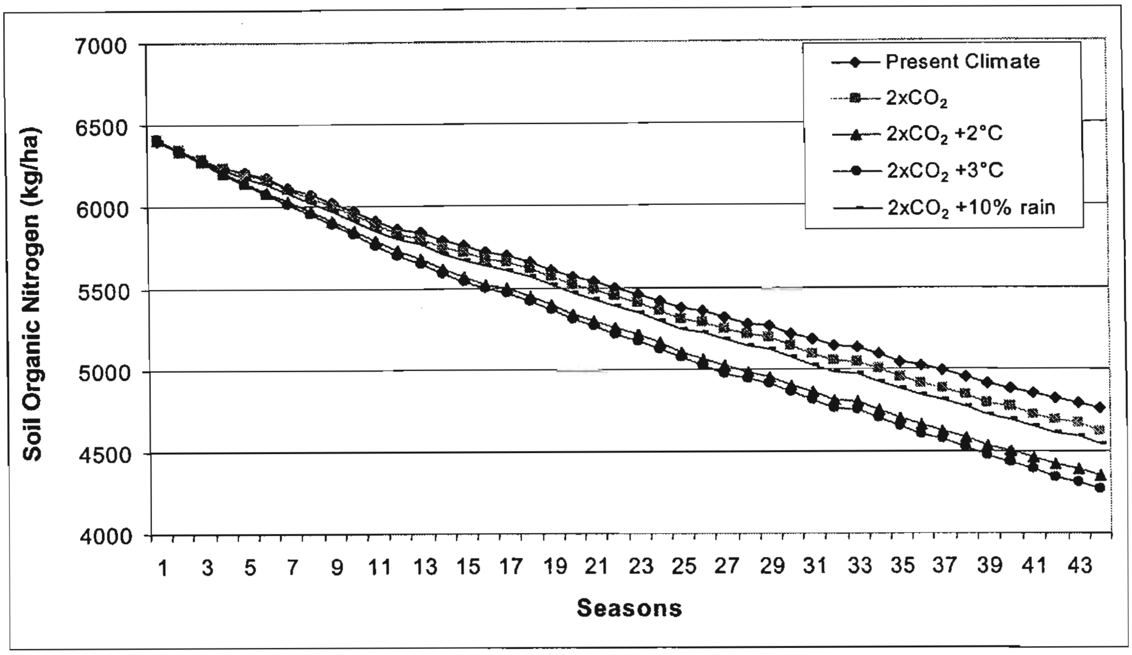


Figure 7.3.15 Decreases in soil organic nitrogen levels over 44 seasons at the Ermelo QC for selected climate scenarios

The higher MAP and increase in temperature results in a faster breakdown of organic matter and it is either used by the crop or leached from the soil. With just an increase in CO_2 the nitrogen recovery for the system increases in 41 out of 44 seasons simulated.

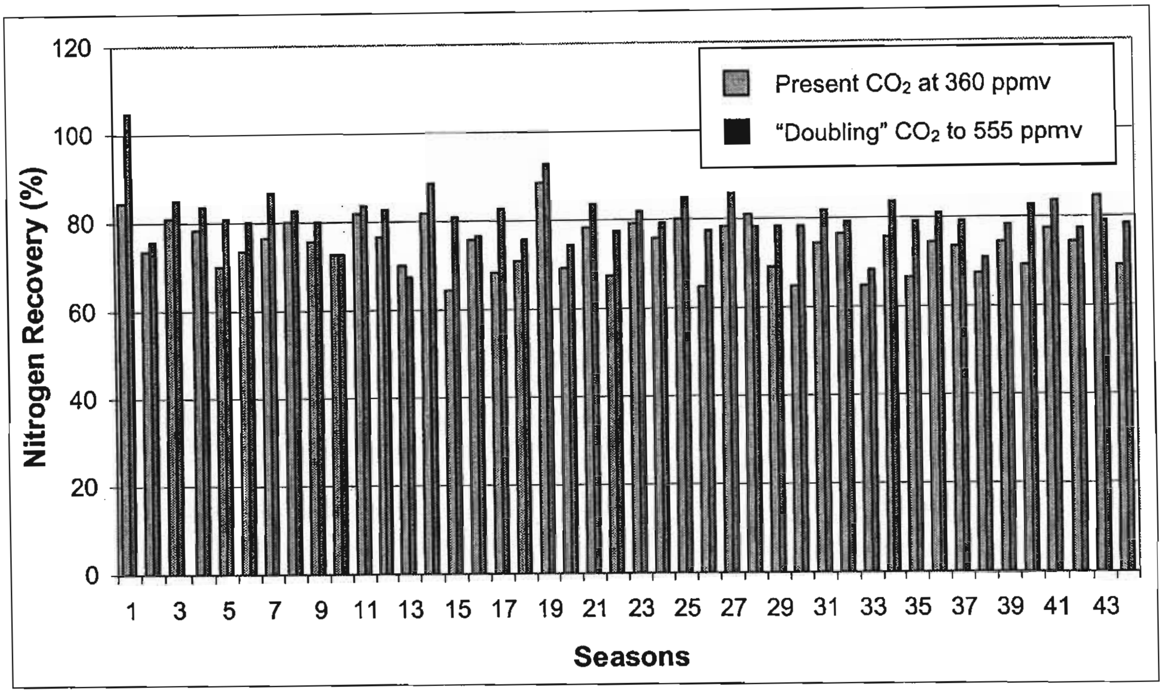


Figure 7.3.16 Comparison of nitrogen recovery at the Ermelo QC over 44 seasons for present CO_2 levels and an effective doubling of atmospheric CO_2 concentrations

7.3.5 Piet Retief (very wet, QC W51C)

Piet Retief has the highest MAP (903 mm) of the five QCs selected for this study and it is located on the eastern fringe of the Highveld region. On average the yields increase by 300 kg/ha from 6 114 kg/ha to 6 406 kg/ha with a doubling of atmospheric CO_2. In only 18 of the 44 seasons modelled the yields are higher with an effective doubling of CO_2 (Figure 7.3.17). Grain yields fall below the break-even figure of 3 600 kg/ha on five occasions with present climate and twice when the CO_2 concentration is increased to 555 ppmv. The biggest positive impact on yields is for the years when there is low rainfall. The largest variation in yield between these scenarios occurs when the yield is around 3 000 kg/ha under present climate conditions. It is in these lower rainfall years at Piet Retief QC that the doubling of atmospheric CO_2 benefits the crop, and where the transpiration feedback in most noticeable.

In the Piet Retief catchment a doubling of CO_2 plus a temperature increase of 2°C produces maize yield increases in 17 out of 44 seasons (Figure 7.3.18). A rise in temperature even with a doubling of effective CO_2 will have a negative effect on the mean grain yield. The higher temperatures cause the available soil water to reduce and, as a consequence, negatively impacts yield.

Yield variability at Piet Retief is the lowest of the five Quaternary Catchments' assessed, as it is the QC with the highest and most reliable rainfall (Table 7.3.6). The climate scenarios that would reduce the variability even further and also increase the mean yields are the ones that contain an effective doubling of CO_2. However, yield variability increases with a rise temperature or a reduction in rainfall.

Table 7.3.6 Mean yields and coefficients of variation of yields over 44 seasons for the Piet Retief QC

	Piet Retief QC	
Climate Scenario	Mean Yield (kg/ha)	CV of Yields (%)
Present Climate	6 114.3	26.7
$2xCO_2$	6 405.7	15.7
Temperature + 2°C	5 130.5	33.8
$2xCO_2$ +1°C	5 948.8	15.9
$2xCO_2$ +2°C	5 834.5	20.6
$2xCO_2$ +3°C	4 930.9	28.8
$2xCO_2$ -10% rainfall	6 402.0	16.9
$2xCO_2$ +10% rainfall	6 502.8	13.0
Plus 10% rainfall	5 679.1	25.3
Minus 10% rainfall	4 927.1	39.9
$2xCO_2$ + 2°C +10% rainfall	5 755.0	21.6
$2xCO_2$ + 2°C -10% rainfall	5 716.9	24.5

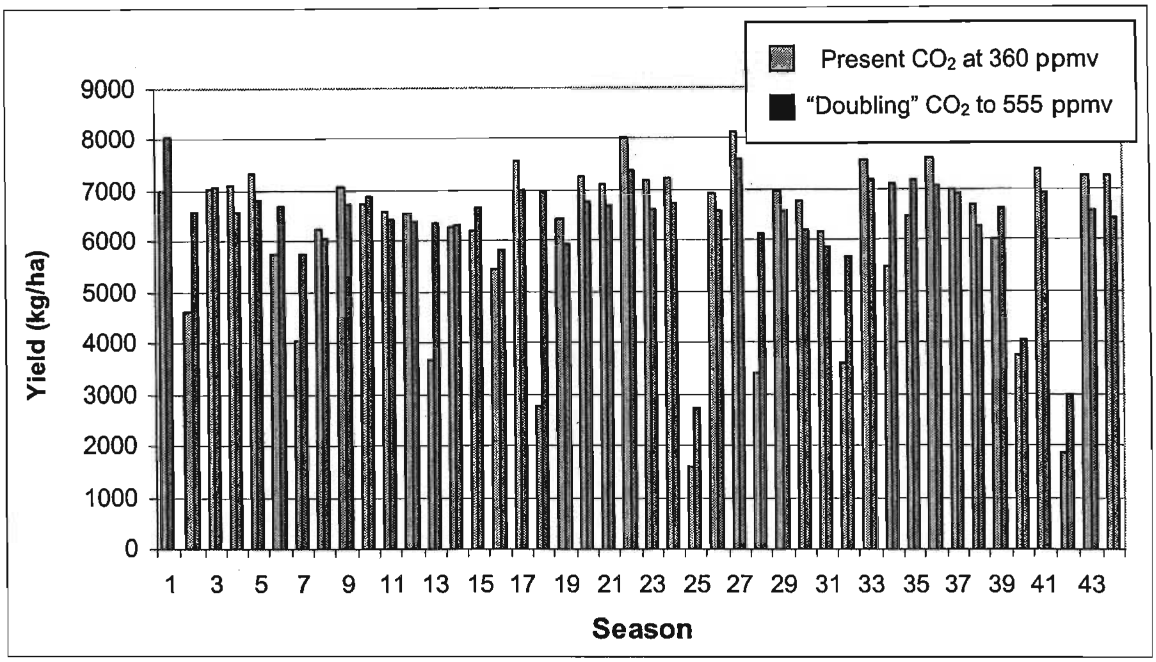


Figure 7.3.17 The influence on maize yield of an effective doubling of atmospheric CO$_2$ concentration for the Piet Retief QC

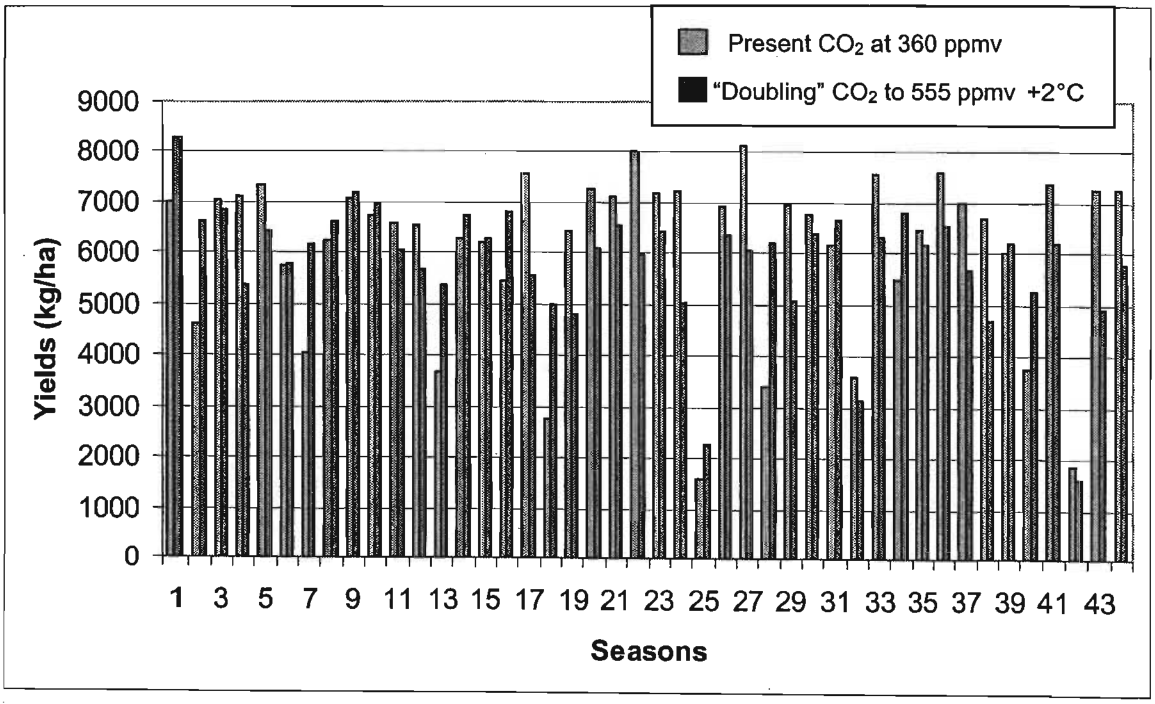


Figure 7.3.18 The influence on maize yield of an effective doubling of atmospheric CO$_2$ concentrations and a 2°C increase in minimum and maximum temperature for the Piet Retief Quaternary Catchment

The soil organic nitrogen losses are highest when climate change scenarios are associated with an increase in temperature. The five scenarios compared with present conditions in Figure 7.3.19 show that an increase in CO_2 will yield organic nitrogen losses from the soil at a faster rate then with the present climate. The recovery of nitrogen added to the soil increases in a 31 out of 44 seasons, but the increase in efficiency is largely small (Figure 7.3.20).

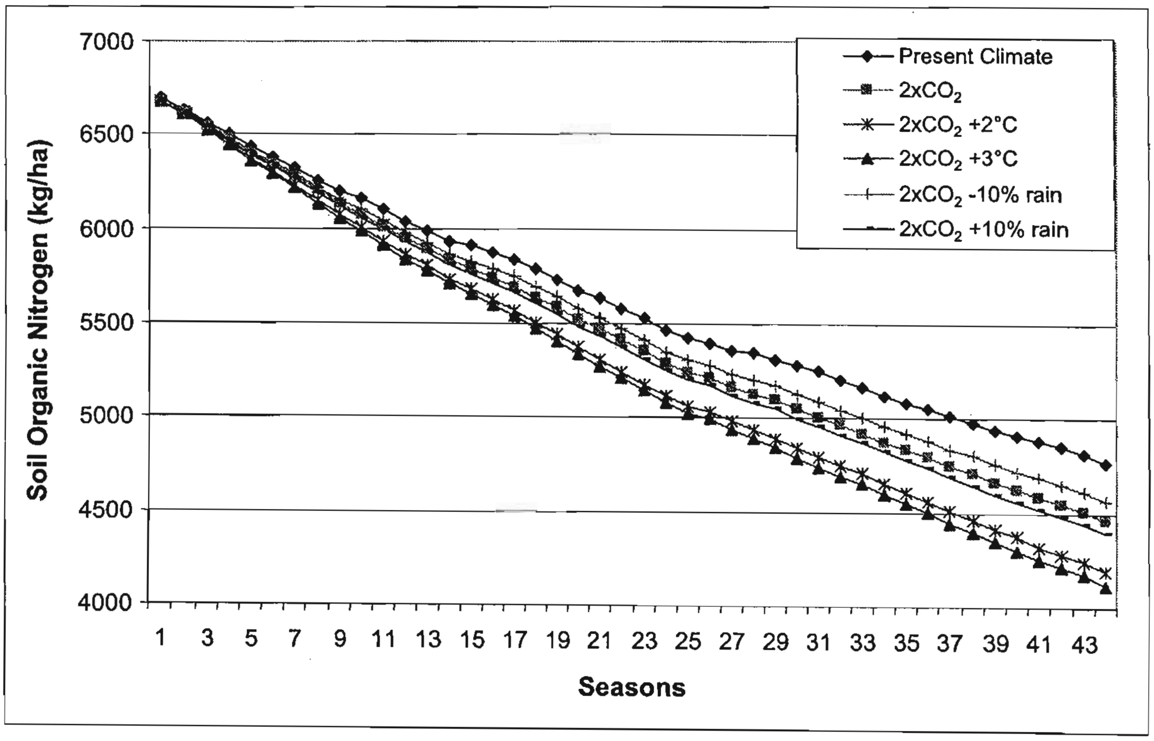


Figure 7.3.19 Decreases in soil organic nitrogen levels over 44 seasons at the Piet Retief QC for selected climate scenarios

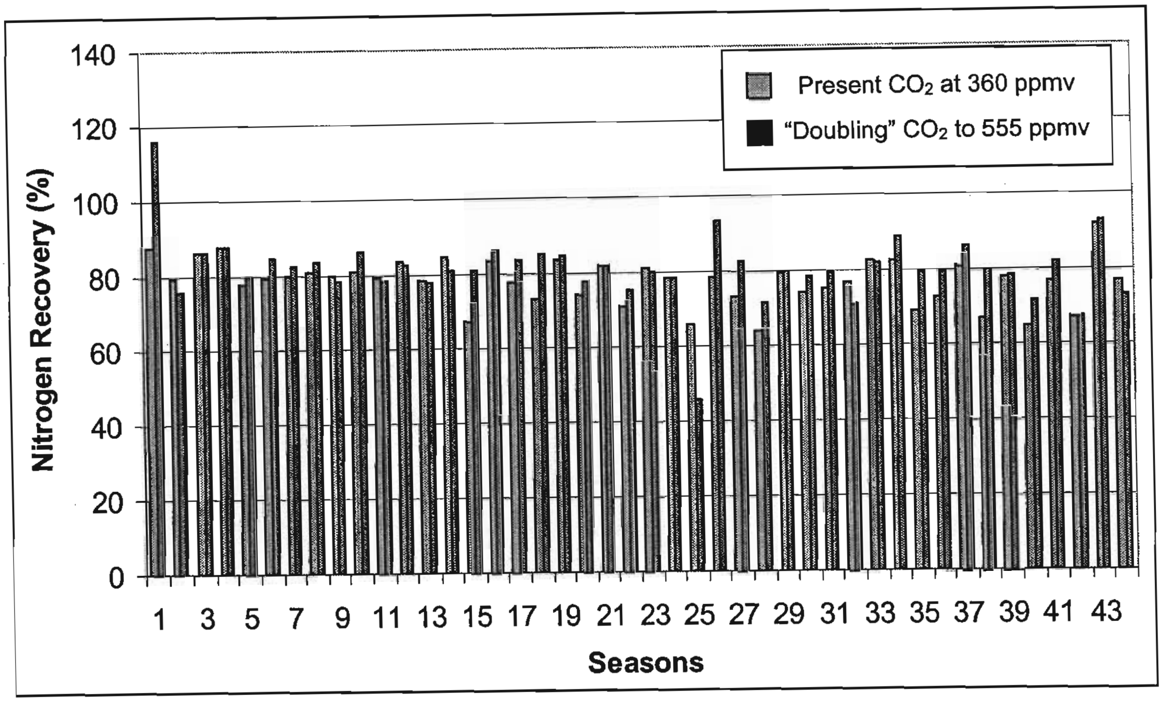


Figure 7.3.20 Comparison of nitrogen recovery at the Piet Retief QC over 44 seasons for present CO_2 levels and an effective doubling of atmospheric CO_2 concentrations

7.4 Management Advice

The intention of this assessment was to investigate how selected agro-ecosystem functions are affected by modifications to the environment. The sustainability goal used for this assessment was:

'for the agro-ecosystems in the Highveld region to continue in the long term, providing quality well-being for farmers and local communities and to maintain ecological integrity' (Section 7.1).

The results in Section 7.3 showed that environmental modifications could have both positive and negative effect on agro-ecosystem sustainability. In general the hypothesised effects on yields and other sustainability indicators of the future climate were shown to be correct. A temperature increase by itself reduces yield, an increase in rainfall increases yields and a decrease in rainfall decreases yield. A maize crop will benefit, especially in terms of mean grain yields, from an effective doubling of CO_2 (Table 7.4.1). However, this benefit can be counteracted when there is a concurrent increase in temperature, particularly of 2°C or more. The effect of the combinations of drivers is of particular interest. The eleven climate scenarios model all showed an increased the rate of depletion of soil organic nitrogen and carbon. The highest losses of soil organic nitrogen (Table 7.4.2) and soil organic carbon (Table 7.4.3) occur where there is a doubling of CO_2 and in an increase in temperature of 2°C or 3°C.

