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Climate change impacts on agro-ecosystem sustainability across three climate regions in the maize belt of South Africa

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Abstract

The Highveld region in South Africa is an important area for its food production for the nation, as 70% of country's cereal crops and 90% of the commercially grown maize is cultivated there. The sustainability of these agro-ecosystems is, therefore, of vital importance for the nation's food security. The western part of the Highveld is characterised by relatively low mean annual precipitation (MAP) and highly variable yields, and while rainfall increases towards the east, inter-annual yield variability remains high. Variability of yields is already a concern for agro-ecosystems and it is hypothesised that it could be exacerbated by future climate changes.

A sustainability framework was used to assess the sustainability agro-ecosystems under plausible future climate scenarios. Three Quaternary Catchments were assessed ranging from relatively dry (MAP 432 mm) to relatively moist (MAP 903 mm). A sensitivity analysis of plausible scenarios was performed with incremental increases in temperature by 1, 2 or 3 °C, increases/decreases of rainfall by 10% and a doubling of pre-industrial atmospheric CO_2 concentrations to 555 ppmv.

From the present and nine plausible future climate scenarios which were modelled using CERES-Maize over a 44-year period, it is shown that climatic changes could have major negative effects on the already drier western, and therefore more vulnerable, areas of the South African Highveld. An increase in temperature increases the variability of yields in the relatively moist Piet Retief area (MAP 903 mm), while at the more sub-humid Bothaville, with a MAP of only 552 mm, the inter-annual variability remains the same but mean yield over 44 seasons is reduced by 30%. A simulated increase in temperature coupled with a doubling of CO_2 increases the rate of soil organic nitrogen depletion from the agro-ecosystem. Therefore, long-term perspectives in regard to human well-being and ecological integrity need to be applied to policies and actions for sustainability of both commercial and smallholder agro-ecosystems, particularly, in the western Highveld.

Keywords: Agro-ecosystem; Climate change; Sustainability; Food security; South Africa

1. Introduction

Agro-ecosystems are ecological systems modified by human beings in order to produce food, fibre or other agricultural products (Conway, 1987). The agro-ecosystems in the Highveld region of South Africa (Fig. 1) produce 70% of the country's commercially grown cereal crops, with 90% of its maize being cultivated there (du Toit et al., 2000). The sustainability of the maize producing agro-ecosystems is of huge consequence to food security in South Africa and to the well-being of the rural economy of the Highveld. A change not only in the mean climate, but also in its variability, can have significant impacts on an agro-ecosystem.

Chambers (1997) recognises that humans are at the centre of agro-ecosystems and that their well-being is a key issue for the sustainability of agro-ecosystems. Based on this concept, a general definition of sustainability used by the authors in this paper is: 'Sustainability is applying long term perspectives, in regard to human well-being and ecological integrity, to policies and actions'. (Walker and Schulze, 2006a).

The sustainability of agro-ecosystems in the region will be influenced, *inter alia*, by the El Niño phenomenon, by climate change and by land use changes resulting from the above two and other market or politically related factors.

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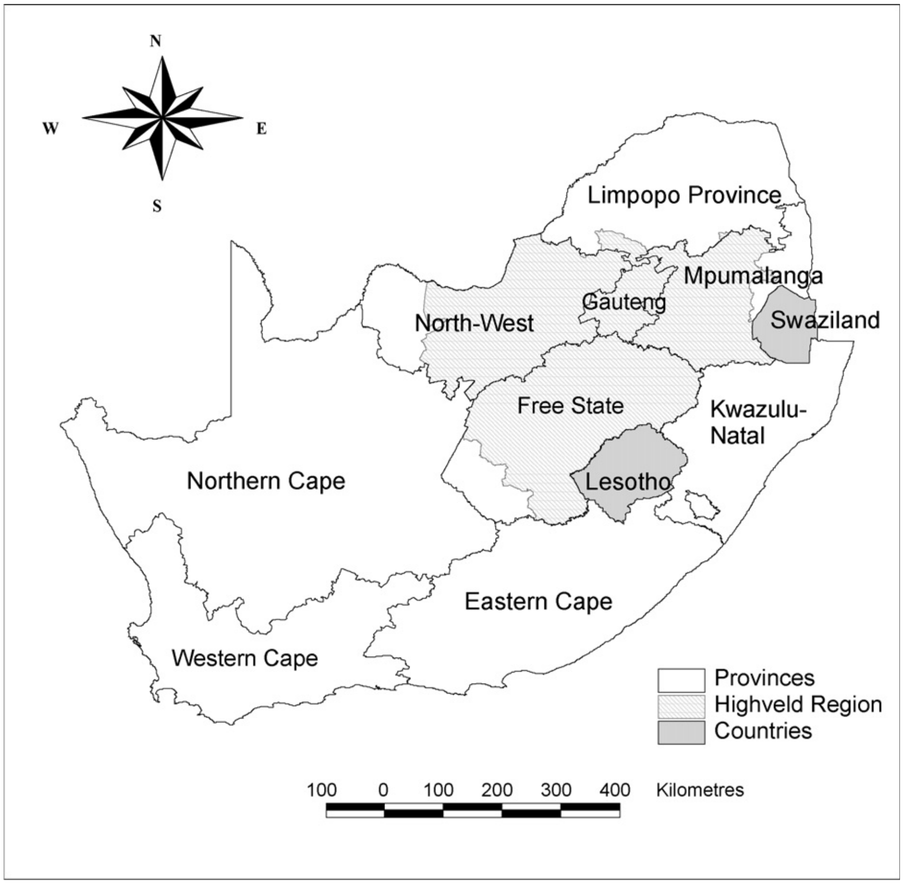

Fig. 1. Highveld region shown in the context of the provinces of South Africa (after du Toit et al., 2002).