The climate scenario '2xCO_2 -10% rainfall' did not perform as hypothesised. The reduction in rainfall was expected to counteract the positive effect of a CO_2 enriched atmosphere, particular at the drier QCs modelled (i.e. Christiana and Bothaville). However, this was not the case, as a mean yield increase was recorded in each of the five QCs modelled with this scenario. In regard to soil organic nitrogen and carbon losses, differences in response to a '2xCO_2 -10% rainfall' scenario were recorded at the five QCs. At the very dry QC, *viz.* Christiana, there was a reduction in the carbon and nitrogen loss from the soil compared with the present climate. At Bothaville the loss was at similar rate compared with present conditions. At Frankfort and Piet Retief the soil organic nitrogen and carbon depletion were at a higher rate, due in part to the higher MAPs for the QCs. At the Ermelo QC, which under the '2xCO_2 -10% rainfall' scenario records a similar mean yield to Frankfort, but has a higher MAP, the soil organic nitrogen and carbon depletion rate is lower. This could be due to both the soil and temperature differences between the QCs.

The '2xCO_2 +3°C' scenario produces an unexpected result at the Ermelo QC. In the other four QCs the temperature increase of 3°C either cancels out the positive effects of the doubling of atmospheric CO_2 (at Christiana) or has a negative impact on the mean yield (at Bothaville, Frankfort and Piet Retief). However, in the Ermelo QC there is an increase in mean yield of 874 kg/ha over 44 seasons. It is surprising that a large increase of minimum and maximum temperature, even of 3°C, can still have a positive influence on yield if coupled with a doubling of CO_2. The soil organic carbon and nitrogen losses under the '2xCO_2 +3°C' scenario increase at a rate comparable to that of the four other QCs modelled. The depletion rate Ermelo is lower than that at Frankfort for this scenario even though Ermelo has a higher MAP.

A similar response occurs at the Ermelo QC with the '2xCO_2 -10% rainfall +2°C' scenario as with the '2xCO_2 +3°C' scenario, in that the rainfall and temperature changes would be expected to cancel out the positive impacts of the increase in CO_2, but instead a mean yield increase of 1008 kg/ha is recorded when compared with present conditions. The increase in loss of soil organic carbon and nitrogen at the Ermelo QC is comparable to that other of the other QCs modelled under this scenario.

Table 7.4.1 Mean grain yields over 44 seasons for five QCs under different climate scenarios

Climate Scenario	**Christiana (kg/ha)**	**Bothaville (kg/ha)**	**Frankfort (kg/ha)**	**Ermelo (kg/ha)**	**Piet Retief (kg/ha)**
Present Climate	2 217	3 394	4 274	3 971	6 114
$2xCO_2$	2 731	4 281	5 170	5 318	6 406
Temperature + 2°C	1 984	2 435	2 967	3 881	5 131
$2xCO_2$ +1°C	2 736	3 700	4 642	5 411	5 949
$2xCO_2$ +2°C	2 561	3 326	3 996	5 332	5 834
$2xCO_2$ +3°C	2 383	2 986	3 492	4 845	4 931
+10% Rainfall	2 346	2 983	4 127	4 104	5 679
-10% Rainfall	1 904	2 552	3 346	3 124	4 927
$2xCO_2$ -10% Rainfall	2 424	3 797	4 795	4 853	6 402
2xCO2 +10% Rainfall	2 967	4 325	5 378	5 874	6 503
$2xCO_2$ +10% Rainfall +2°C	2 722	3 799	4 172	5 495	5 755
$2xCO_2$ -10% Rainfall +2°C	2 175	3 061	3 714	4 979	5 716

Figure 7.3.1 revealed that positive environmental conditions in terms of yield might not necessarily be beneficial in terms of sustainability of the agro-ecosystem. The scenarios '$2xCO_2$ +10% rainfall' and '$2xCO_2$ +10% Rainfall +2°C' both increase the soil organic nitrogen and carbon depletion rates, although an increase in yield is also gained. With this scenario the stakeholders concerned would need to decide if the increase in yield was worth the loss in soil quality in the long term and whether ecological integrity of the agro-ecosystem and other ecosystems functions and services would be impaired or damaged. It could be argued that any substantial increase in yield would increase the farmer and community well-being. However, stakeholders would need to consider tradeoffs between increasing yield and maintaining agro-ecosystem integrity.

It is noteworthy that a very dry QC such as Christiana does not have an improved sustainability likelihood with a scenario of a doubling of CO_2 and a 10% increase in rainfall. Although there is an increase in the mean grain yield, there is increased runoff and increase in the loss of soil organic nitrogen and carbon, giving the Christiana QC reduced sustainability likelihood. In reality this climate scenario should generally be highly beneficial to an agro-ecosystem, therefore management changes could be made to take advantage of such favourable climate conditions. The thresholds assigned to Christiana are from existing literature (Durand and du Toit, 1999; Arshad and Martin, 2002). The results for the '$2xCO_2$+10% rainfall' scenario illustrate the problem of assigning weights and measures for sustainability indicators. In regard to sustainability and the results obtained at the Christiana QC, stakeholders would need to consider the tradeoffs concerning the environmental and health impacts of agricultural output. Not all outcomes from the agro-ecosystem need to be viewed as tradeoffs, because win-win cases can occur, for example, a form of conservation tillage could be employed which could help in reducing runoff and simultaneously reduce the rate of loss of organic nitrogen and carbon from the soil while maintaining yield levels.

Table 7.4.2 Percentage changes in simulated soil organic nitrogen levels over 44 seasons for five QCs under different climate scenarios

Climate Scenario	**Christiana (%)**	**Bothaville (%)**	**Frankfort (%)**	**Ermelo (%)**	**Piet Retief (%)**
Current	-21.2	-27.3	-27.9	-25.5	-28.8
$2xCO_2$	-22.9	-28.8	-31.4	-27.8	-33.2
Temperature + 2°C	-26.7	-31.5	-32.9	-30.5	-34.3
$2xCO_2$ +1°C	-24.6	-30.2	-33.1	-30.3	-35.9
$2xCO_2$ +2°C	-26.0	-32.1	-34.1	-32.2	-37.2
$2xCO_2$ +3°C	-27.2	-33.3	-35.3	-33.4	-38.3
+10% Rainfall	-24.5	-30.4	-30.6	-28.0	-31.0
-10% Rainfall	-20.8	-26.8	-27.3	-25.0	-27.9
$2xCO_2$ -10% Rainfall	-20.9	-27.4	-29.2	-26.3	-31.6
$2xCO_2$ +10% Rainfall	-25.0	-30.9	-33.0	-29.1	-34.2
$2xCO_2$ +10% Rainfall +2°C	-35.5	-46.9	-48.6	-44.5	-52.5
$2xCO_2$ -10% Rainfall +2°C	-24.3	-31.1	-32.8	-30.5	35.6

The organic nitrogen and carbon losses are less severe in those Quaternary Catchments with the lower MAPs, namely Christiana and Bothaville. To limit soil organic nitrogen and carbon losses, forms of tillage other than conventional could be used. A reduced tillage or no-till system would reduce organic matter loss and help prevent soil erosion. A negative aspect of a no-till system is the increased used of herbicides. Alternatives to this method of weed control could be investigated.

Table 7.4.3 Percentage changes in simulated soil organic carbon levels over 44 seasons for five QCs under different climate scenarios

Climate Scenario	**Christiana (%)**	**Bothaville (%)**	**Frankfort (%)**	**Ermelo (%)**	**Piet Retief (%)**
Current	-21.3	-25.8	-27.7	-24.6	-27.9
$2xCO_2$	-23.0	-27.4	-29.7	-26.2	-32.4
Temperature + 2°C	-26.2	-30.6	-31.3	-29.2	-33.8
$2xCO_2$ +1°C	-24.6	-29.0	-31.9	-29.7	-35.3
$2xCO_2$ +2°C	-25.1	-30.6	-32.8	-30.8	-36.8
$2xCO_2$ +3°C	-26.2	-32.3	-34.4	-32.3	-36.8
+10% Rainfall	-24.6	-29.0	-29.7	-26.2	-29.4
-10% Rainfall	-19.7	-25.8	-27.7	-24.6	-26.5
$2xCO_2$ -10% Rainfall	-19.7	-25.8	-28.1	-24.6	-30.9
2xCO2 +10% Rainfall	-24.6	-30.6	-31.3	-27.7	-33.8
$2xCO_2$ +10% Rainfall +2°C	-34.7	-45.7	-46.8	-42.9	-50.0
$2xCO_2$ -10% Rainfall +2°C	-23.0	-30.6	-31.2	-29.2	-35.3

As discussed in Section 6.4, there appears to be limited scope for up-scaling from the Quaternary Catchment scale to the regional level. Part of managing risk in agriculture consists of coping with the inter-seasonal variability of production. At the regional level (Chapter 5), governments have to ensure an adequate food supply to the population of all sectors of society. At the household level it may be crucial for the farmer to minimise the fluctuations in household income over time, or to maintain (or increase) a particular wealth level and nutritional status (Thornton and Wilkens, 1998). Sustainability of the smallholder agro-ecosystem and its effects on household food security are discussed in Chapter 8.

8 ASSESSMENT OF AGRICULTURAL SUSTAINABILITY FOR SMALLHOLDER AGRO-ECOSYSTEMS: A CASE STUDY IN KWAZULU-NATAL, SOUTH AFRICA

The population in sub-Saharan Africa is predicted to increase to over one billion by 2025 (Inocencio *et al.*, 2003). To meet the food requirements of the population increase and achieve food security by 2015, agricultural production would need to increase by 6 per cent per annum (Inocencio *et al.*, 2003). These advances will need to be made with the added problem of climate change. Climate change will affect the lives of people in many ways, particularly in Africa where many poor smallholders depend on agriculture for their livelihood and where there are few alternatives of earning a living (Jones and Thornton, 2003).

The need to improve smallholder rainfed maize production in a sustainable manner is important in South Africa as maize is a staple food. However, sustainable maize production is not only a question of yields, but of government policy on agriculture, protection of the environmental resource base, social welfare, and the livelihoods of farmers and rural and urban communities. Sustainability for the small-scale farmer raises questions of equity, economic viability and household food security. It is valuable to investigate sustainability at the field scale using both field data and model simulations for a better understanding of food security at the household level. At the household level it is crucial for the farmer to minimise the fluctuations in household income over time, as well as to maintain or increase a particular wealth level and nutritional status (Thornton and Wilkens, 1998). The small-scale farmer is more susceptible to climate variability and its impact on yields, and to shocks to the agro-ecosystem.

Small-scale maize production is often characterised by low yields, which are often significantly lower than the potential for the land. Agricultural research and development projects have often failed to reverse this. The applied research that is often carried out seeks the optimum management system for a crop in a specific environment. According to Collinson (2001; p. 29) the reasons for this type of research failing are that:

- 'It fails to recognise that physical productivity is never the evaluation criterion used by farmers. Improved labour and capital productivity are their primary goals; they recognise higher yield as a means to these ends;

- It fails to recognise that beyond ecology, both economic and cultural diversity also create discrete environments which require accommodation in technology choice and design.

Intensification of cropping practices and the increased productivity of small-scale farming is required in order to produce food for an increasing population. However, this should be pursued in a manner which uses sustainable levels of external input in combination with local resources and knowledge (Smith *et al.*, 2004). This means that at the farm level many of the decisions made would need to consider the trade-offs between different biophysical and socio-economic objectives (Kropff *et al.*, 2001). However, in assessing the socio-economic component of small-scale agro-ecosystems, problems are encountered when incorporating individuals, possibly from different backgrounds, and assuming that they will all react in the same way or that they will all act in a unique way (Edwards-Jones *et al.*, 1998).

In order to assess the sustainability of small-scale agro-ecosystems the goal orientated system utilised in Chapter 5, 6 and 7 will be employed. The steps in the adapted goal orientated system are:

- Identifying the goal (Section 8.2)
- Sustainability modelling (Section 8.3)
- Evaluation (Section 8.4) and
- Management advice (Section 8.5).

The aim of this assessment is to investigate sustainability at the small-scale agro-ecosystem level by simulating the system under different management strategies and climate regimes. The agro-ecosystem that has been simulated is at Potshini village, which is about 10 km from the town of Bergville in the western-central region of KwaZulu-Natal province, South Africa (Figure 8.1.1).

8.1 Background

The Bergville district of KwaZulu-Natal (Figure 8.1) is an area where maize is produced by both commercial farmers and those emerging farmers who own smaller plots of land and have limited access to external inputs. Maize production forms part of the smallholders' livelihood. Other work, if available, is often taken and families are also reliant on those in the family who are able to claim a pension. The majority of the small-scale farmers in the Bergville area are women. This is indicative of small-scale agriculture in much of Africa where 60-80% of the agricultural labour force is female (Williams, 1994).

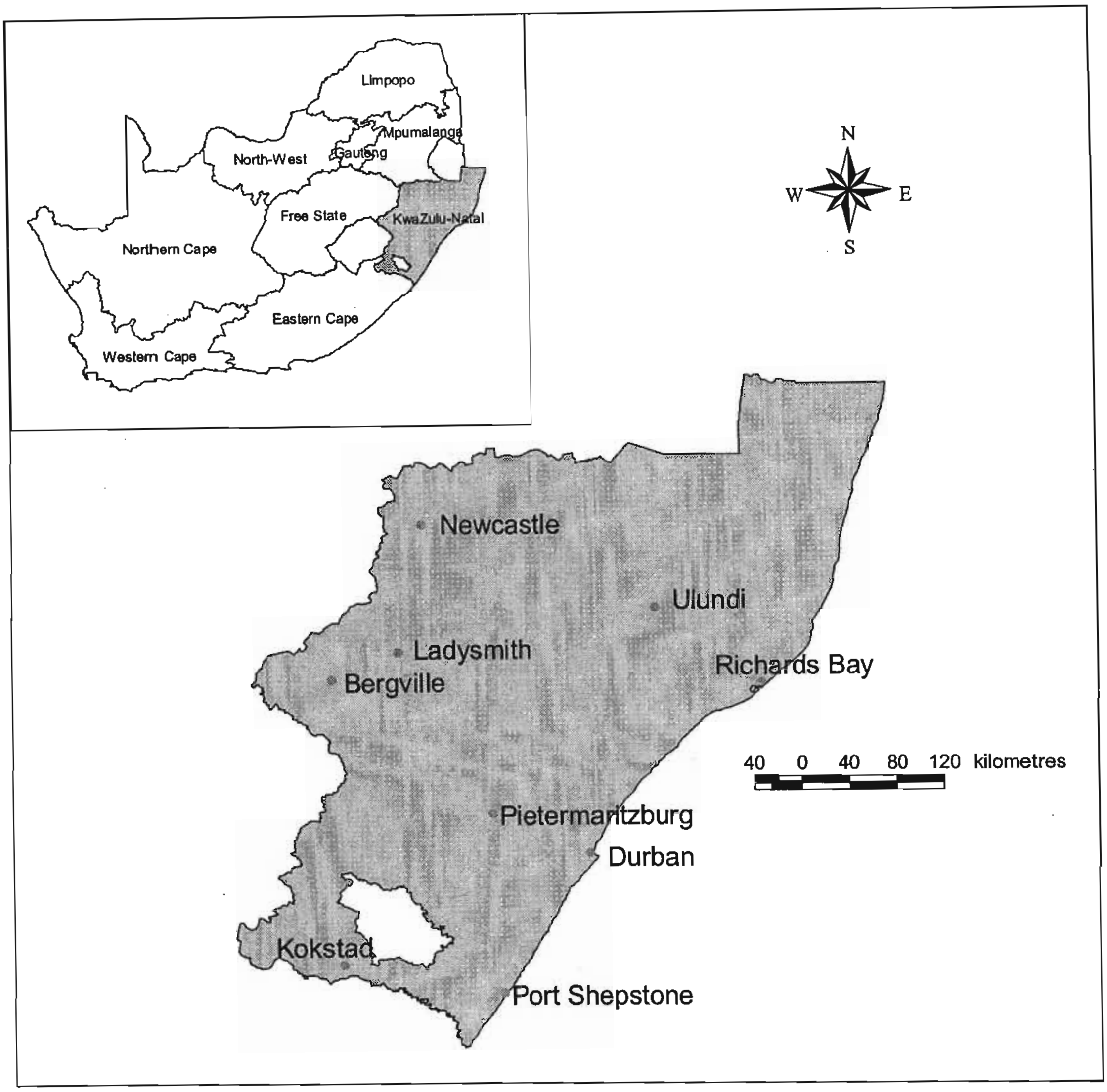


Figure 8.1.1 Location of Bergville in KwaZulu-Natal, South Africa

Even though Bergville is situated outside of the Highveld this author thought the choice of Bergville for modelling smallholder agro-ecosystems was a valid one as upscaling the results from the main trial site was not an aim of this thesis. The agricultural development work run by the ARC-ISCW in the Bergville area through the LandCare project allowed comparisons of modelling work with field trials to be made. Soils data and yield results were made available to this author, which allowed simulated yields to be compared with actual yields.

The small-scale farmers in the area generally have around one hectare of land to farm and this is situated close to their homestead. A photo of a typical homestead and field at Potshini, near Bergville, KwaZulu-Natal, South Africa is shown in Figure 8.1.2. The soils in the area are highly acidic. Therefore, extensive liming is required to improve yields (Smith *et al.*, 2004). Although one of the local varieties of maize (landrace maize) has a high tolerance to acidic soils, liming is still required. The soil in the agro-ecosystem simulated is an Avalon soil form with a depth of 900 mm (Smith *et al.*, 2004). Bergville is in South Africa's summer rainfall area (October-March) and with rainfed agriculture the planting date for maize is around mid-November. The altitude for the site is 1150 m above sea-level and it has a MAP of 684 mm (Lynch, 2004).

Figure 8.1.2 Homestead at Potshini, near Bergville, KwaZulu-Natal, South Africa

This area was chosen to assess sustainability at the farm level as there has been an extensive LandCare project in the area. This has been carried out by the Department of National Agriculture, the Agricultural Research Council's (ARC) Institute for Soil, Climate and Water (ISCW) along with several other ARC institutes, and the School of Applied Environmental Science from the University of KwaZulu-Natal in Pietermaritzburg. These institutions have worked with local farmers to assist them with implementing appropriate land management technologies, which have included conservation tillage, crop rotation and grazing management (Smith *et al.*, 2004). An experimental main trial site for maize used for training purposes by the ARC is shown in Figure 8.1.3.

Figure 8.1.3 Maize (approximately 60 days after planting) at the ARC main trial site at Potshini, near Bergville, KwaZulu-Natal, South Africa (13th January 2004)

8.2 Goal Definition

The World Bank (1986; p. 1) defines food security as 'access by all people at all times to enough food for an active healthy life.' Therefore, the goal definition for smallholder agro-ecosystem sustainability in Potshini should have household food security incorporated into it.

The goal definition used for this assessment is:

'The goal is for smallholder agro-ecosystems in the Potshini area to continue in the long term, providing quality well-being for farmers and local communities and to maintain ecological integrity.'

At the smallholder agro-ecosystem level, the optimisation of resource use is a key issue to achieve the different goals with respect to food supply, income and protection of the environment. This requires an understanding of the interactions between genotype, environment and management options. The objectives set by the farmer and society will determine how these interactions can be optimised (Kropff *et al.*, 2001).

One of the purposes of this evaluation was to examine how the agro-ecosystem functions are affected by modifications to the environment. Any major changes, positive or negative, will have significant bearing on the long-term food security of the village of Potshini.

8.3 Sustainability Modelling

A range of management options was assessed. These options include several types of tillage practice in combination with applications of either inorganic fertiliser or manure. The various management strategies that were modelled are shown in Table 8.3.1 and details of the site at Potshini are shown in Table 8.3.2. The recommended inorganic fertiliser level is that given by Smith *et al.* (2004) for small-scale farmers at the Potshini site near Bergville. The inorganic nitrogen fertiliser used is ammonium nitrate (200 kg/ha). The amount of manure added has a nitrogen content of 67.8 kg N/ha (Lumsden and Schulze, 2004). The plant density for maize was 4.0 plants/m^2 with a row space of 0.90 m (Smith *et al.*, 2004).