The influence of El Niño on the seasonal rainfall in the Highveld region is a reality for farmers (du Toit and Prinsloo, 1998), since it influences directly both their economic security in the long term and local food security in the shorter term. Superimposed climatic changes of enhanced concentrations of CO_2 in the atmosphere and resultant increases in temperature and changes in rainfall patterns (IPCC, 2001; Engelbrecht, 2005) could affect food security and agro-ecosystem sustainability significantly in the long run.

Average maize yields in the drier western half of the Highveld are particular sensitive to climate variability under present climate conditions already, with current average commercial yields being between 1000 and 3000 kg ha^{-1} (du Toit et al., 2000), depending on farming practices and the amount of rainfall during the growing season and it is hypothesised that their vulnerability will increase with climate change. This raises issues of sustainability at a regional and national level, as breakeven yields for a commercial farmer in the western Highveld of South Africa are just over 2000 kg ha^{-1} (du Toit et al., 2000).

In attempting to understand the inter-relationships between social, economic and environmental influences that are associated with sustainability, a systems approach to sustainability is therefore essential (Ikerd, 1993; Hansen and Jones, 1996). For such a systems approach a framework was adapted from von Wiren-Lehr's (2001) goal-orientated system. Hansen (1996) considers it necessary to characterise the concept of sustainability when using it to identify constraints, to identify research foci and for policy development. Incorporating Hansen's and Jones' (1996) method to characterise sustainability, the adapted sustainability framework has the following four steps:

- Goal definition (i.e. defining sustainability, spatial scales, stating required framework outputs; ensuring that the goal selected is one that is realistic to obtain);
- Sustainability modelling (i.e. selecting the simulation model and the model outputs to use as quantitative indicators of sustainability);
- Evaluation strategy (i.e. comparing quantitative measures of different strategies to managing the system); and
- Management advice (i.e. making recommendations that are predictive, with constraints to sustainability being identified).

This paper concentrates on part of the system, i.e. sustainability modelling. The objective of this assessment is to investigate agro-ecosystem sustainability in response to a range of plausible climate scenarios at the spatial scale of Quaternary Catchments in the Highveld region of South Africa. Quaternary Catchments are climatically,

Table 1
Details of Quaternary Catchments used in this study

Attribute	Christiana	Bothaville	Piet retief
General description of rainfall regime	Dry	Medium	Wet
Quaternary Catchment identifier	C91B	C24J	W51C
Mean annual precipitation (mm)	432	552	903
Mean maize yield (kg ha^{-1}) (Walker, 2005)	2169	3178	6299
Conventional planting date (du Toit et al., 2000)	Mid-December	Mid-November	Mid-October
Thickness of topsoil horizon (m) (Schulze, 1997)	0.24	0.21	0.28
Thickness of subsoil horizon (m) (Schulze, 1997)	0.33	0.30	0.50
Dominant soil texture class (Schulze, 1997)	SaLm	SaClLm	SaClLm
Heat units (degree days) October–March (Schulze, 1997)	2078	2011	1872
Reference potential evaporation (mm), a-pan equivalent: October–March (Schulze, 1997)	1600	1493	1143

topographically, hydrologically and agriculturally relatively homogenous areas, which have been delineated by the South African Department of Water Affairs and Forestry for purposes of operational planning. Agro-ecosystem sustainability under the range of climate scenarios used was assessed in regard to changes in maize yield and soil organic nitrogen.

2. Study sites

The Highveld region of South Africa (Fig. 1) ranges in altitude from 900 to 1800 m above sea level. It is part of the inland plateau of the southern African subcontinent. The Highveld region includes parts of North-West, the Free State, Mpumalanga provinces and all of the province of Gauteng. The region is characterised by plains with low to moderate relief, generally low drainage density and low stream frequency (Kruger, 1983). The section of the Highveld that stretches into Mpumalanga province has low mountains with high relief, as well as plains (du Toit et al., 2002). The soils are generally of a sandy clay loam texture, with soil thickness ranging from 400 to 1200 mm, but with clay soils occurring in parts of Gauteng and Mpumalanga (Schulze and Horan, 2006). The soils are considered nutrient poor and are of sandstone origin (du Toit and Prinsloo, 1998).

For this study three Quaternary Catchments (QCs) which display a range of mean annual precipitation (MAP) from 432 to 903 mm, were selected. For the purpose of geographical identification the three QCs are named after towns located in them, viz. Christiana, Bothaville and Piet Retief. Details of the selected sites are shown in Table 1 and the locations of the three QCs are shown in Fig. 2. The heat units shown in Table 1 are expressed as degree days, these are an accumulation of mean temperatures above a certain lower threshold value (10 °C) below which active development of maize is considered not to take place, and below an upper limit (30 °C) above which growth is considered to remain static or even decline over a period of time.

The Highveld is located in a summer rainfall area which receives the vast majority of its precipitation between the months of October and March. According to Schulze's (1997) delineation of southern Africa into regions of rainfall seasonality, the eastern Highveld (Piet Retief) is designated an early summer rainfall area (December maximum), the central Highveld (Bothaville) a mid-summer rainfall area (January maximum) and the western Highveld (Christiana) a late summer rainfall area (February maximum).

A mid-summer dry spell occurs in the Highveld in about 9 out of 10 years, with low rainfall for days to weeks and high temperatures (du Toit et al., 2000). Solar radiation is higher in the western than the eastern parts of the Highveld (Schulze, 1997). In January the (mid-summer) solar radiation ranges from 32 to 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 mid-winter, i.e. July, solar radiation is considerably lower, ranging from 16 to 19 MJ m^{-2} day^{-1} (Schulze et al., 2006).

Monthly means of daily maximum temperature in the summer months, i.e. December to March, range from 28 to 30 °C in the west and 26–30 °C in the east, while the means of minimum temperatures in these months are between 12 and 16 °C across the region (Schulze, 1997). 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 the end of September (Schulze, 1997), i.e. 4–6 weeks before planting commences.

3. Methods

3.1. Sustainability modelling

In order to assess the sustainability of agro-ecosystems at a Quaternary Catchment scale, the adapted goal-orientated framework was utilised, the four steps of which were described previously. This study examines how the agro-ecosystem functions are affected by plausible changes in climatic parameters.

In this assessment the goal of the framework in regard to sustainability is defined as follows: 'The goal is for the agro-ecosystems in the Highveld region to continue in the long

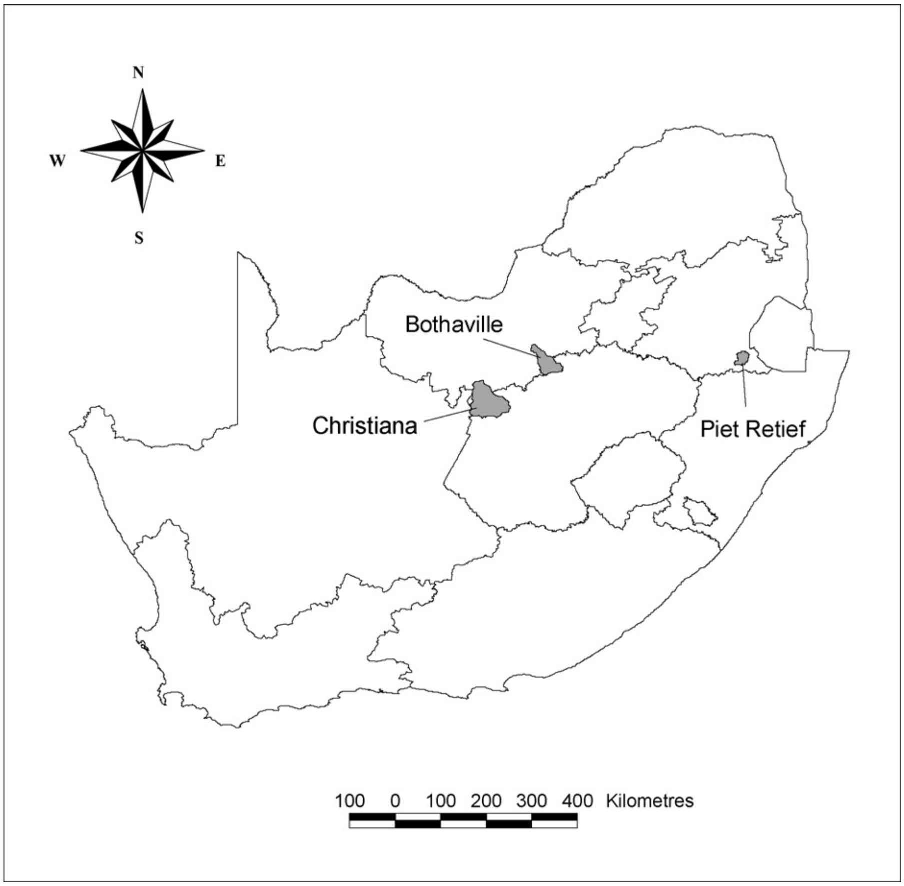

Fig. 2. Location of three Quaternary Catchments selected for the sustainability assessment.

term, providing quality well-being for farmers and local communities and to maintain ecological integrity'.

For the commercial farmer it becomes economically viable to produce maize only when its production exceeds 2200 kg ha^{-1} in western Highveld and exceeds 3600 kg ha^{-1} in the eastern Highveld (Durand and du Toit, 1999). Yield levels for viable production were calculated assuming the maize price to be US \$95 per 1000 kg and total production costs to be US \$200 per hectare (Durand and du Toit, 1999).