Table 8.3.1 Management strategies simulated over 49 seasons at the Potshini trial site near Bergville in KwaZulu-Natal

Treatment	Crop	Tillage Type	Fertiliser Application
1	Maize	No Till	Inorganic
2	Maize	Rip	Inorganic
3	Maize	Disc	Inorganic
4	Maize	Shallow Tine	Inorganic
5	Maize	No Till	Manure
6	Maize	Rip	Manure
7	Maize	Disc	Manure
8	Maize	Shallow Tine	Manure

Table 8.3.2 Details of the trial site at Potshini

Attribute		Source
MAP (mm)	684	Lynch, 2004
Average Maize Yield (kg/ha)	4228	Simulated
Thickness A Horizon (m)	0.24	Quaternary Catchments Database
Thickness B Horizon (m)	0.60	Quaternary Catchments Database
Dominant Soil Texture Class	SaClLm	Quaternary Catchments Database
Heat Units (° days) October-March	2000	Schulze, 1997

The CERES-Maize model version 3.5 is unable to distinguish between effects of different tillage practices on evapotranspiration and root growth of crops. Therefore, du Toit *et al.* (2002a) developed algorithms from extensive field tillage trials at Potchefstroom in South Africa to calculate the soil root growth factor at different soil depths for several tillage practices which they simulated and they then compared simulated yield with actual yield. The algorithms were developed as a function of water extraction patterns measured by time domain reflectometry. The soil growth root factor is one of the input options in the CERES-Maize soil file.

The tillage practices simulated at Potshini consist of disc, rip, no till and shallow tine. The functions for all tillage treatments resemble the form of a half normal distribution. Root length density is expressed in terms of an index, which ranges between zero and one, where Y is the corresponding root density index as determined by soil depth (X) for different tillage treatments (du Toit *et al.*, 2002a). The functions are:

- No-till $Y = (-18.13 - 3.913E{-10} / X) / (-18.13 - 3.913E{-10} * X^{6.437})$
- Rip $Y = (6.76 + 6.142E{-8} / X) / (6.76 + 6.14E{-8} * X^{4.511})$
- Disc $Y = (7.01 + 2.74E{-4} / X) / (7.01 + 2.74E{-4} * X^{2.914})$
- Shallow tine $Y = (12.06 + 1.54E{-5} / X) / (12.06 + 1.54E{-5} * X^{3.709})$

These tillage practices equate, respectively, to forms of conventional tillage, reduced tillage, conservational tillage and reduced tillage (again). Conservation tillage is considered to be any tillage or planting system that maintains at least 30% residue cover of the soil surface after planting (Gold, 1999; Uri, 1999). The conservation tillage practiced at Potshini consists of a no till. Reduced tillage is one that has between 15-30% residue cover after planting. At Potshini this is represented by rip and also by shallow tine ploughing. Conventional tillage types leave less than 15% residue cover after planting (Uri, 1999). The conventional tillage simulated at Potshini consists of a plough and disc.

Yield is impacted by site specific factors which include soil characteristics, local climate conditions and cropping patterns. A change from conventional tillage to conservation tillage system can affect soil characteristics such as structure, organic matter content, and soil microbial populations, which have the potential to increase yield. An increase in the amount of crop residue cover on the soil would have beneficial impacts which include increased organic matter, improved moisture retention and permeability, and reduced nutrient losses from erosion (Uri, 1999).

The management strategies in Table 8.3.1 were modelled for present climate conditions and under plausible climate change scenarios for southern Africa, which were also used in Chapter 7. The climate change scenarios were as follows:

- a doubling of pre-industrial CO_2 atmospheric concentrations to 555 ppmv

- increasing both minimum and maximum daily temperatures by 2°C
- $2xCO_2$ + 1°C minimum and maximum daily temperature increase
- $2xCO_2$ + 2°C minimum and maximum daily temperature increase
- $2xCO_2$ + 3°C minimum and maximum daily temperature increase
- $2xCO_2$ with 10% reduction in rainfall and
- $2xCO_2$ with 10% increase in rainfall.

The different scenarios were modelled over 49 seasons (i.e. 50 years) and modifications to the CERES-Maize input files were performed to model the different climate regimes. The daily rainfall data used were from a climate station situated in Bergville and the daily maximum and minimum temperatures were obtained from the School of BEEH's gridded temperature database (Schulze and Maharaj, 2004). The use of nitrogen fixing crops was not considered as access to genetic coefficients of soya for use in the DSSAT models was limited (Section 6.2). The DSSAT model SOYGRO, which would be used to simulate soya growth, has not undergone the same extensive regional calibration as CERES-Maize.

8.4 Evaluation Strategy

A sustainability index was employed to assess the sustainability of maize production under different management and climate regimes. This was the same index discussed in Chapter 4 with averages calculated for each indicator from values over 49 seasons of simulated maize production. The average value was compared against a critical limit, or threshold value, and was then scored accordingly. The scores for each agro-ecosystem function were summed for the treatment. The result gave a likelihood of sustainability for the agro-ecosystem under a particular management or climate regime. Four options are given for likelihood of sustainability: minimal, low, medium and high.

The break-even yield was set at 3 600 kg/ha for treatments involving inorganic fertiliser. This is the same as for commercial farmers in the eastern Highveld, which also have conditions that are favourable for growing maize (du Toit *et al.,* 1999). For treatments using manure a break-even is more difficult to assess as it will vary hugely from farmer to farmer. However, a level of 2 000 kg/ha was assumed for sustainable maize production.

Results from the sustainability modelling are shown in the tables below and consist of sustainability likelihood, mean yield and the coefficient of variation of yield which is used here as a measure of risk. The mean yield and CV have also been ranked and then multiplied together for each treatment for the different climate regimes. The treatment which has the combination of highest yield with the lowest CV will be ranked 1, i.e. a rank of 1 being the most favourable for sustainability and a score of 8 the least favourable. The procedure for combining mean yield with CV might not always give a unique ranking, but allows for a quick comparison of the effects of tillage practices on yield.

8.4.1 Present Climate Conditions

The results for the four tillage types modelled at Potshini under present climate conditions are shown in Table 8.4.1. When using inorganic fertiliser as the nitrogen input into the system, all four tillage types have medium sustainability likelihood. The simulated yields achieved using inorganic fertiliser are above the break-even level set and the four tillage types have relatively low yield variability. When manure is used as the nitrogen input into the system the mean yield is significantly lower and the yield variability increases over time.

The organic carbon and nitrogen loss from the simulated agro-ecosystem are considerably higher than the losses modelled on a Quaternary catchment scale in Chapter 6. This could be due to the higher average daily temperatures at Potshini during the growing season, coupled with a relatively high MAP for the area (MAP is 684mm for Bergville compared with 704 mm for the Ermelo QC, which had been classed as a "wet QC" in Chapters 6 and 7). Figure 8.4.1 shows the soil organic nitrogen lost from the agro-ecosystem over 49 seasons with constant nitrogen input each season. Under present climate conditions the CERES-Maize crop model shows little difference in the amount of soil organic nitrogen loss between the tillage methods.

The treatments that utilise manure have higher soil organic nitrogen losses than those using inorganic nitrogen. The differences between the losses from the different tillage types are slight, with rip (reduced) tillage having the lowest organic carbon and nitrogen losses under present climate conditions. However, using version 3.5 of CERES-Maize to model differences in organic matter one encounters problems, as the method which is used to distinguish between tillage types was designed primarily to show yield differences (du Toit *et al.*, 2002a).

Table 8.4.1 Agricultural sustainability under different management regimes for present climate conditions

Trt No.	Tillage	Nitrogen Application	Mean Yield (kg/ha)	CV of Yields (%)	Yield/CV Index Ranking	Sustainability Likelihood
1	No till	Inorganic	3 857	36	3	Medium
2	No till	Manure	1 784	74	8	Minimal
3	Rip	Inorganic	4 050	38	2	Medium
4	Rip	Manure	2 121	66	5	Low
5	Disc	Inorganic	4 050	37	1	Medium
6	Disc	Manure	2 032	71	6	Low
7	Shallow tine	Inorganic	4 026	37	4	Medium
8	Shallow tine	Manure	2 000	71	7	Minimal

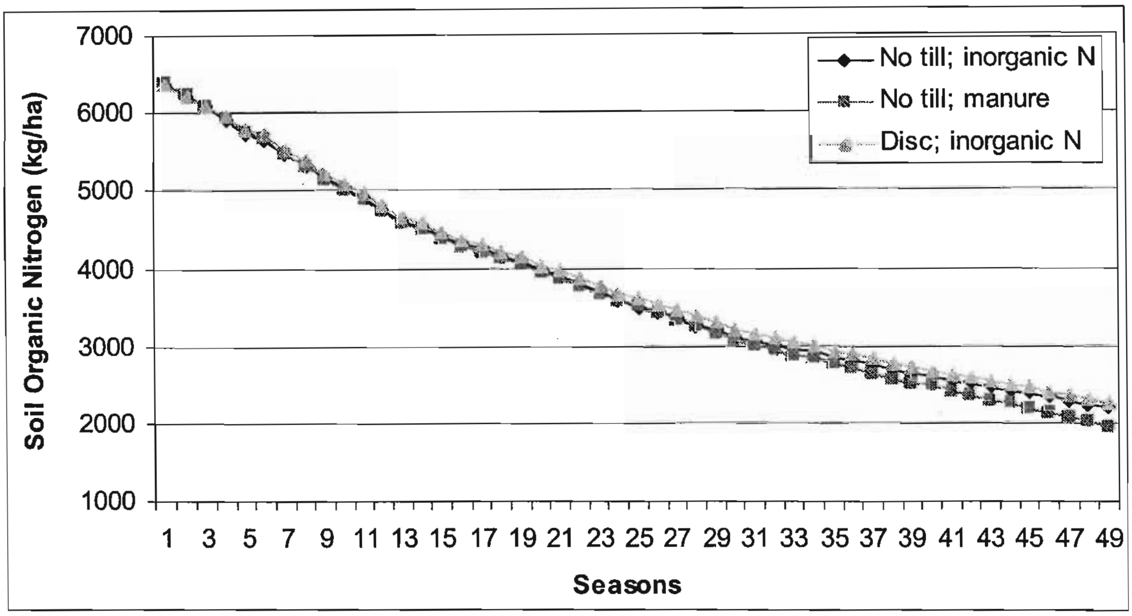


Figure 8.4.1 Soil organic nitrogen levels at Potshini over 49 seasons for different tillage practices and modes of fertiliser application under present climate conditions

The use of this method shows that no till has higher soil organic carbon and nitrogen losses than disc tillage. This is not the case in practice at Potshini, however, as the no till method has been used successfully to maintain organic matter levels (Smith *et al.*, 2004). The yield variability of present day conditions is compared with the yield variability for different climate scenarios in the following sections of this chapter.

8.4.2 Increase in temperature of 2°C

The increase in temperature increases the potential evapotranspiration, and therefore, the intensity of the mid-summer dry spell that often occurs in the Bergville area in January. The result of the mid-summer dry spell is a reduction in yield. A prolonged dry spell at that time of year also appears to reduce the range of yields that occur.

An increase in temperature of 2°C at Potshini results in a drop in yield of ~600 kg/ha for the four treatments using inorganic fertiliser, when compared to yield under present climate conditions (Table 8.4.2). The reduction in yield for those treatments using manure is ~100 kg/ha. The inter-annual variability of yields is reduced for all treatments; however, the largest reductions in CV occur for treatments when manure is used, rather than for inorganic fertiliser. Mean yields for those treatments using manure are much lower than those using inorganic nitrogen. Yields could be improved by using an increased application of manure or switching to another source of adding nitrogen to the soil. Maize could be growing in rotation with soybean, as this is a nitrogen fixing plant. Another option is the use of inorganic fertiliser; however, access to fertiliser would be required long term. The fertiliser should be used in quantities that would not cause a lowering of the groundwater quality in the area, as this is the source of drinking water for the community.

Figures 8.4.2 and 8.4.3 show comparisons of maize yields from two tillage systems, *viz.* ripping and disc tillage, when the form of fertiliser used is manure. The simulations are for present climatic conditions and for a future climate scenario with both maximum and minimum temperatures increased by 2°C. Inorganic fertiliser is not always accessible to the smallholder for reasons such as transport and access to credit.

Table 8.4.2 Agricultural sustainability under different management regimes with an increase in temperature of 2°C (bracketed values denote yields and CV for present conditions)

Trt No.	Tillage	Nitrogen Application	Mean Yield (kg/ha)	CV of Yields (%)	Yield/CV Index Rank	Sustainability Likelihood
9	No till	Inorganic	3 260 (3 857)	34 (36)	4	Medium
10	No till	Manure	1 766 (1 784)	65 (74)	8	Minimal
11	Rip	Inorganic	3 408 (4 050)	34 (38)	3	Medium
12	Rip	Manure	2 051 (2 121)	51 (66)	5	Low
13	Disc	Inorganic	3 413 (4 050)	33 (37)	1	Medium
14	Disc	Manure	1 922 (2 032)	60 (71)	6	Minimal
15	Shallow tine	Inorganic	3 390 (4 026)	33 (37)	2	Medium
16	Shallow tine	Manure	1 888 (2 000)	62 (71)	7	Minimal

The simulated yields for disc tillage (Figure 8.4.3) show that yields are high when rainfall is reliable, but in the seasons that have below average rainfall (seasons 36, 40, 42, 48 and 49) the yield is lower when compared to that of rip tillage. In both Figure 8.4.2 and 8.4.3 the yields are, in general, reducing over time for both climate scenarios. The use of the amount of manure applied over an extended period of time does not provide enough nitrogen for the crop. As a consequence yields reduce, along with the soil quality, due to increasing amounts of soil organic nitrogen and carbon being lost.

There could be several reasons for the rapid loss of soil organic carbon and nitrogen loss. The level of manure added (67.8kg N/ha, Section 8.3) might not be high enough for the plant density used. The increase in temperature could also produce a higher rate of organic matter decomposition. This will release more nutrients into the soil at a faster rate, which plants can then utilise, or the nutrient may be leached from the system. This loss of organic nitrogen and carbon produces a marked reduction in yield over the 49 seasons modelled. The sustainability index in this case does not fully capture the effect of the reduction in organic nitrogen, as the ecological integrity of the agro-ecosystem could be compromised by such a decrease and the ability of the agro-ecosystem to produce vital services reduced. In regard to treatments using manure as the source of nitrogen, perhaps mean yield is not a good measure to include in the sustainability index as higher yields in the early seasons mask the rapid decline in yields over the 49 seasons.

A famine level of 900 kg of maize grain for smallholders with a 1 ha plot has been suggested (Durand and du Toit, 1999). This is the amount of maize a family of four can survive on until the next harvest. If yields fall below this level, the smallholder farmers will not be producing enough maize to live on. Under present day climate conditions yields dropped below the famine level in eight out of 49 seasons when using rip tillage with manure and in 10 out of 49 seasons for disc tillage with manure. With an increase in temperature of 2°C the yield is below 900 kg in seven seasons for rip and 10 for disc tillage.

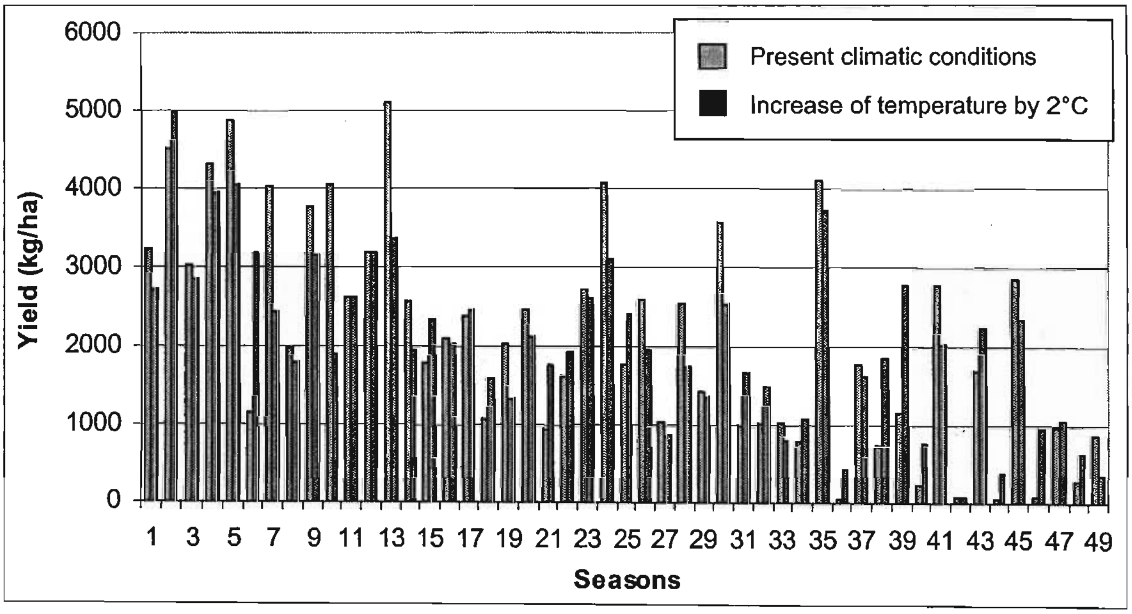


Figure 8.4.2 The influence of an increase in temperature of 2°C on maize yield for rip tillage when fertilising with manure

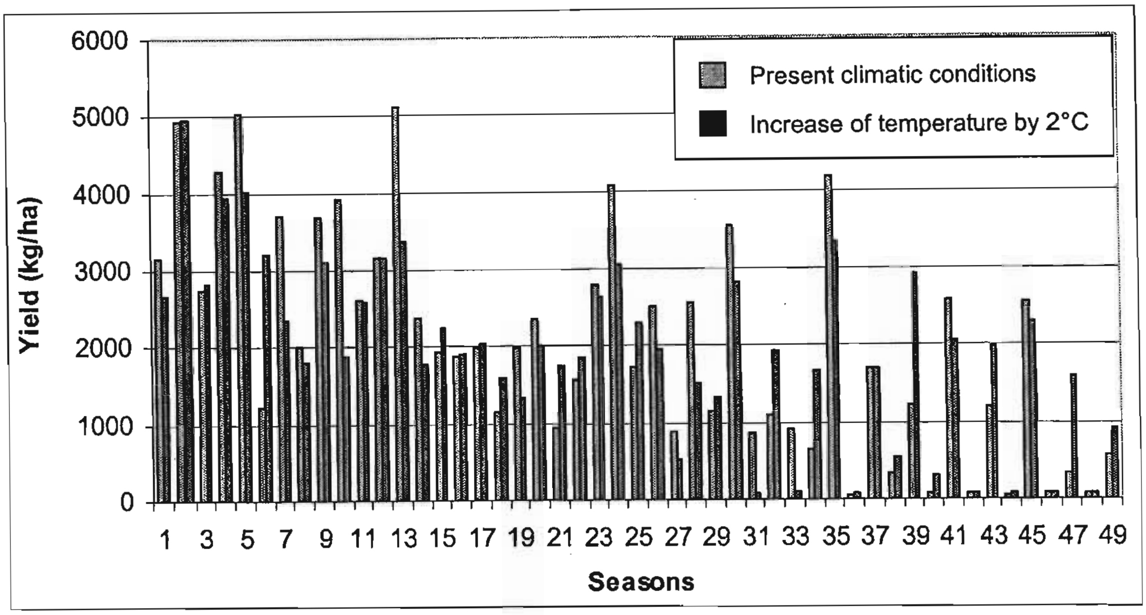


Figure 8.4.3 The influence of an increase in temperature of 2°C on maize yield for disc tillage when fertilising with manure

The inter-seasonal yields for both disc and rip tillage, when using inorganic nitrogen in place of manure, are shown in Figures 8.4.4 and 8.4.5. Under rip tillage the yield is higher under present climate conditions in 36 out of 49 seasons than compared with yields when there is 2°C rise in temperature. For disc tillage the figure is slightly lower, at 36 out of 49 seasons (Figure 8.4.4). The larger differences in yield between the climatic regimes occurs when yield under present conditions is above 3 500 kg/ha. The soil organic nitrogen and carbon losses are higher for all treatments with an increase in temperature of 2°C. Figure 8.4.6 shows soil organic nitrogen for no till and disc with different nitrogen inputs. The results show little difference between the tillage types.