The CERES-Maize (Jones and Kiniry, 1986) model was used in sequential mode over 44 seasons to estimate maize yields and soil organic nitrogen loss. CERES-Maize version 3.5 has received extensive regional calibration for southern Africa (du Toit et al., 1994; du Toit et al., 1997) and the model contains a range of useful management options. 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. The appeal of sequential modelling is that long term trends in the end-of-season output such as yield or soil organic nitrogen level can be determined.

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). This database contains, for each QC, a 44-year record of quality controlled daily rainfall, temperature (Schulze and Maharaj, 2004) and solar radiation values, as well as relevant soils information (Schulze and Horan, 2006).

CERES-Maize was run sequentially for 44 years with daily climate plus soils information from this database, assuming conventional planting dates for the three QCs modelled (Table 1) and 120 kg ha^{-1} of inorganic nitrogen fertiliser per season (Walker and Schulze, 2006b).

3.2. Simulations undertaken

A sensitivity analysis of present and plausible future climate conditions formed part of this study. To determine what would be 'plausible' in future, output for South Africa was analysed from a number of regionally downscaled General Circulation Models (Perks et al., 2000), including the Conformal-Cubic Atmospheric Model (C-CAM), a regional climate model developed by the CSIRO in Australia. C-CAM was validated for present climate conditions (1975–2005) and then applied by Engelbrecht (2005) for simulations of a 2070–2100 future climate over southern and tropical Africa. Cognisant of the fact that climate change predictions suggest different temporal distributions of daily rainfall and temperature (e.g. Perks et al., 2000; Engelbrecht, 2005), a simple approach was adopted by considering 'plausible' rainfall changes from the present (i.e. ΔP) in the Highveld to range from $\Delta P = -10$ to +10% by linear change of present daily values, while plausible temperature perturbations derived from the various Global Climate Models (GCMs) for the Highveld were taken to be ΔT = +1, +2, +3 °C when compared with present daily values. In the sensitivity analysis for this study the following nine future climate scenarios were evaluated in relation to present climate conditions:

- An effective doubling of pre-industrial atmospheric CO_2 concentrations to 555 ppmv ($2 \times CO_2$),
- increasing both minimum and maximum daily temperatures by 2 °C,
- $2 \times CO_2$ + 1 °C minimum/maximum daily temperature increase,
- $2 \times CO_2$ + 2 °C minimum/maximum daily temperature increase,
- $2 \times CO_2$ + 3 °C minimum/maximum daily temperature increase,
- $2 \times CO_2$ with a 10% reduction in rainfall,
- $2 \times CO_2$ with a 10% increase in rainfall,
- $2 \times CO_2$ + 2 °C minimum/maximum daily temperature increase with a 10% reduction in rainfall, and
- $2 \times CO_2$ + 2 °C minimum/maximum daily temperature increase with a 10% increase in rainfall.

Whilst not realistically representative of actual combinations of future climates, these incremental analyses are useful in determining the sensitivity of the "exposure unit" (e.g. changes in yield or organic nitrogen). The principal climatic driver for agriculture in South Africa is precipitation. A linear increase and decrease of precipitation was used in the simulations. Although this approach shows the sensitivity of each QC to changes in precipitation it also has limitations. This method does not include changes in variability and extremes of rainfall.

4. Results

The nine climate scenarios were modelled using CERES-Maize at the three selected QCs in the Highveld and the results were compared with simulations for present climatic conditions. Outputs assessed were:

(1) maize yield,
(2) the inter-annual coefficient of variation (CV) of yield, which is used here as a measure of risk, and
(3) soil organic nitrogen levels.

An increase in both daily maximum and minimum temperatures by 2 °C promotes rate of crop development, but simultaneously, through increased evaporative demand, can dry out the soil more rapidly. An increase in the rate of development reduces the time available for the crop to capture solar radiation and convert CO_2 to biomass. In a southern African context in which climates are generally rainfall limited but not radiation limited, yields generally decrease with an increase in temperature by itself, as illustrated from the results in Table 2 for each of the three QCs modelled.

Overall results from present climatic conditions and nine plausible future climatic scenarios are given for the climatic regimes represented by the three QCs in Table 2 (yield and variability of yield changes) and Table 3 (soil organic nitrogen loss changes), while other more specific time series results are discussed by QC.

4.1. Results from the relatively "Dry" Christiana Quaternary Catchment

The simulated mean grain yield over 44 seasons for the Christiana QC is 2217 kg ha^{-1} for present climatic conditions and 2730 kg ha^{-1} for an effective doubling of atmospheric CO_2 concentrations but with no changes to the rainfall or temperature regimes (Table 2).