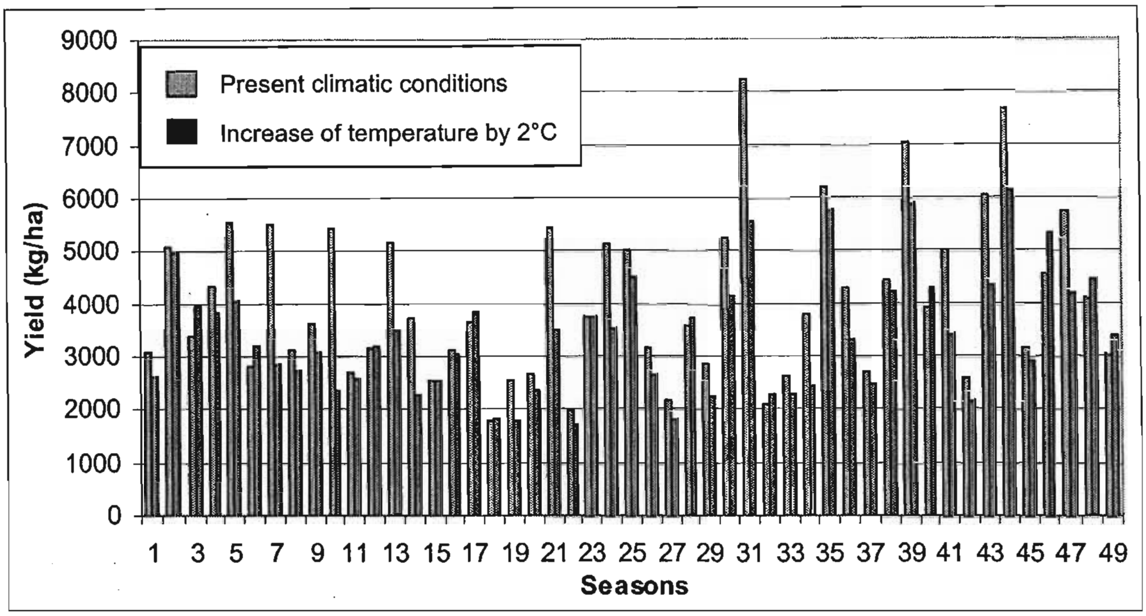


Figure 8.4.4 The influence of an increase in temperature of 2°C on maize yield for disc tillage, when using inorganic fertiliser

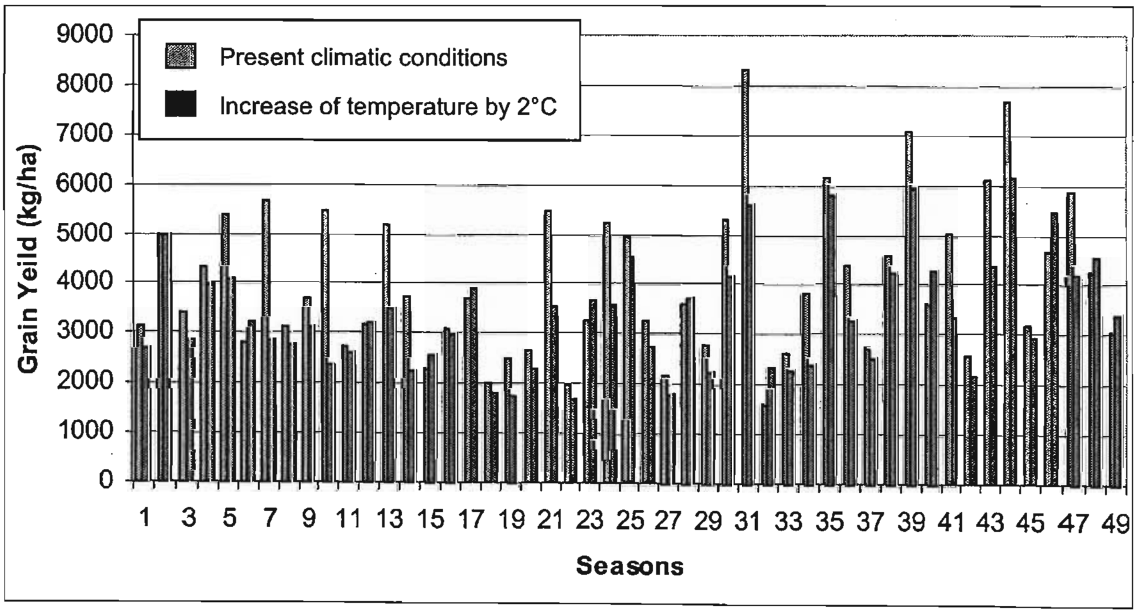


Figure 8.4.5 The influence of an increase in temperature of 2°C on maize yield for rip tillage, when using inorganic fertiliser

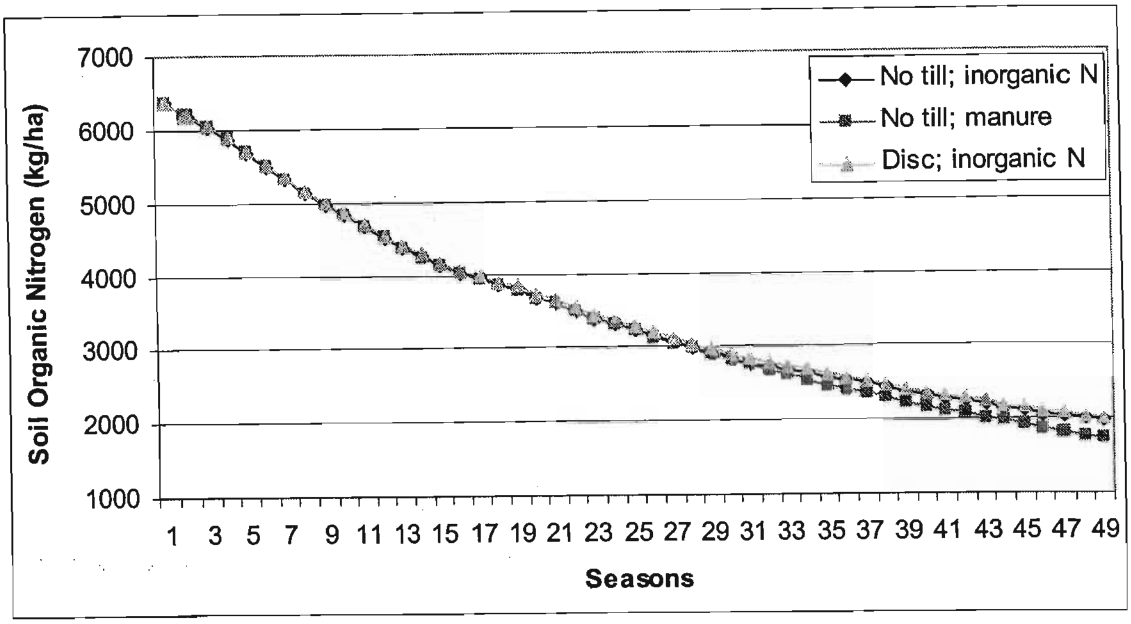


Figure 8.4.6 Soil organic nitrogen levels at Potshini over 49 seasons under a 2°C temperature increase for different tillage practices and modes of fertiliser application

8.4.3 An effective doubling of CO_2

An effective doubling of CO_2 by itself has a positive effect on the mean maize yield for all treatments (Table 8.4.3). For farmers using inorganic nitrogen there is a simulated increase of over 1 000 kg/ha and for those using manure, where nitrogen available to the plant is limited, the yield gains are more modest at ~300 kg/ha (Table 8.4.3). The possibility of sustainability for those treatments using manure has increased and these treatments now have a low sustainability likelihood rating, whereas it was minimal in two of four treatments under present climate conditions.

Although an effective doubling of CO_2 has a positive effect on plant growth and maize yield for the treatment using manure, it also increases yield variability when compared with present conditions. For the treatments using manure the increase in CO_2 produces larger yields in years where there is adequate rainfall (Figures 8.4.7 and 8.4.8). In the seasons when rainfall is lower than average (e.g. seasons 36, 42, 44 and 46), crop failure is experienced for all types of tillage modelled. Figures 8.4.7 and 8.4.8 show that there is a marked decrease in yields through the seasons. This is due to the lack of nitrogen being added to the soil and the quality of the soil decreasing over the 49 seasons modelled.

For the treatments using inorganic fertiliser the potential yields are considerably enhanced with the CO_2 increase, as nitrogen is not a growth limiting factor (Figures 8.4.9 and 8.4.10). With an increase in CO_2 mean yields are over 5 000 kg/ha for all tillage types simulated (Table 8.4.3) and variability is relatively low. The yield was below 3 000 kg/ha in 4 out of 49 seasons for rip tillage and 5 out of 49 seasons for disc.

For $2xCO_2$ the organic nitrogen and carbon losses are higher than under present conditions, but not as high when there is a temperature increase of 2°C. Figure 8.4.11 shows the soil organic nitrogen trends over time for tillage options under manure compared with present conditions. The rip tillage has the least amount of organic matter loss.

Table 8.4.3 Agricultural sustainability under different management regimes with an effective doubling of CO_2 (bracketed values denote yields and CV for present conditions)

Trt No	Tillage	Nitrogen Application	Mean Yield (kg/ha)	CV of Yields (%)	Yield/CV Index Ranking	Sustainability Likelihood
17	No till	Inorganic	5 003 (3 857)	32 (36)	2	Medium
18	No till	Manure	2 127 (1 784)	76 (74)	8	Low
18	Rip	Inorganic	5 279 (4 050)	33 (38)	2	Medium
20	Rip	Manure	2 502 (2 121)	65 (66)	5	Low
21	Disc	Inorganic	5 277 (4 050)	33 (37)	1	Medium
22	Disc	Manure	2 355 (2 032)	71 (71)	6	Low
23	Shallow tine	Inorganic	5 238 (2 026)	33 (37)	4	Medium
24	Shallow tine	Manure	2 300 (2 000)	72 (71)	7	Low

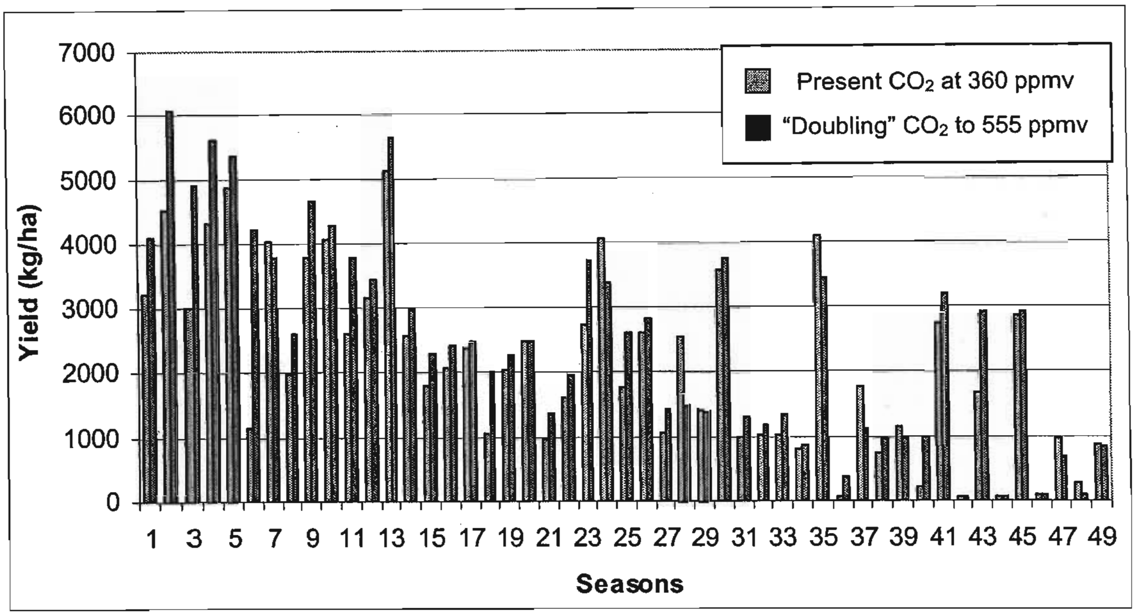


Figure 8.4.7 The influence of an effective doubling of CO_2 on maize yield with rip tillage when fertilising with manure

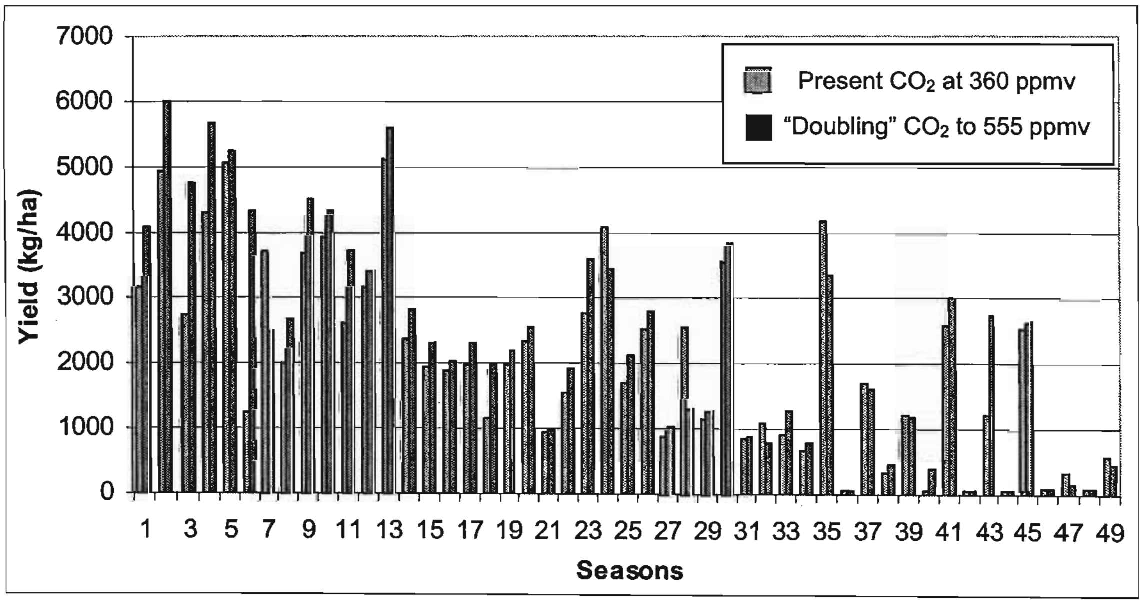


Figure 8.4.8 The influence of an effective doubling of CO_2 on maize yield with disc tillage when fertilising with manure

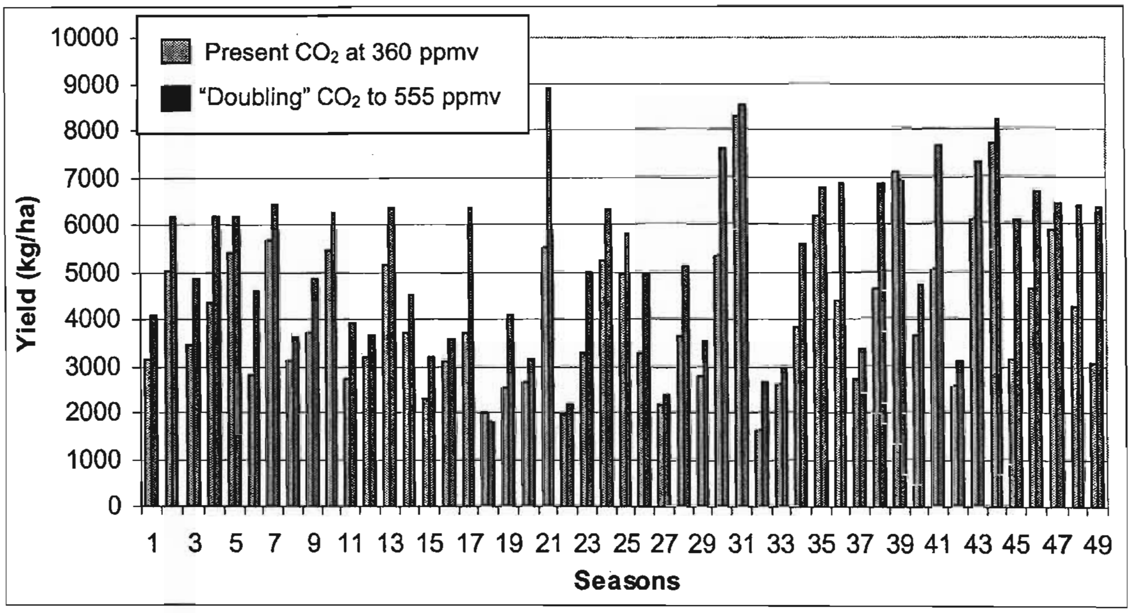


Figure 8.4.9 The influence of an effective doubling of CO_2 on maize yield with rip tillage, when using inorganic fertiliser

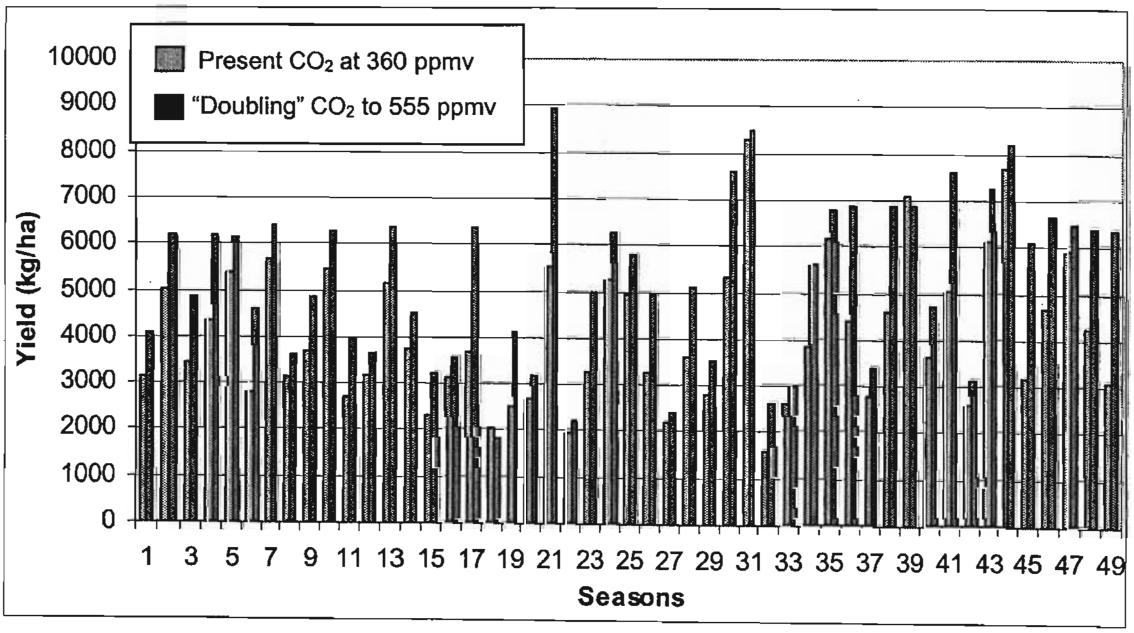


Figure 8.4.10 The influence of an effective doubling of CO_2 on maize yield with disc tillage, when using inorganic fertiliser

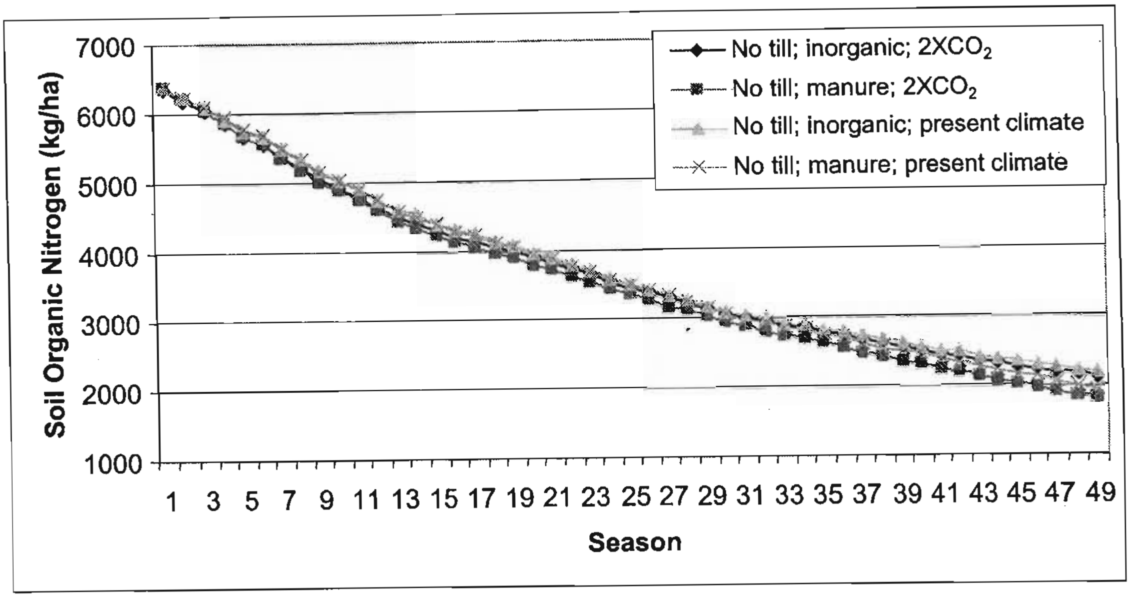


Figure 8.4.11 Soil organic nitrogen levels for a no till practice and different modes of fertiliser application at Potshini over 49 seasons for present climate conditions and under an effective doubling of CO_2

8.4.4 An effective doubling of CO_2 and a 1°C increase in temperature

An effective doubling of CO_2 coupled with a 1°C increase in temperature increases yield when compared with present climatic conditions (Table 8.4.4). The 1°C in temperature implies that the yield increases are not as high as when there was just a doubling in CO_2. The yield variability is reduced compared to present climatic conditions. Treatment 27 (rip with inorganic fertiliser) is the favoured tillage type under these climatic conditions.