At the Christiana QC a doubling of CO_2 in association with a temperature increase of 2 °C results in the maize yields increasing in 28 out of 44 seasons (Fig. 3). An

Table 2
Summary of simulations of mean yields and inter-annual coefficients of variation of yields for different climate scenarios under three rainfall regimes over 44 seasons

Climate scenario	Christiana (MAP = 432 mm)		Bothaville (MAP = 552 mm)		Piet retief (MAP = 903 mm)	
	Yields (kg ha^{-1})	CV of yields (%)	Yields (kg ha^{-1})	CV of yields (%)	Yields (kg ha^{-1})	CV of yields (%)
Present climate	2217	86.8	3393	54.3	6114	26.7
$2 \times CO_2$	2730	79.8	4280	42.7	6405	15.7
Temperature + 2 °C	1983	56.2	2435	54.3	5130	33.8
$2 \times CO_2$ + 1 °C	2735	71.9	3700	46.9	5948	15.9
$2 \times CO_2$ + 2 °C	2561	69.5	3325	49.0	5834	20.6
$2 \times CO_2$ + 3 °C	2382	63.7	2 986	52.2	4930	28.8
$2 \times CO_2$ − 10% rainfall	2424	84.8	3797	48.7	6402	16.9
$2 \times CO_2$ + 10% rainfall	2967	73.4	4325	35.3	6502	13.0
$2 \times CO_2$ + 2 °C + 10% rainfall	2722	68.5	3799	42.7	5755	21.6
$2 \times CO_2$ + 2 °C − 10% rainfall	2175	69.1	3061	59.8	5716	24.5

Table 3
Summary of simulated soil organic nitrogen loss for different climate scenarios under three rainfall regimes over 44 seasons

Climate scenario	Soil organic nitrogen loss (%)		
	Christiana (MAP = 432 mm)	Bothaville (MAP = 552 mm)	Piet retief (MAP = 903 mm)
Present climate	−21.2	−27.3	−28.8
$2 \times CO_2$	−22.9	−28.8	−33.2
Temperature + 2 °C	−26.7	−31.5	−34.3
$2 \times CO_2$ + 1 °C	−24.6	−30.2	−35.9
$2 \times CO_2$ + 2 °C	−26.0	−32.1	−37.2
$2 \times CO_2$ + 3 °C	−27.2	−33.3	−38.3
$2 \times CO_2$ − 10% rainfall	−20.9	−30.4	−31.0
$2 \times CO_2$ + 10% rainfall	−25.0	−26.8	−27.9
$2 \times CO_2$ + 2 °C + 10% rainfall	−35.5	−46.9	−52.5
$2 \times CO_2$ + 2 °C − 10% rainfall	−24.3	−31.1	−35.6

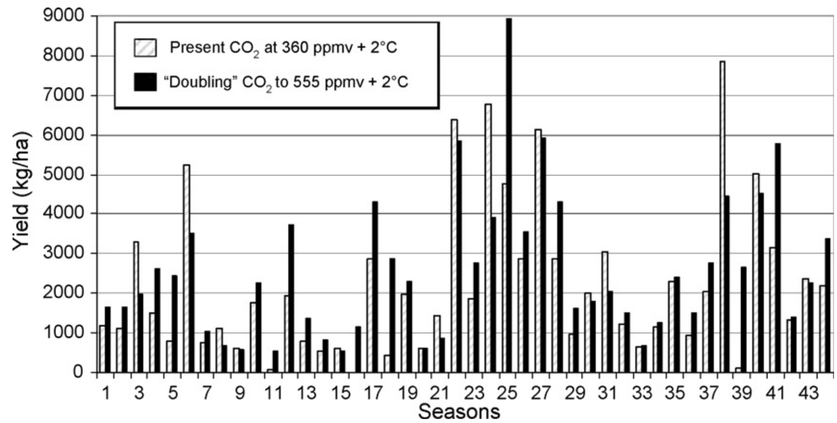

Fig. 3. The influence on maize yield of an effective doubling of atmospheric CO_2 concentrations in combination with a 2 °C increase in minimum and maximum temperatures for the relatively dry Christiana Quaternary Catchment.

increase in just temperature by itself negatively affects the mean grain yields in the Christiana QC (from 2217 to 1983 kg ha^{-1}), but for a doubling of CO_2 in conjunction with temperature increases the yields are higher and CVs lower, even for a temperature increase of +3 °C. For present climate conditions the maize yield at Christiana was below 1000 kg ha^{-1} in 12 seasons out of 44 compared with only 8 seasons for the $2 \times CO_2$ + 2 °C scenario (Fig. 3). Yield was below the break-even value of 2200 kg ha^{-1} in 28 seasons out of the 44 simulated, while the biggest differences in yield for the two climate scenarios occur in seasons when the present yield is above 2000 kg ha^{-1} (Fig. 3).

Previous studies using GCMs predicted that this area will have reduced rainfall and increased temperature, which will negatively affect yields. The scenarios were generated from the Climate Systems Model (CSM) of the National Centre for Atmospheric Research in the USA and from the UK Meteorological Office, Hadley Centre the HadCM2 model with no sulphate forcing. du Toit et al. (2000) found that, in the area that corresponds with the Christiana QC, results from both models suggested yield would decrease by between 20 and 40%.

An increase in rainfall increases the soil organic nitrogen loss (Table 3). This could be due to the increase in biomass production that the experienced with a 10% increase in annual rainfall. With the scenarios that have a 10% decrease in the annual rainfall, biomass production is reduced and so is the soil organic nitrogen loss.

4.2. Results from the "Medium" rainfall Bothaville Quaternary Catchment

At the Bothaville QC, which has a moister climate regime than Christiana (Table 1), the average yields over 44 seasons with the '$2 \times CO_2$' scenario increased from 3393 to 4280 kg ha^{-1}, with the year-to-year variability of yields reducing. For 38 out of 44 seasons the yields are simulated to be higher than for present climate conditions with a doubling of CO_2 (Fig. 4). There are 14 seasons under present climate conditions where the yield is below 2200 kg ha^{-1}, which is the break-even yield, with this reducing to 9 seasons out of 44 with a doubling of CO_2. The yields with this climate scenario are still highly variable (42.7% compared to 54.3% under present climate) due to the variability of rainfall. The increase in temperature of 2 °C counteracts the photosynthetic benefit to the plant of an effective doubling of CO_2, i.e. the grain yield under this scenario is similar to that under present conditions (Table 2).

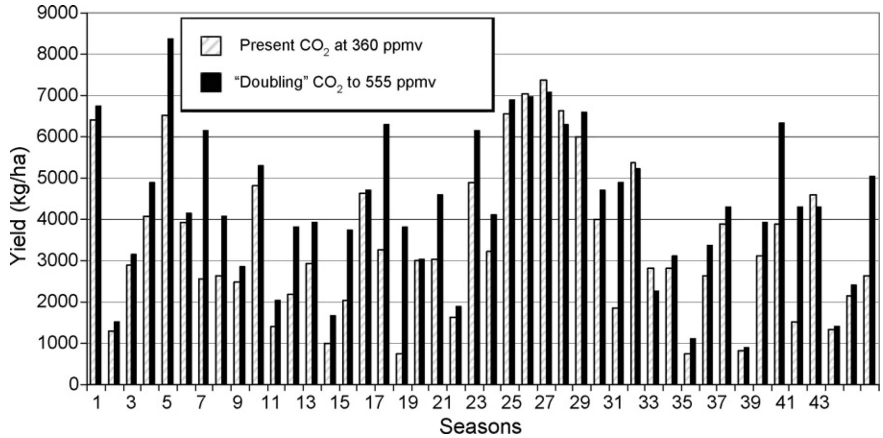

Fig. 4. The influence on maize yield of an effective doubling of atmospheric CO_2 concentrations for the Bothaville Quaternary Catchment.

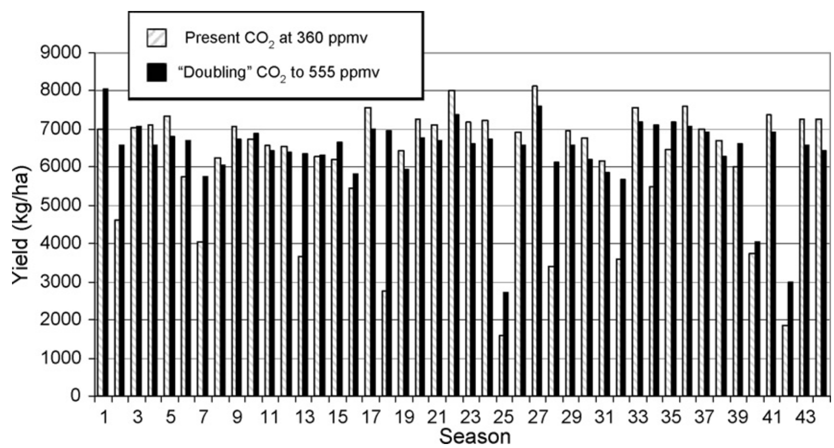

Fig. 5. The influence on maize yield of an effective doubling of atmospheric CO_2 concentrations for the relatively wet Piet Retief Quaternary Catchment.

The highest simulated soil organic nitrogen losses occur with a doubling of CO_2 concentrations in combination with either a 3 °C increase in temperature or with a 2 °C increase coupled with a 10% increase in rainfall (Table 3). Higher temperatures and increased rainfall lead to an increase in microbial activity in the soil and this combination accelerates the breakdown of organic matter, thereby increasing the readily available nitrogen in the soil to the plant. The effective doubling of CO_2 would 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.

4.3. Results from the relatively "Wet" rainfall Piet Retief Quaternary Catchment

Piet Retief has the highest MAP (903 mm) of the three QCs selected for this study and it is located on the eastern fringe of the Highveld region. On average the simulated yields increase by ~300 kg ha^{-1} from 6114 to 6406 kg ha^{-1} with a doubling of atmospheric CO_2 concentrations (Fig. 5). In only 18 of the 44 seasons modelled are the yields higher with an effective doubling of CO_2. Grain yields fall below the breakeven yield of 3600 kg ha^{-1} for this region on five occasions with present climate and twice when the CO_2 concentration is increased to 555 ppmv (Fig. 5). The biggest positive impact on yields at Piet Retief is generally for those seasons when there is low rainfall (e.g. seasons 18, 25, 28 or 42 in Fig. 5). The largest variation in simulated yield between these scenarios occurs when the yield is around 3000 kg ha^{-1} under present climate conditions. It is in these lower rainfall years at the Piet Retief QC that the doubling of atmospheric CO_2 (Fig. 5) would benefit the crop, and where the transpiration feedback would be most noticeable.