For the treatment using manure, yields are below the famine level of 900 kg in seven out of 49 seasons for rip and nine out of 49 for disc (Figures 8.4.12 and 8.4.13). When nitrogen is limited for both rip and disc tillage the yields do not fall below the famine level (Figure 8.4.14 and 8.4.15). Using inorganic fertiliser the yields are higher in 41 out of 49 seasons for rip tillage under a climate regime with an effective doubling of CO_2 and a 1°C temperature increase. This figure is slightly less than with disc tillage, where increases are seen in 40 out of 49 seasons.

The temperature increases imply a higher rate of soil organic carbon and nitrogen loss than with a CO_2 increase only. The increase in organic carbon and nitrogen is illustrated in Figure 8.4.16, which shows the loss under no till for two climate regimes.

Table 8.4.4 Agricultural sustainability under different management regimes with an effective doubling of CO_2 and a 1°C increase in temperature (bracketed values denote yields and CV for present conditions)

Trt No.	Tillage	Nitrogen Application	Mean Yield (kg/ha)	CV of Yields (%)	Yield/CV Index Ranking	Sustainability Likelihood
25	No till	Inorganic	4 576 (3 857)	34 (36)	4	Medium
26	No till	Manure	2 055 (1 784)	71 (74)	8	Low
27	Rip	Inorganic	4 799 (4 050)	32 (38)	1	Medium
28	Rip	Manure	2 375 (2 121)	62 (66)	5	Low
29	Disc	Inorganic	4 786 (4 050)	32 (37)	2	Medium
30	Disc	Manure	2 332 (2 032)	65 (71)	6	Low
31	Shallow tine	Inorganic	4 767 (4 026)	32 (37)	3	Medium
32	Shallow tine	Manure	2 288 (2 000)	65 (71)	6	Low

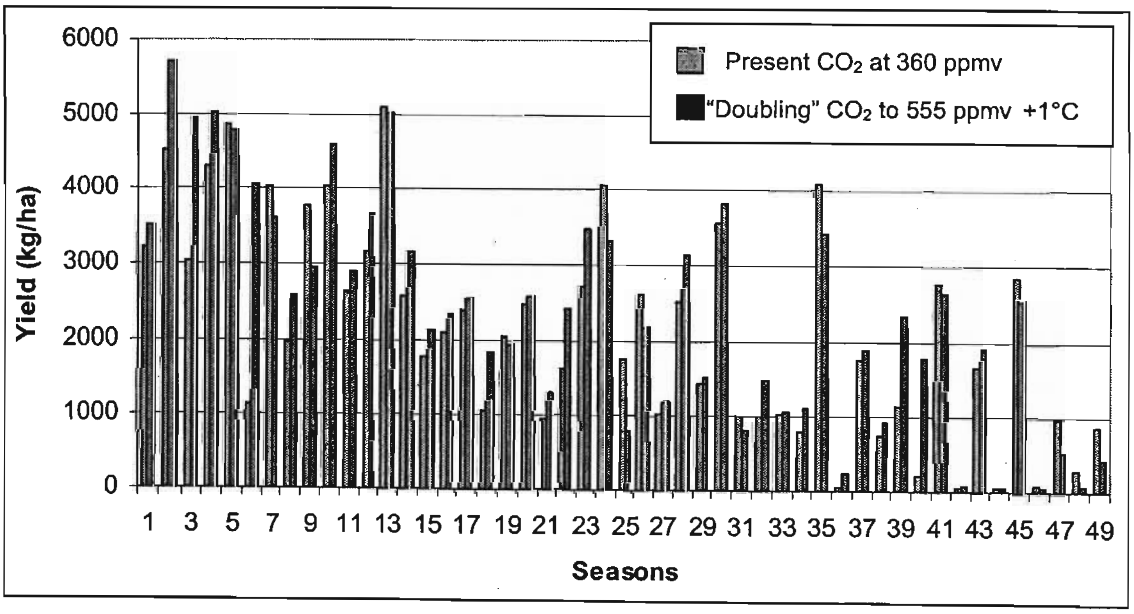


Figure 8.4.12 The influence of an effective doubling of CO_2 with a temperature increase of 1°C on maize yield with rip tillage and fertilising with manure

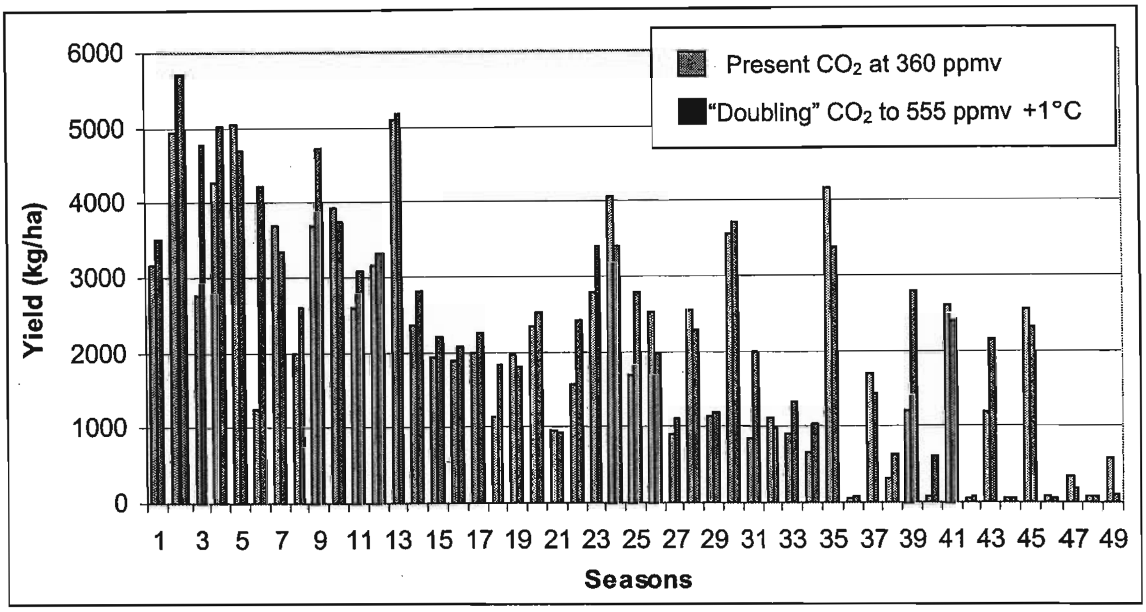


Figure 8.4.13 The influence of an effective doubling of CO_2 with a temperature increase of 1°C on maize yield with disc tillage and fertilising with manure

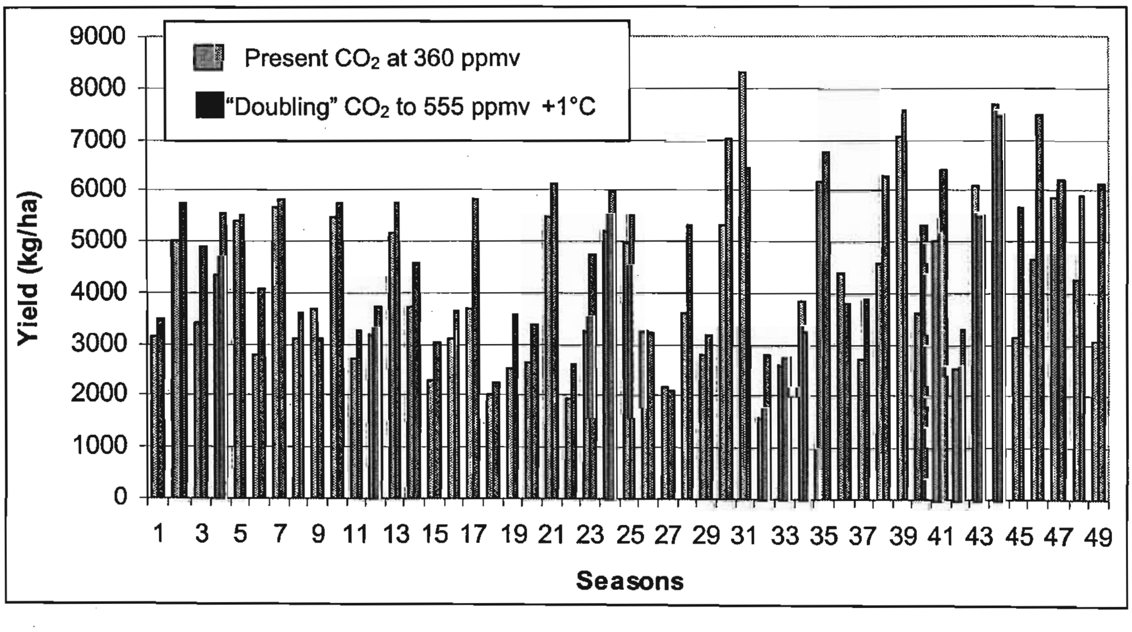


Figure 8.4.14 The influence of an effective doubling of CO_2 with a temperature increase of 1°C on maize yield with rip tillage, when using inorganic fertiliser

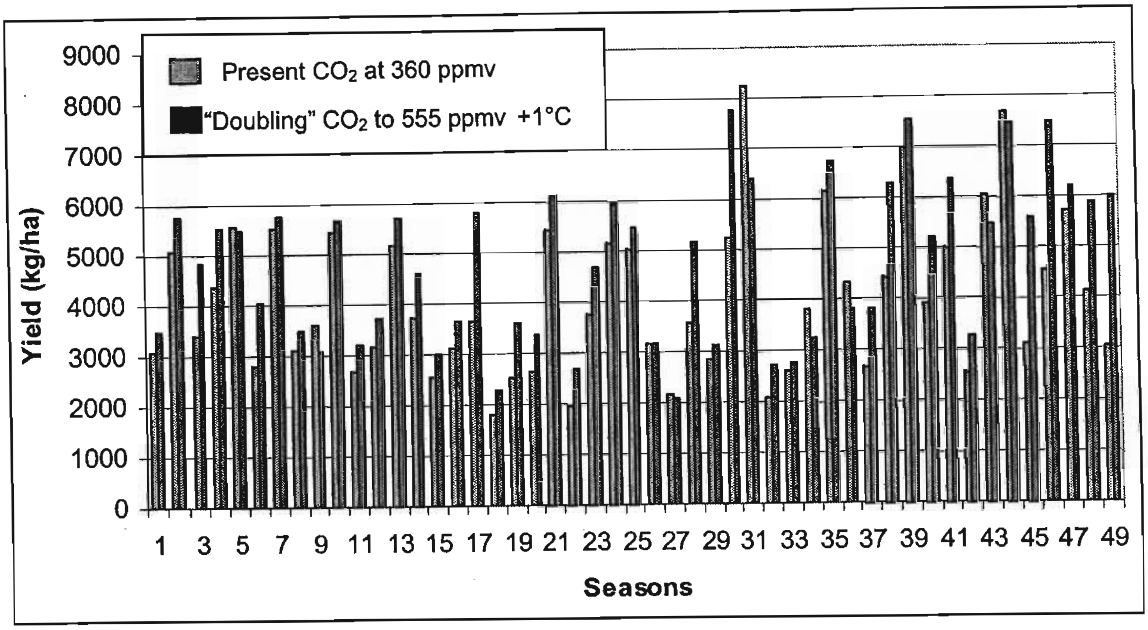


Figure 8.4.15 The influence of an effective doubling of CO_2 with a temperature increase of 1°C on maize yield with disc tillage, when using inorganic fertiliser

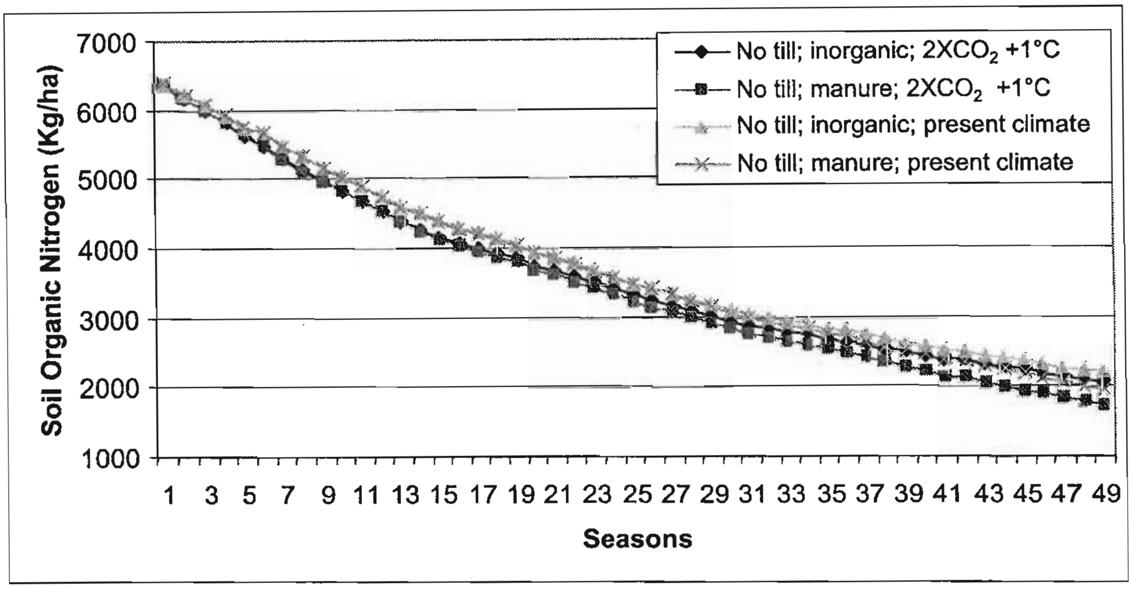


Figure 8.4.16 Soil organic nitrogen levels for a no till practice and different modes of fertiliser application at Potshini over 49 seasons for present climatic conditions under an effective doubling of CO_2 with a 1°C temperature increase

8.4.5 An effective doubling of CO_2 with a 2°C increase in temperature

An effective doubling of CO_2 combined with a 2°C increase in temperature results in yield increases when compared to presents day conditions, but less than with a $2XCO_2$ +1°C temperature increase (Table 8.4.5). The increase in temperature is reducing the positive effect that the increase in CO_2 is having on the maize yield.

The yield is less than 900 kg/ha in 11 out of 49 seasons for rip tillage using manure (Figure 8.4.17) and 13 out of 49 seasons for disc (Figure 8.4.18). The yield falls below the famine level more often with this climate regime than with present day conditions.

For treatments using inorganic fertiliser the yield increases in 32 out of 49 seasons for both rip (Figure 8.4.19) and disc tillage (Figure 8.4.20). Figures 8.4.19 and 8.4.20 illustrate that the variability of yield over 49 seasons is significantly less than for present climate conditions.

Table 8.4.5 Agricultural sustainability under different management regimes with an effective doubling of CO_2 with a 2°C increase in temperature (bracketed values denote yields and CV for present conditions)

Trt No.	Tillage	Nitrogen Application	Mean Yield (kg/ha)	CV of Yields (%)	Yield/CV Index Ranking	Sustainability Likelihood
33	No till	Inorganic	4 192 (3 857)	31 (36)	4	Medium
34	No till	Manure	2 037 (1 784)	69 (74)	8	Low
35	Rip	Inorganic	4 410 (4 050)	30 (38)	1	Medium
36	Rip	Manure	2 387 (2 121)	60 (66)	5	Low
37	Disc	Inorganic	4 385 (4 050)	30 (37)	1	Medium
38	Disc	Manure	2 246 (2 032)	67 (71)	6	Low
39	Shallow tine	Inorganic	4 364 (4 026)	30 (37)	3	Medium
40	Shallow tine	Manure	2 227 (2 000)	67 (71)	6	Low

The inorganic matter loss is 5% higher for manure treatments under this climate regime (Figure 8.4.21) with the increase in loss for treatments using inorganic nitrogen is 3.5%.

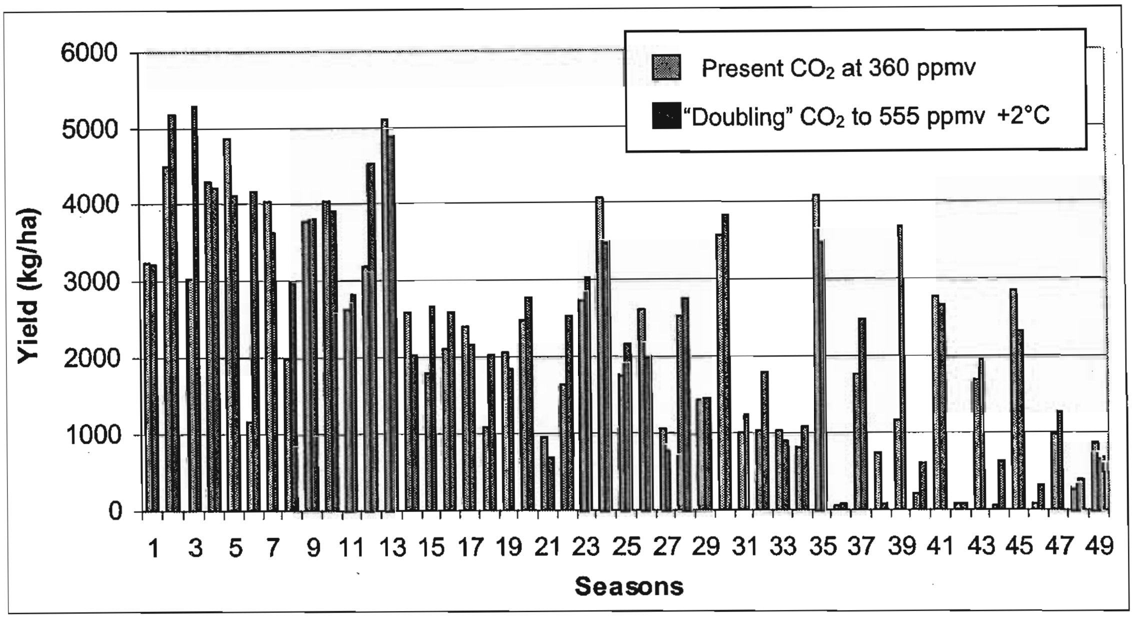


Figure 8.4.17 The influence of an effective doubling of CO_2 with a temperature increase of 2°C on maize yield with rip tillage and fertilising with manure

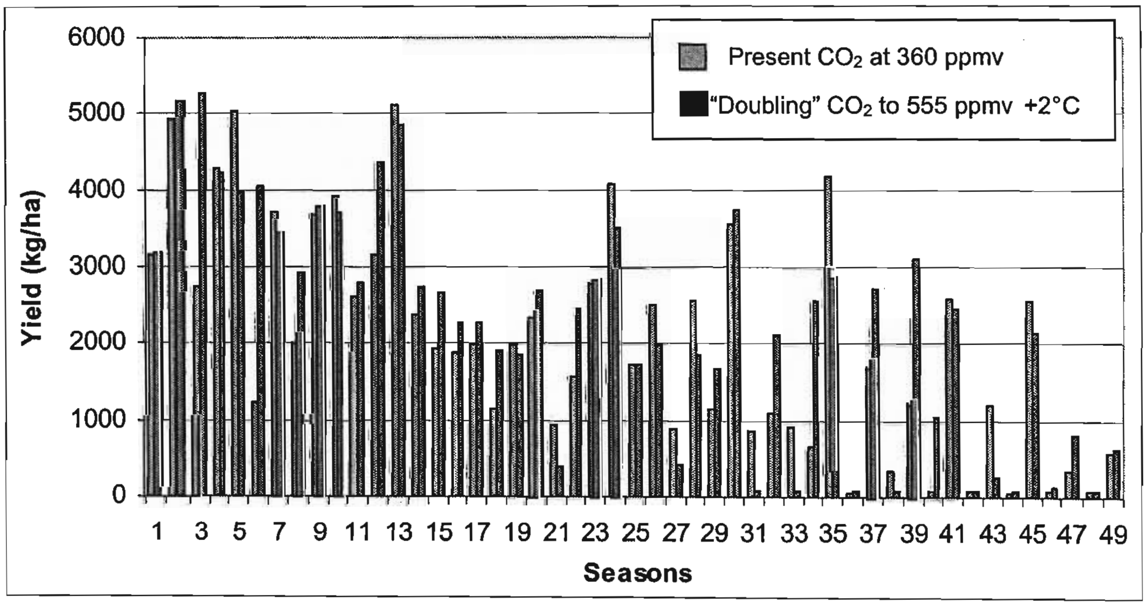


Figure 8.4.18 The influence of an effective doubling of CO_2 with a temperature increase of 2°C on maize yield with disc tillage and fertilising with manure

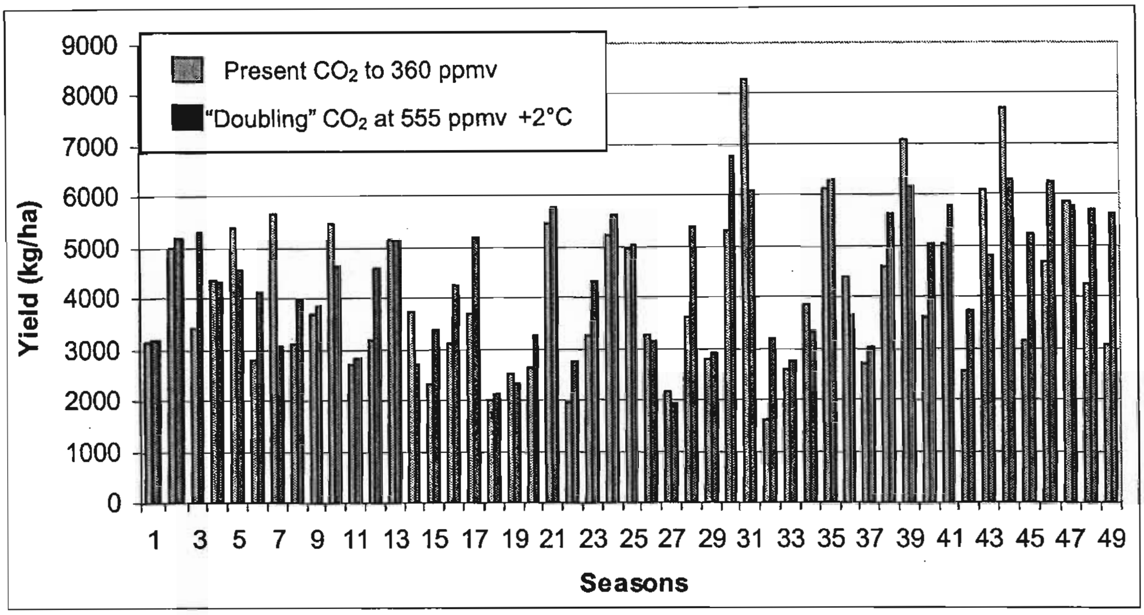


Figure 8.4.19 The influence of an effective doubling of CO_2 with a temperature increase of 2°C on maize yield with rip tillage, when using inorganic fertiliser

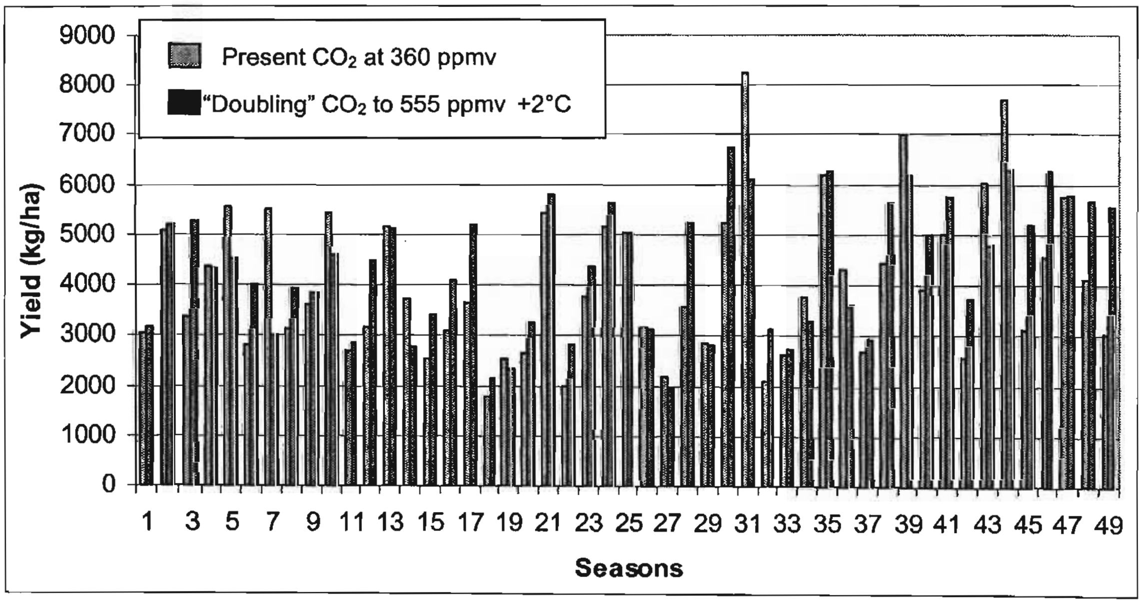


Figure 8.4.20 The influence of an effective doubling of CO_2 with a temperature increase of 2°C on maize yield with disc tillage, when using inorganic fertiliser

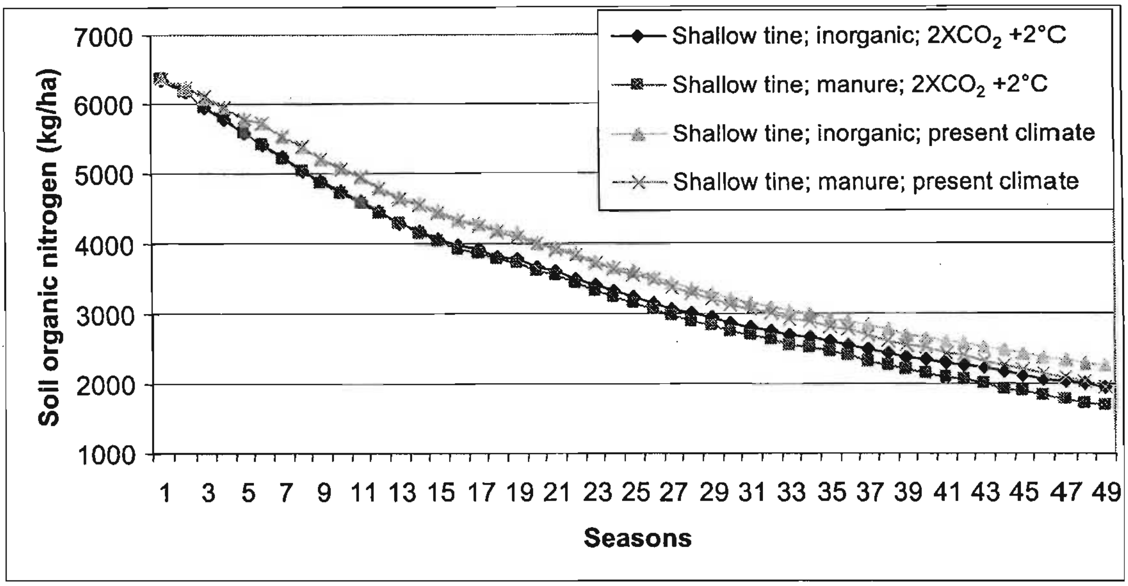


Figure 8.4.21 Soil organic nitrogen levels for shallow tine practices and different modes of fertiliser application at Potshini over 49 seasons for present climatic conditions under an effective doubling of CO_2 with a 2°C temperature increase

8.4.6 An effective doubling of CO_2 with a 3°C increase in temperature

A 3°C increase with an effective doubling of CO_2 still has a positive effect on yields (Table 8.4.6). However, the effect of the CO_2 increase on yields is significantly reduced with the 3°C increase in the maximum and minimum daily temperatures.

The increase of 1°C from $2XCO_2$ with 2°C increase to $2XCO_2$ with 3°C increase has not caused the frequency of yield falling below the famine level with rip and disc tillage to enlarged (Figures 8.4.22 and 8.4.23). In fact the figures are the same, at eleven out of 49 seasons, for rip tillage using manure and 13 out of 49 seasons for disc tillage using manure.

The treatments using inorganic nitrogen experience an increase in yields in 27 out of 49 seasons for rip and in 26 out of 49 seasons for disc tillage.

With each incremental temperature rise the loss of soil organic nitrogen and carbon also rises. Figure 8.4.26 shows how the system under no till responds to the climate regime. The losses are 5% more for both manure and inorganic fertiliser treatments when compared with present conditions.

Table 8.4.6 Agricultural sustainability under different management regimes with an effective doubling of CO_2 with a 3°C increase in temperature (bracketed values denote yields and CV for present conditions)

Trt No.	Tillage	Nitrogen Application	Mean Yield (kg/ha)	CV of Yields (%)	Yield/CV Index Ranking	Sustainability Likelihood
41	No till	Inorganic	3 955 (3 857)	30 (36)	4	Medium
42	No till	Manure	1 963 (1 784)	68 (74)	8	Minimal
43	Rip	Inorganic	4 121 (4 050)	30 (38)	2	Medium
44	Rip	Manure	2 319 (2 121)	60 (66)	5	Low
45	Disc	Inorganic	4 103 (4 050)	30 (37)	1	Medium
46	Disc	Manure	2 195 (2 032)	66 (71)	6	Low
47	Shallow tine	Inorganic	4 085 (4 026)	29 (37)	2	Medium
48	Shallow tine	Manure	2 165 (2 000)	66 (71)	7	Low

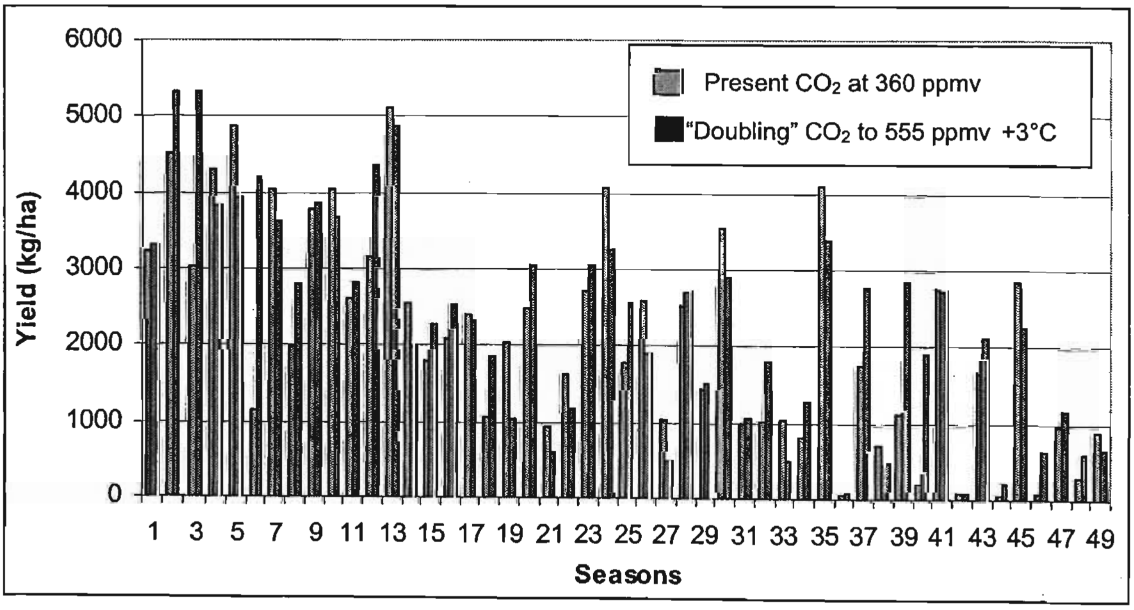


Figure 8.4.22 The influence of an effective doubling of CO_2 with a temperature increase of 3°C on maize yield with rip tillage and fertilising with manure

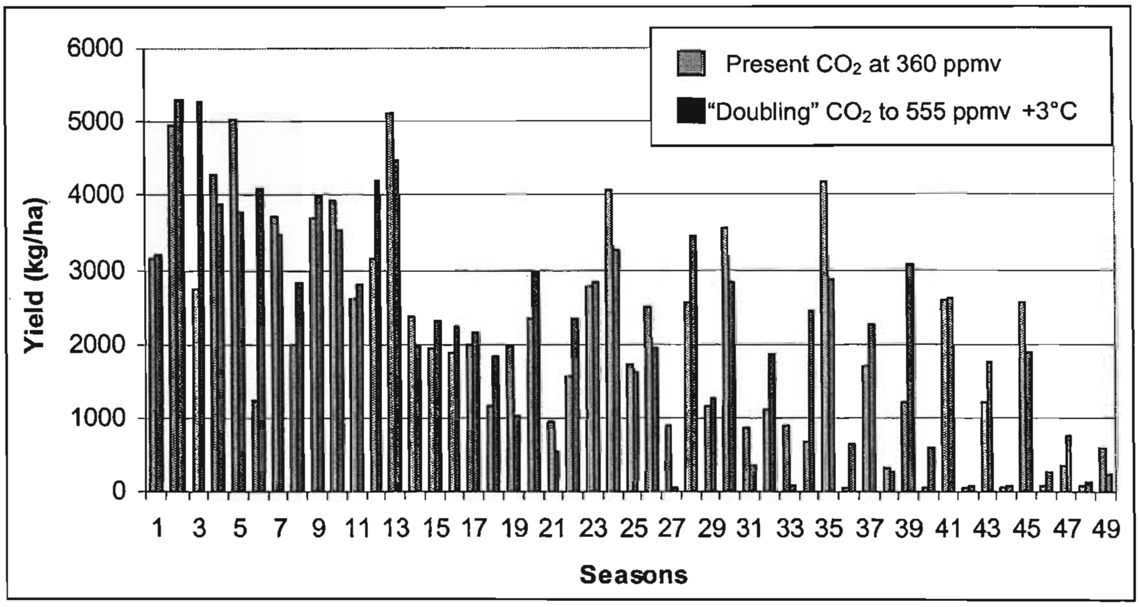


Figure 8.4.23 The influence of an effective doubling of CO_2 with a temperature increase of 3°C on maize yield with disc tillage and fertilising with manure

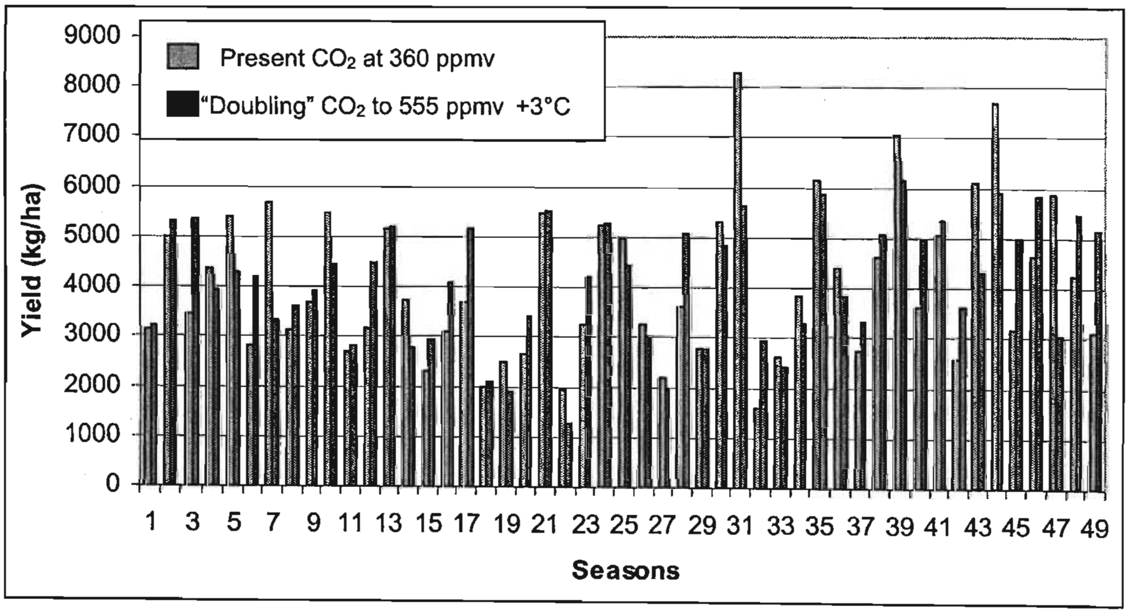


Figure 8.4.24 The influence of an effective doubling of CO_2 with a temperature increase of 3°C on maize yield with rip tillage, when using inorganic fertiliser

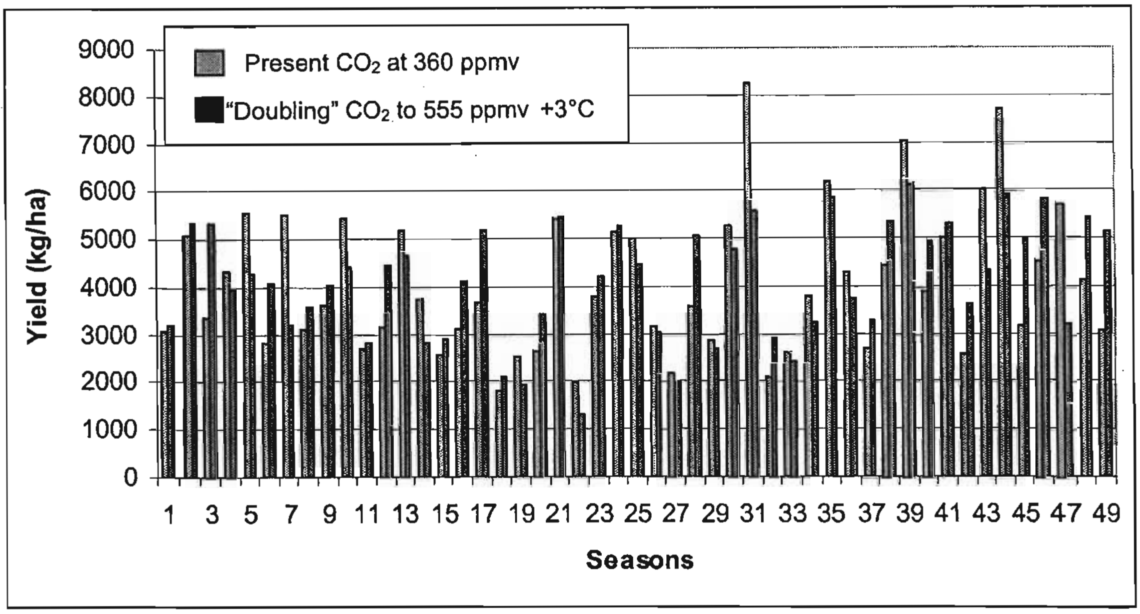


Figure 8.4.25 The influence of an effective doubling of CO_2 with a temperature increase of 3°C on maize yield with disc tillage, when using inorganic fertiliser

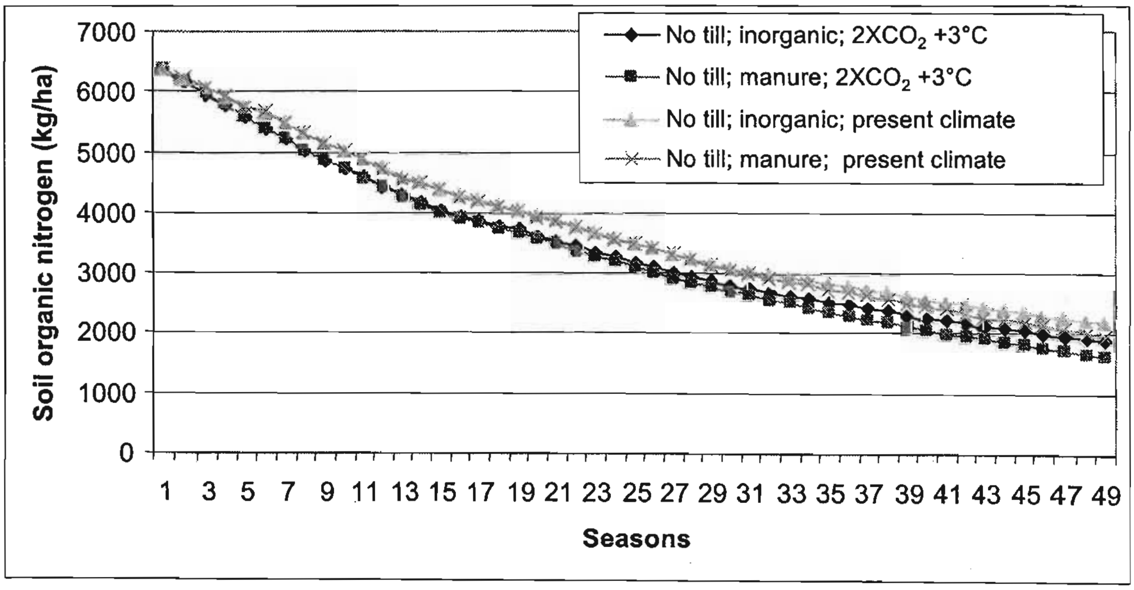


Figure 8.4.26 Soil organic nitrogen levels for a no till practice and different modes of fertiliser application at Potshini over 49 seasons for present climatic conditions and under an effective doubling of CO_2 with a 3°C temperature increase

8.4.7 An effective doubling of CO_2 with a 10% increase in rainfall

An increase in rainfall of 10% with an effective doubling of CO_2 sees large gains in grain yield (Table 8.4.7). The rip and disc tillage have the highest ranking of the treatments using inorganic fertiliser and rip has the highest ranking of those treatments when using manure.