A rise in temperature by 2 °C or more, even with a doubling of effective CO_2, has a negative effect on the mean grain yield at Piet Retief (Table 2). The higher temperatures result in reductions in available soil water and, as a consequence, negatively impact yield. Results from a previous study (du Toit et al., 2000) showed that the impacts on maize yield on the area that corresponds to the Piet Retief QC predicted there to be either no appreciable difference in yield (CSM model) or a 10–20% reduction in yield (HadCM2 no sulphates).

Yield variability at Piet Retief is the lowest of the three QCs assessed, as it is the QC with the highest and most

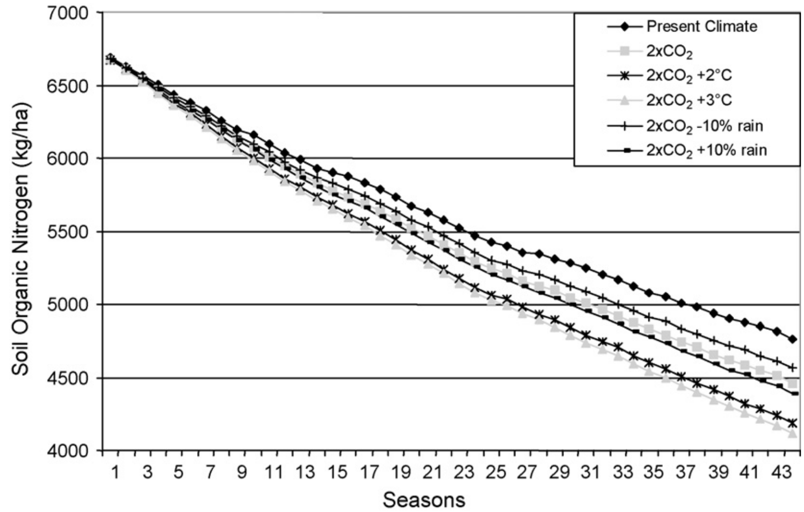

Fig. 6. Decreases in simulated soil organic nitrogen levels over 44 seasons at the Piet Retief QC for selected climate scenarios.

reliable rainfall (Table 2). The climate scenarios that would reduce the variability even further than at present, and also increase the mean yields, are the ones that contain an effective doubling of CO_2. However, yield variability increases with a rise in temperature or a reduction in rainfall (Table 2).

The soil organic nitrogen losses at the Piet Retief QC (Fig. 6) and the other QCs (not illustrated in this paper, but available from the authors) are highest when climate change scenarios are associated with an increase in temperature. The five scenarios in Fig. 6 which are compared with present climatic conditions show that an increase in CO_2 will yield organic nitrogen losses from the soil at a faster rate than under present climate, with the greatest simulated losses associated with $2 \times CO_2 + 2\ ^{\circ}C$ and $2 \times CO_2 + 3\ ^{\circ}C$ climate scenarios.

5. Discussion

In the Highveld region, particularly in the drier western parts, rainfall is the major limiting factor to crop development. At Christiana, the driest of the three QC modelled, the scenario of enhanced CO_2 with reduced rainfall and increased temperatures was shown to inhibit crop development and reduce yields, while in regard to soil organic nitrogen it was a combination of drivers that resulted in higher losses, as illustrated for the moist Piet Retief QC. Gbetibouo and Hassan (2005) report that maize grown in the Highveld was sensitive to marginal increases in temperature and that the range of tolerance to increased temperature was narrow compared to changes in precipitation. The analysis, however, was on a broad provincial spatial scale. The results from Christiana QC in Table 2 show that maize yield is sensitive to a decrease in rainfall and has an immediate negative impact on yield.

The effects of combinations of an effective doubling of atmospheric CO_2 plus increased temperatures (the '$2 \times CO_2$ with +1, +2 and +3 °C' scenarios) was that the "drivers" in these climate scenarios were self-cancelling up to a point, with the '$2 \times CO_2$ +3 °C' climate scenario producing reduced simulated yields.

The enhancement of atmospheric CO_2 concentrations from present levels of around 360 to 555 ppmv, i.e. the so-called $2 \times CO_2$ scenario, results in enhanced photosynthetic rates plus enhanced stomatal closure, with the latter implying reduced transpiration rates. The increase in CO_2 concentrations increased yield across the three rainfall regimes. Enhanced CO_2 levels not only increases yield, but also reduces the CV of yields, and therefore reduces the farmers' risk of crop failure. The CV of maize yields is linked closely to the reliability of rainfall, and in the Highveld the CV of yields increases from east towards the west, in tandem with reductions in mean annual precipitation.

An increase in temperature by itself increases the variability of yields at the QC with the highest rainfall, viz. Piet Retief, while at the Bothaville QC with the medium MAP the variability remains similar, but mean yield over the 44 seasons for which simulations were undertaken is reduced by up to 30%.