Even with the increased rainfall, yields fall below the famine level 10 out of 49 seasons with rip and 12 out of 49 seasons with disc tillage (Figures 8.4.27 and 8.4.28). The limit on available nitrogen for those treatments prevents yields being higher. Even though overall rainfall has increased by 10% the mid-summer dry spell will still be experienced using this type of modelling, as daily rainfall sequences have not been changed just the total MAP.

The increase in rainfall coupled with the CO_2 increase sees yields increase in 48 out of 49 seasons with rip, and in 46 out of 49 seasons with disc tillage (Figures 8.4.29 and 8.4.30).

Table 8.4.7 Agricultural sustainability under different management regimes with an effective doubling of CO_2 with a 10% increase in rainfall (bracketed values denote yields and CV for present conditions)

Trt No.	Tillage	Nitrogen Application	Mean Yield (kg/ha)	CV of Yields (%)	Yield/CV Index Ranking	Sustainability Likelihood
49	No till	Inorganic	5 265 (3 857)	31 (36)	4	Medium
50	No till	Manure	2 013 (1 784)	80 (74)	8	Low
51	Rip	Inorganic	5 508 (4 050)	30 (38)	1	Medium
52	Rip	Manure	2 486 (2 121)	69 (66)	5	Low
53	Disc	Inorganic	5 484 (4 050)	30 (37)	1	Medium
54	Disc	Manure	2 377 (2 032)	74 (71)	6	Low
55	Shallow tine	Inorganic	5 431 (4 026)	30 (37)	3	Medium
56	Shallow tine	Manure	2 338 (2 000)	74 (71)	6	Low

This climate regime causes soil organic nitrogen and carbon to be lost at a higher rate than under present climate conditions. Figure 8.4.31 shows the rate of loss of organic nitrogen under shallow tine tillage.

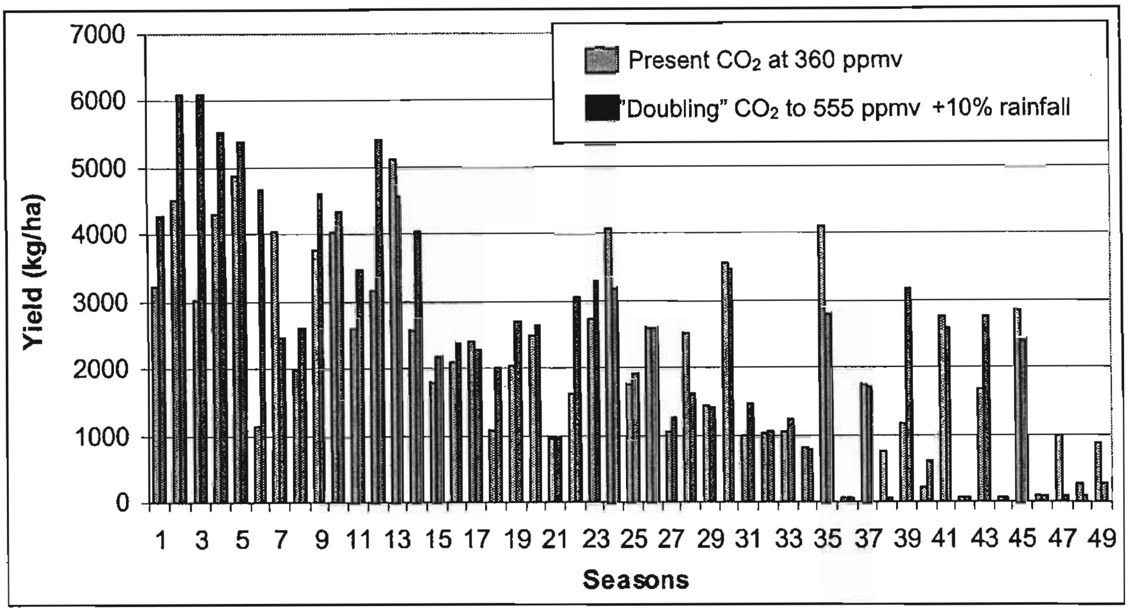


Figure 8.4.27 The influence of an effective doubling of CO_2 with a 10% increase in rainfall on maize yield using rip tillage and fertilising with manure

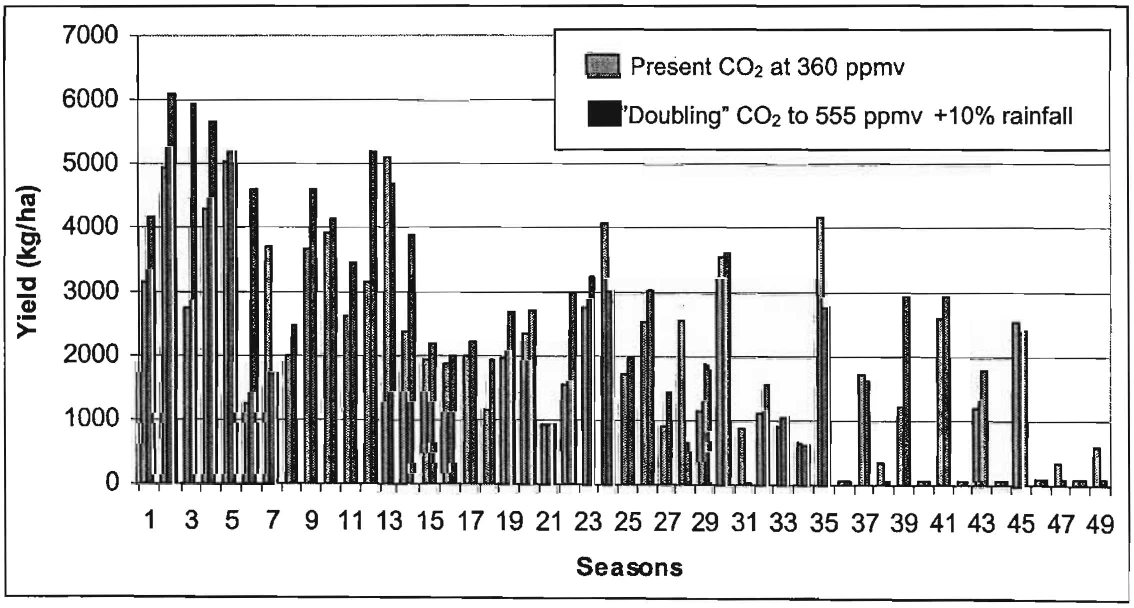


Figure 8.4.28 The influence of an effective doubling of CO_2 with a 10% increase in rainfall on maize yield using disc tillage and fertilising with manure

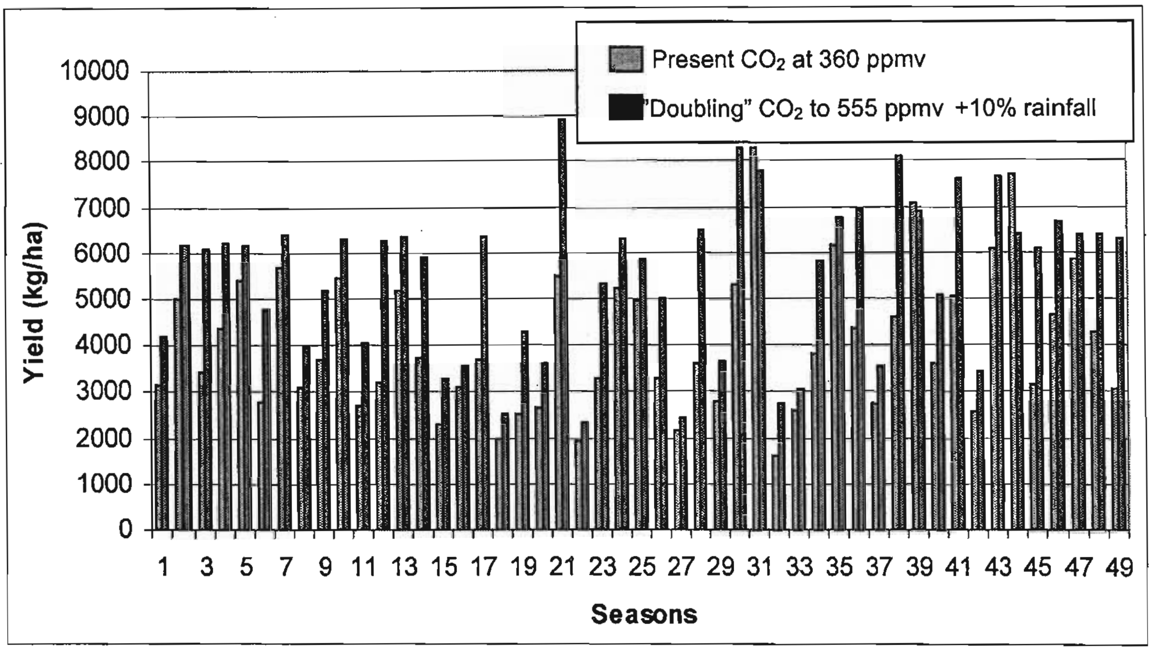


Figure 8.4.29 The influence of an effective doubling of CO_2 with a 10% increase in rainfall on maize yield with rip tillage, when using inorganic fertiliser

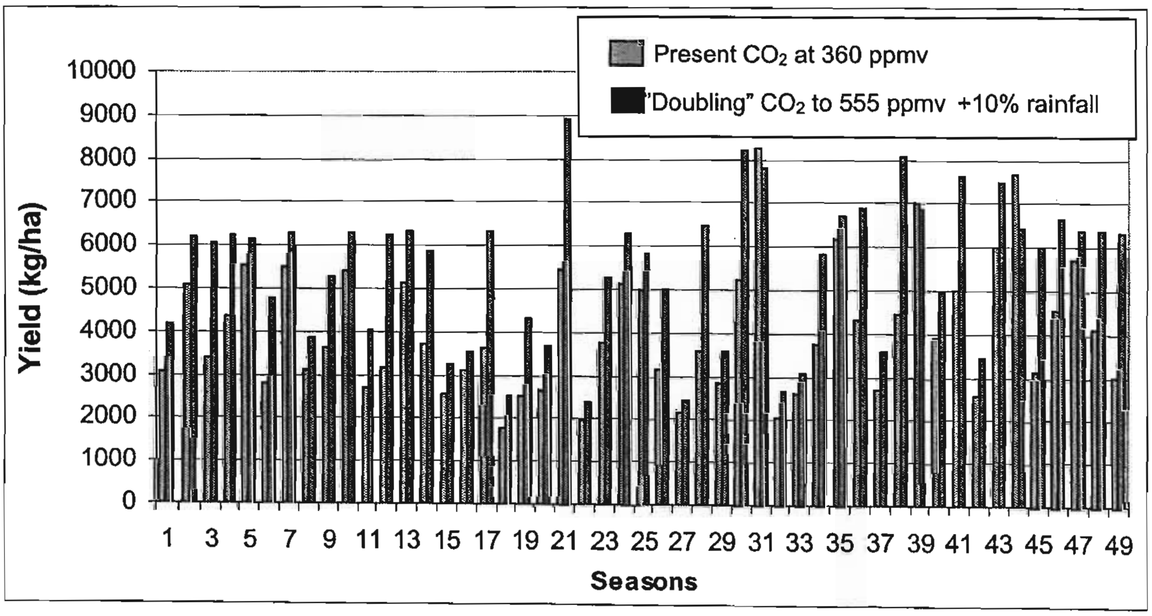


Figure 8.4.30 The influence of an effective doubling of CO_2 with a 10% increase in rainfall on maize yield with disc tillage, when using inorganic fertiliser

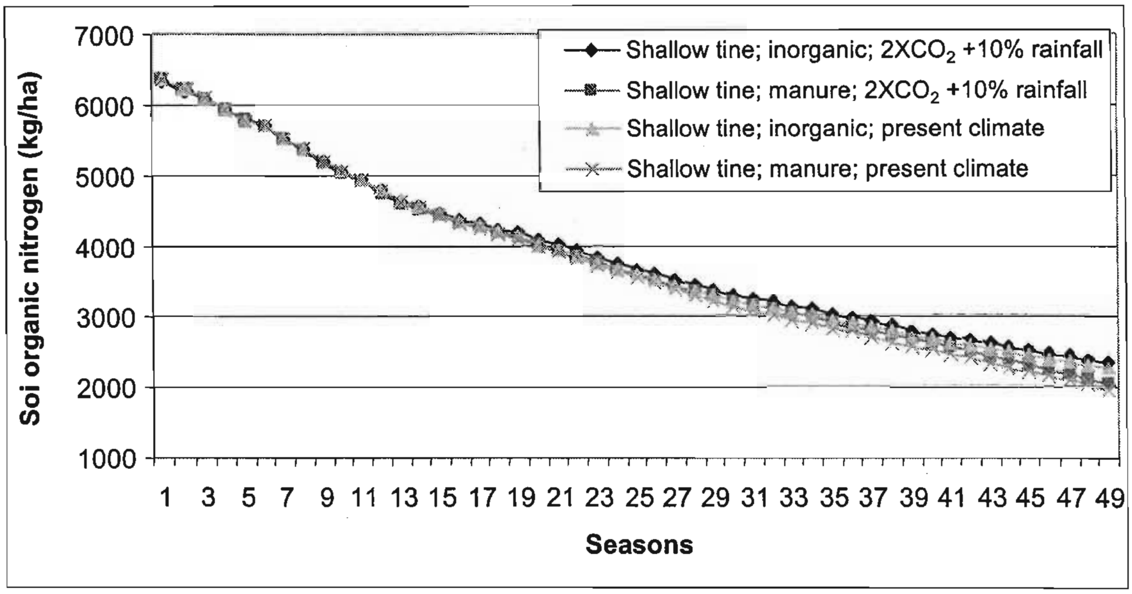


Figure 8.4.31 Soil organic nitrogen levels for shallow tine practice and different modes of fertiliser application at Potshini over 49 seasons for present climate conditions and under an effective doubling of CO_2 with a 10% increase in rainfall

8.4.8 An effective doubling of CO_2 with a 10% reduction in rainfall

An effective doubling of CO_2 with a 10% reduction in rainfall still increases yields compared with those under present climate conditions (Table 8.4.8). However, the reduction in rainfall limits the positive effect the CO_2 increase has on plant growth. The rip tillage gives the highest ranked yields for both inorganic nitrogen and manure inputs.

With this climate regime the yields fall below the famine level on nine occasions for rip and six for disc over the 49 seasons modelled (Figures 8.4.32 and 8.4.33). For the treatments using inorganic fertiliser, yield is increased 48 out of 49 times using rip for this climate regime and 49 out of 49 for disc tillage (Figures 8.4.34 and 8.4.35). The yield increases are not as high as with an increase in rainfall, but even with the reduced amount of precipitation the doubling of CO_2 increases yields in nearly all seasons compared with present conditions. With a reduction in rainfall the soil organic nitrogen loss under no till is reduced by 2% using manure and by 1% with inorganic fertiliser (Figure 8.4.36).

Table 8.4.8 Agricultural sustainability under different management regimes with an effective doubling of CO_2 with a 10% reduction in rainfall (bracketed values denote yields and CV for present conditions)

Trt No.	Tillage	Nitrogen Application	Mean Yield (kg/ha)	CV of Yields (%)	Yield/CV Index Ranking	Sustainability Likelihood
57	No till	Inorganic	4 709 (3 857)	35 (36)	4	Medium
58	No till	Manure	2 199 (1 784)	70 (74)	8	Low
59	Rip	Inorganic	5 000 (4 050)	35 (38)	1	Medium
60	Rip	Manure	2 568 (2 121)	58 (66)	5	Low
61	Disc	Inorganic	4 977 (4 050)	35 (37)	2	Medium
62	Disc	Manure	2 453 (2 032)	62 (71)	6	Low
63	Shallow tine	Inorganic	4 931 (4 026)	35 (37)	3	Medium
64	Shallow tine	Manure	2 418 (2 000)	64 (71)	7	Low

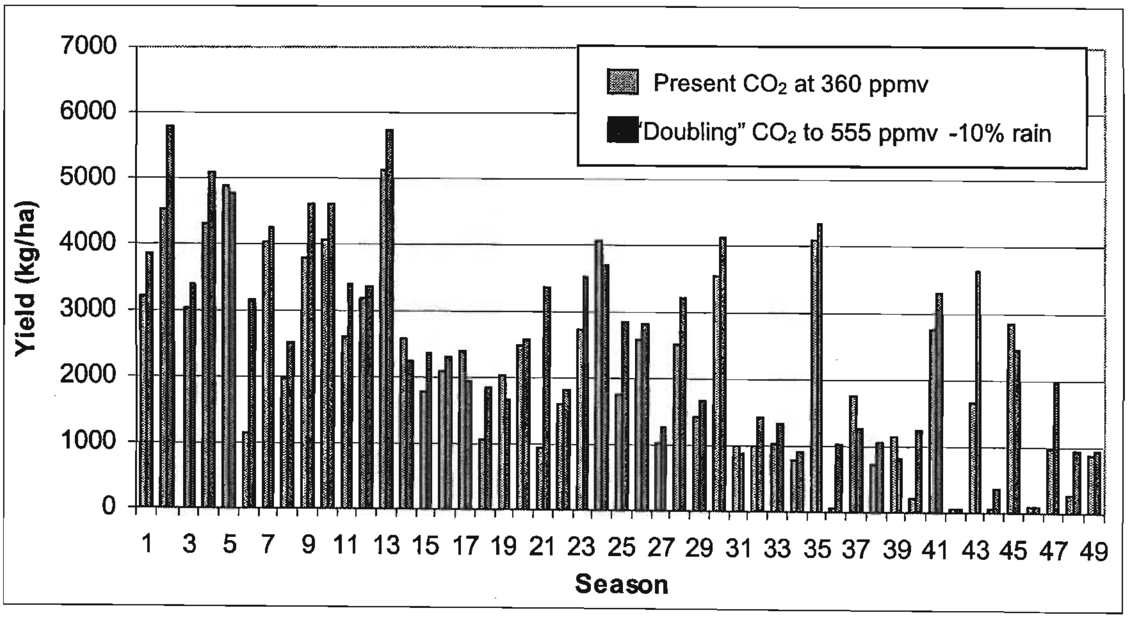


Figure 8.4.32 The influence of an effective doubling of CO_2 a 10% reduction in rainfall on maize yield using rip tillage and fertilising with manure