The three agro-ecosystems that were modelled at the QC level assuming conventional tillage as the management practice. Soil nitrogen losses in the three QCs modelled range from 27 to 29% under present climatic conditions (Table 3), resulting from intensive tillage practices and nutrient poor soil of sandstone origin. Soil organic nitrogen losses increase with enhanced CO_2 levels, temperature increases and increase in rainfall (Table 3 and Fig. 5). Lobe et al. (2001) analysed soil samples from agro-ecosystems in the Free State to understand the effects of long-term cultivation (up to 98 years) on organic matter levels. Soil organic nitrogen was found to be reduced by up to 55%. This is higher than the simulated losses under present conditions recorded in Table 3. The differences can be attributed wind erosion and to the simulations being over a shorter period.

From the possible climate scenarios modelled it has been shown that climatic changes could have major negative effects especially in the drier western and, therefore, more vulnerable area of the South African Highveld region. It has previously been shown that South Africa experiences rainfall quasi-cycles of approximately 20 years (Tyson, 1986). Such a rainfall cycle is well illustrated in Fig. 3 by the inter-annual variability of mean maize yields at the Christiana QC. A key to sustainability of agro-ecosystems in the Christiana area is an understanding of how possible climatic changes could affect apparent rainfall cycles.

The modelling was carried out at a regional scale, each QC consisting of several hundred square kilometres. Within each QC both commercial and emerging farmers produce maize. The Christiana QC is a marginal maize producing area under present climatic conditions. The results from climate sensitivity analysis showed that it is more vulnerable than the QCs with higher MAPs (Bothaville and Piet Retief) to increases in temperature and decreases in rainfall and, therefore, adaptation strategies for the Christiana QC need to be considered. The IPCC fourth assessment report synthesised results from several maize adaptation simulations from multiple sites under different climate regimes and showed that adaptations could provide an approximate 10% increase in yield compared to those simulations where adaptations were not used (Easterling et al., 2007).

Adaptations can be categorised as either autonomous or planned. Autonomous adaptations are those that happen naturally as farmers observe a changing climate (Carter et al., 1994). In the context of maize production in the Christiana QC this could include a move to conservation agriculture, the introduction of rainwater harvesting and supplementary irrigation, a change in maize variety grown, i.e. to one with a shorter growing season, or a move to a crop that is more drought tolerant. Planned adaptations included developing new infrastructure, and formulating policy to build capacity to adapt. An example of a planned adaptation for the Christiana QC would be research into improved seasonal climate forecasts and applying them to agriculture (Fankhauser et al., 1999).

Conservation farming is a minimum tillage method that maintains at least 30% residue cover after planting, this has the potential to trap moisture, improve the quality of the soil, minimises soil erosion and create growing conditions that exhibit a high drought tolerance (Uri, 1999). Crop residue cover could also protect the soil from erosion by rainfall which would grow in importance if rainfall events intensify under a future climate. A significant crop residue can increase the soil water holding capacity and lower soil water evaporation which at the Christiana QC could be beneficial as temperatures increase. No till or minimum tillage is often characterised by an increase in weeds. However, weeding during winter has been used successfully to combat this (Oldrieve, personal communication). CERES-Maize version 3.5 used in this research and could not model conservation tillage effects on a regional scale satisfactorily (Walker and Schulze, 2006a).

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. This option maybe viable for smallholder farmers but for the commercial farmers particularly in the Christiana QC where large areas are given to maize production the use of harvested rain water for irrigation may not be feasible. The cost of storage tanks to store harvest water maybe prohibitive but those methods that don’t use tanks such as contour bunds and strip catchment tillage could be introduced.

Under present climatic conditions the optimum planting date for QCs in the western Free State such as Christiana is mid-December (du Toit et al., 2000) and using a maize hybrid with a medium length growing season (130–145 days) produces the highest yields with the lowest variability (Schulze and Walker, 2006). A rise in temperature or a change in rainfall patterns may shorten the growing season. A feasible strategy under future climate with higher temperature and a change in rainfall pattern would be to grow hybrids with a short growing season (115–130 days). Abraha and Savage (2005) found that varying the planting date was beneficial in lessening the impact of possible climate change. However, their research was in the KwaZulu-Natal midlands, which is an area of South Africa where increased precipitation could occur in future climates.

6. Conclusion

The use of the adapted framework (goal definition, sustainability modelling, evaluation, management advice) enabled possible constraints to agro-ecosystem sustainability to be identified. The constraints identified include: soil organic losses at all three QCs, reduced crop growth at Christiana if rainfall reduces and temperature increases, and at temperatures increases above +3 °C (for all three QCs) the positive effect of enhanced CO_2 levels is negated and yields begin to decline. Therefore, long-term perspectives in regard to human well-being and ecological integrity need to be applied to policies and actions for sustainability of both commercial and smallholder agro-ecosystems, particularly, in the western Highveld. These policies and actions include the formulation of strategies to combat climatic changes, favourable trade policies, as well as improved access to credit and markets. In practice, the adaptation strategies discussed may be used in combination. Future research could focus on conservation tillage practices used in combination with shorter season hybrids and applying seasonal climate forecasts.

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