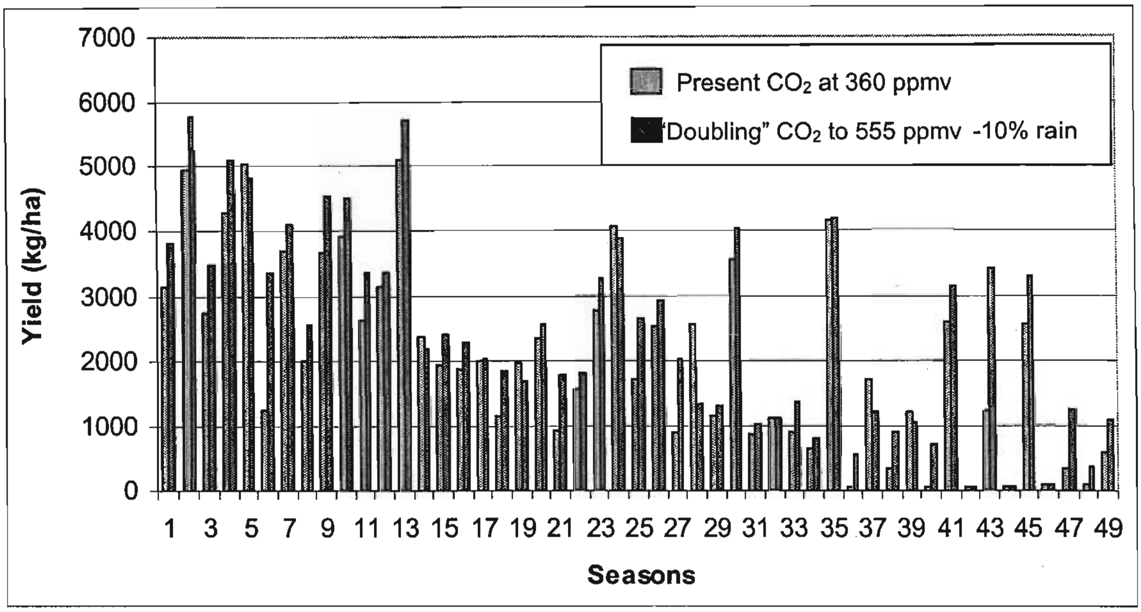


Figure 8.4.33 The influence of an effective doubling of CO_2 a 10% reduction in rainfall on maize yield using disc tillage and fertilising with manure

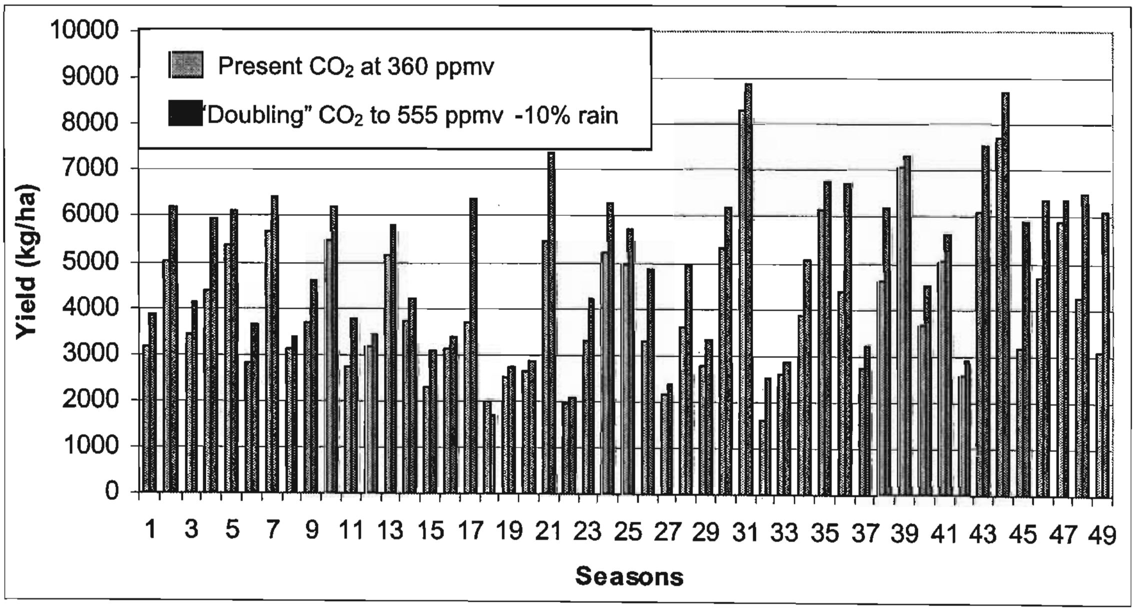


Figure 8.4.34 The influence of an effective doubling of CO_2 a 10% reduction in rainfall on maize yield using rip tillage, when using inorganic fertiliser

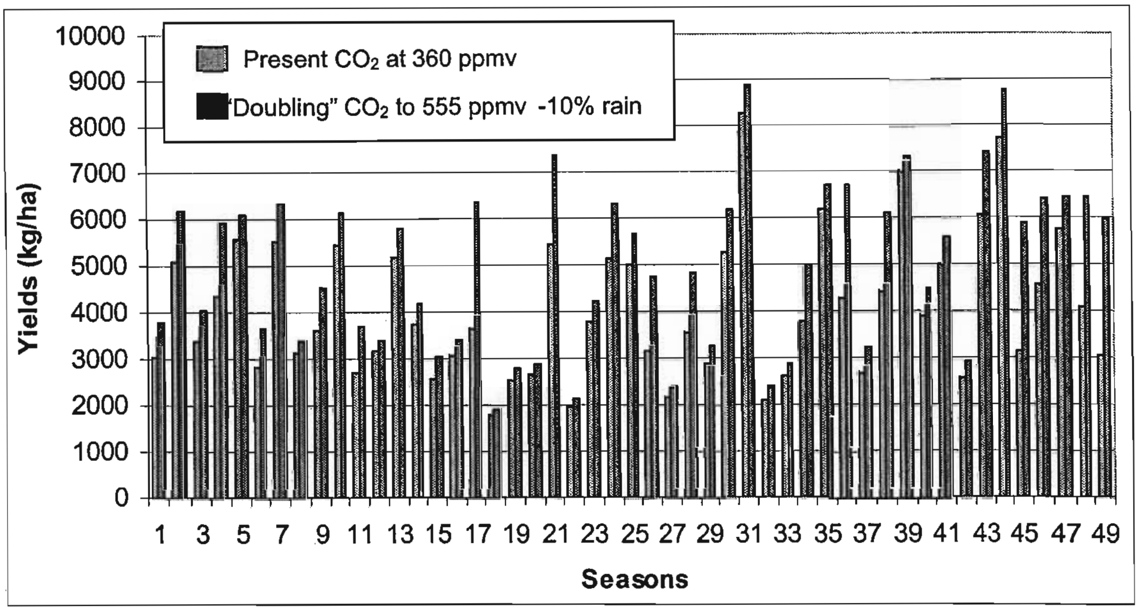


Figure 8.4.35 The influence of an effective doubling of CO_2 a 10% reduction in rainfall on maize yield using disc tillage, when using inorganic fertiliser

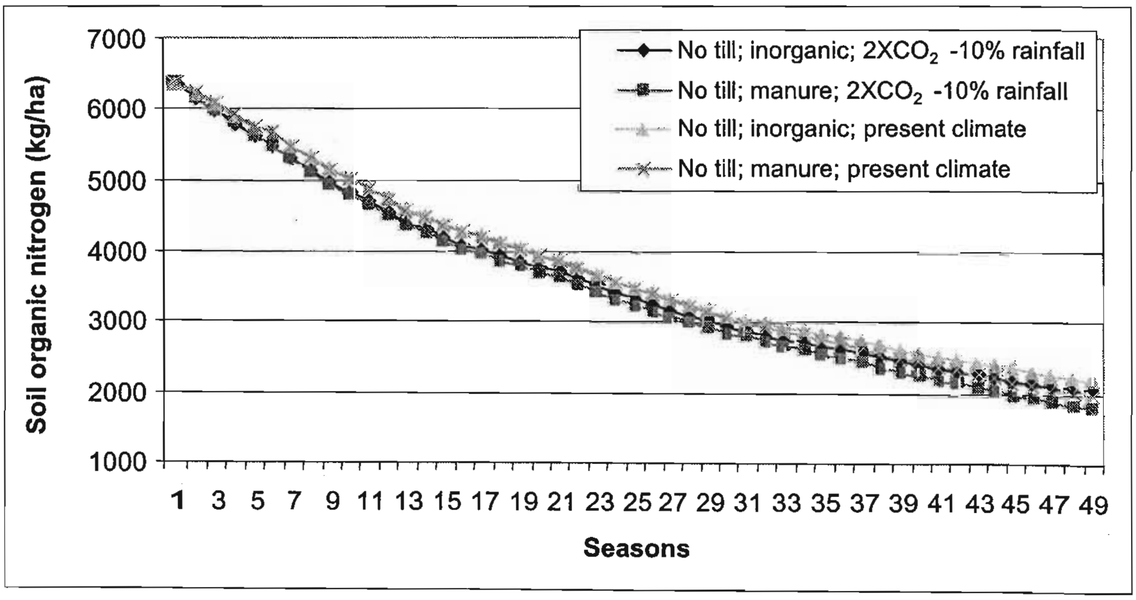


Figure 8.4.36 Soil organic nitrogen for a no till practice and different modes of fertiliser application levels at Potshini over 49 seasons for present climatic conditions and under an effective doubling of CO_2 with a 10% reduction in rainfall

The two tillage types that consistently scored the highest rank under each of the selected climate regimes was disc and rip, both with inorganic fertiliser added (Table 8.3.1).

Uri (1999) comments that conservation tillage has been found to be riskier in terms of yield variability than conventional tillage practices. In the simulation for the trial site in Potshini no significant difference was found in the yield variability between tillage practices. In terms of yield variability it was found that the use of manure caused the variability of yields to be high (<60%) when compared with inorganic fertiliser as the nitrogen source for the system. However, crop yields vary as a result of more to weather conditions than the tillage system used.

The climate regimes which included an effective doubling of CO_2 saw gains in terms of yield compared with present climate conditions. However, an increase in temperature or a reduction in rainfall reduces the positive impact of the CO_2 on maize yield. A 3°C increase almost negates the affect completely. The tillage system which was ranked the highest under all the climate regimes was the rip type.

8.5 Management Advice

The author-defined goal for this assessment at a smallholder farm scale is:

'The goal is for smallholder agro-ecosystems in the Potshini area to continue in the long term, providing quality well-being for farmers and local communities and to maintain ecological integrity.'

Four tillage options were modelled, under different plausible climate scenarios using both inorganic fertiliser and manure. In general the use of rip (reduced tillage) with manure was found to reduce the number of times yield falls below the famine level when compared to disc (conventional tillage). The modelling results showed that one way for smallholders to improve yields considerably would be the addition of inorganic nitrogen to the system. It was found that this management action would prevent the yield falling below the famine level of 900 kg in all years for the scenarios run and therefore have a positive effect on household food security. Obstacles that could prevent the smallholder from using fertiliser rather than manure would be lack of access to credit and transport. Also the decision to use capital to buy fertiliser might not be a current family priority. However, increases in inorganic fertiliser could have negative effects on groundwater quality, which is the main source of water for domestic use in the area. It would prove useful to monitor the nitrate levels in boreholes, water from which is used for domestic consumption.

The response of yield and other sustainability indicators were, for the most part, as hypothesised in Section 8.3. A temperature increase by itself reduced yields and a doubling of atmospheric CO_2 increased yields for all treatments. It was hypothesised that with the '$2xCO_2$ with -10% rainfall' scenario the drivers would be self cancelling up to a point. Yet all treatments recorded an increase in yield when compared with those from present climate conditions, for example, the yield for the 'no till inorganic fertiliser' treatment increased by 852 kg/ha and with the 'disc manure' treatment yield increased by 421 kg/ha.

The Bergville area often has a mid-summer dry spell in January (Smith *et al.*, 2004). The dry spell retards plant growth and can reduce maize grain yield. This is perhaps where conservation tillage would be of advantage particular to rain-fed maize production; as the soil under conservation tillage would hold moisture for longer and thus reduce the effect of the dry spell. The results from the CERES-Maize model do not show this, however. Yields from the conventional tillage type (disc) were ranked highest under most of the climatic conditions modelled, including present climate conditions. This perhaps shows weaknesses in the version of the CERES-Maize model used when simulating conservation tillage effects and also in the algorithms used to calculate the soil growth root factor. Smallholder farmers (~1 ha field size) in the Potshini area have seen an increase in yield when conservation tillage practices have been used on their land (Smith *et al.*, 1994).

These results suggest that further verification of the tillage practice routines is needed. The difference between yields simulated and observed is a combination of factors. Tillage has a complex effect on maize. The algorithms developed by du Toit *et al.* (2002a) account for some of the effects, but not all, particularly in regard to the beneficial effect of no till and the protection that a good mulch cover provides for the soil. Du Toit *et al.* (2002) attempted to account for tillage within the existing CERES-Maize routines. New tillage routines need to be incorporated into the model so that tillage can be modelled successfully across a range of environments. This obviously requires funding and expertise to undertake.

The climate and soils in the Potshini area have the potential for smallholder farmers to produce yields in excess of four tonnes per hectare using inorganic fertiliser and conservation tillage techniques. There is a desire within the Department of Agriculture in KwaZulu-Natal to see the successful small-scale farmers in Potshini and its surrounding wards to become commercial farmers. However, there are several factors that are preventing this, the main one being that each farmer has only up to one hectare of land to farm. The limited supply of land would seem to prevent farming more than this. However with good farming practice the small-scale farmers are already on the way to becoming semi-commercial, i.e. they are producing a high yield on the small farms that they have. The income could then be supplemented by off farm employment. Good farming practices would also reduce their vulnerability to climate change. This would need to be coupled with sound grazing management for cattle and goats. These measures would increase the ability of the agro-ecosystem to cope with shocks and therefore increase the resilience of agro-ecosystem.

Maize production under rain-fed conditions, however, still remains vulnerable to the adequacy, reliability and timeliness of rainfall. Farmers are averse to taking risks and investing in inputs and improvements, resulting in low levels of productivity (Inocencio *et al.*, 2003). Along with conservation tillage another management option which could be utilised in the Potshini area is rainwater harvesting. Rainwater harvesting is the process of conserving rainfall runoff in the field or in storage structures. This can help mitigate the effects of temporal and spatial variability of rainfall of the high risks of intra-seasonal dry spells (Inocencio *et al.*, 2003). The use of this technology would also help alleviate the reduction in yields that a rise in temperature would bring.

9 CONCLUSIONS

In this chapter a summary is provided on what has been learned from the research. The aims of this study that were set out in Figure 1.1 in the first chapter were to review the concept of sustainability and its relevance to agro-ecosystems and then to devise a framework to assess sustainability across a range of spatial scales. Agro-ecosystem sustainability with regard to maize production was then to be assessed at the regional scale of the Highveld of South Africa, at Quaternary Catchment scale and at the smallholder farm scale, assuming both presently prevailing climate conditions and those which could plausibly occur in the future.

9.1 Sustainability Summarised

In the review of sustainability definitions and concepts it found was that many of the definitions assessed seemed cumbersome and problematic to apply practically to agro-ecosystems. However, this is not considered a reason to abandon an ideal such as sustainability of agro-ecosystems. Pertinent definitions of sustainability are vital if strategies and methodologies are to be developed to achieve sustainability. These definitions can then give understanding in the selection of relevant goals or objectives that should be realised for long-term sustainability of agro-ecosystems.

Based on the work of Chambers (1997), the definition of sustainability used by the author in this thesis is:

> '*Sustainability is applying long term perspectives, in regard to human well-being and ecological integrity, to policies and action'* (Section 2.7).

Working definitions of agricultural sustainability were then derived and used as the goal for the sustainability assessments carried out at different scales. The working definition of sustainability applied to agriculture in the Highveld of South Africa (Chapters 5, 6, 7) is:

'for the agro-ecosystems in the Highveld region to continue in the long term, providing quality well-being for farmers and local communities and to maintain the ecological integrity of the agro-ecosystem.'

The working definition of sustainability applied to smallholder agro-ecosystems in the Potshini area, near Bergville in KwaZulu-Natal, South Africa (Chapter 8) is:

'for smallholder agro-ecosystems in the Potshini area to continue in the long term, providing quality well-being for farmers and local communities and to the maintain ecological integrity of the agro-ecosystem.'

Having a pertinent working definition for sustainability and for agricultural sustainability was found to be helpful as it enabled a clear framework to be developed in which to assess sustainability. The working definitions also give direction to the assessment. These working definitions were used as the goal of the framework that was developed in Chapter 4. The framework has four stages:

- Identifying the goal
- Sustainability modelling
- Evaluation and
- Management advice.

Problems were encountered in selecting output from CERES-Maize to use as sustainability indicators at a range of scales (in the sustainability modelling stage) and in applying CERES-Maize to broader scales than the farm level and also with trying to account for tillage variations within the model.

9.2 Lessons Learned with Developing a Sustainability Framework

The sustainability assessment was performed using a systems approach in an integrated modelling environment. The work involved extensive programming in FORTRAN and linking of national environmental database information with crop growth models and GIS (Section 5.3.1). The modelling performed for the Highveld region built on previous work (Schulze *et al.*, 1993; du Toit *et al.*, 1994 a, b, c; du Toit *et al.*, 1997, du Toit *et al.*, 1998; du Toit and Prinsloo, 2000) and for the first time incorporated daily temperatures in the model whereas previously monthly means of temperatures had been used. Furthermore, the soils information used for each QC is from the current land type soils database of the Institute of Soil, Climate and Water in South Africa, whereas previous work used the soil input from the much simpler 84 soil zones. Previous work on a regional scale using information from the South African Quaternary Catchments Database was performed in a UNIX environment. The FORTRAN programs that were used for this were converted for use in PC format.

Some inadequacies were found in version 3.5 of the CERES-Maize model, which was the version readily available when this research commenced. The limitations of CERES-Maize v. 3.5 that were encountered by the author during this research were:

- The modelling of soil organic carbon and nitrogen levels
- The modelling of runoff and drainage at scales larger than the farm and
- The ability of the model to incorporate effects of tillage practices.

The above inadequacies could be solved in two possible ways: first, by writing new routines and adding them to the model (which might involve changing the structure of the model), or secondly, by linking CERES-Maize to other models. It is recognised that version 4 of the DSSAT suite of models released in 2004 would have been better suited in terms of analysis of soil organic nitrogen and carbon levels, as it has the soil organic matter residue model from CENTURY incorporated into it (Gijsman *et al.*, 2002). Likewise, the linking of CERES-Maize to the *ACRU* agrohydrological model (particularly under South African conditions) would have enabled runoff and drainage to have been modelled more accurately at the Quaternary Catchment and regional scale. In terms of tillage practices, it is suggested that new routines may need to be written to incorporate it fully into the CERES structure, as tillage can affect so many different areas within the agro-ecosystem. For example, the type of tillage could affect organic matter levels, soil loss, drainage and runoff generation.

The stated limitations of CERES-Maize for modelling the different agro-ecosystem functions also then limits the scope of up-scaling results from the farm scale to the Quaternary Catchment scale and on to the regional scale (although this was not an aim of the research). An aim of the research was to derive a framework that could be used at various scales within South Africa (Chapter 4). The derived framework was applied with a degree of success at the different scales, but there were some difficulties in selecting indicators that could be used at the various scales. This was a primary reason for yield being the only indicator of sustainability used at a regional scale (Chapter 5). Only having one indicator for an assessment of sustainability at a regional scale could be considered a narrow view. However, this author decided that to use one indicator that could give good estimates was preferable to using a combination of indicators with which there would be considerable doubt in the validity of the simulated results. Using only yield as an indicator (Chapter 5) also limits the assessment of ecological integrity at a regional scale. This is the major criticism of the sustainability assessment in Chapter 5. There is then a perceived need to incorporate either an external model into the sustainability framework, or provide new routines, that can simulate agro-ecosystem functions such as nutrient cycling on broader scales such as that of the Highveld.

Mean grain yield was the dominant indicator at all the scales modelled. Yield is of vital importance to the well-being and, therefore, the quality of life to both the commercial and smallholder farmers. Yield has importance both economically and socially on the local community. The hydrological indicators within CERES-Maize were found to be less sensitive to the climatic changes and to threshold changes.

9.3 Final Conclusion to the Research

This research has been concerned with developing a framework to assess the sustainability of maize production at various scales in South Africa. The use of a complex crop model such as CERES-Maize within the sustainability framework meant that agro-ecosystem responses to different management options and climate changes could be quantified. With an understanding of the model limitations, inferences can be drawn regarding the effect on the agro-ecosystem functions, as well as on goods and services. This type of assessment can provide a tool so that the processes and components that constitute an agro-ecosystem can be better understood, and as a result, ecological integrity and good quality farmer and community well-being to be achieved.

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