Global climate change and agricultural productivity in southern Africa

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An analysis tool was developed to simulate primary productivity and crop yields for both present and possible future climate conditions. Southern Africa was delineated into 712 relatively homogeneous climate zones, each with specific climate, soil and vegetation response information. The primary productivity and crop yield models were linked with the climate zones via a cell-based agrohydrological model, with the final output coordinated using a Geographic Information System. The results of this preliminary study show a large dependence of production and crop yield on the intra-seasonal and inter-annual variation of rainfall. The most important conclusion from the study is the readiness of the developed tool and associated infrastructure for future analysis into social, technological and political responses to food security in southern Africa.

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[1]J.D. Arbuthnot, *The Impact of Environmental Change on Southern African Agri-*
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The population of southern Africa (defined in the context of this paper as South Africa and the still independent/self-governing states within it, plus the Kingdoms of Lesotho and Swaziland) is projected to increase from its present 40 million to between 70 and 90 millon by the year 2035. To meet the food demands of this growing population, crop production will have to expand at 3% per annum.[1] This is not an easy task, however, as the southern African subcontinent is largely semi-arid and sub-humid and has a diversity of soils, of physiography, of agricultural crops grown, and of management levels at which they are grown. Above all those factors, however, is the wide range of climates, characterized by a marked intra-seasonal and inter-annual variability of rainfall. In terms of resource management, this is a high-risk environment which, in the agricultural industry, be it in the commercial or subsistence sector, implies in most areas uncertain productivity, frequent crop failures and consequently a drain on state finances through subsidies and drought relief.

Of the total land area in southern Africa, most is used for agriculture. In South Africa, for example, this proportion is 89%. However, 17 000 ha of agricultural land is lost per annum to industrial expansion, mining, and formal as well as informal urban expansion. A further 18 000 ha of agricultural land per annum is currently being converted to commercial afforestation.[2] This shrinking area of agricultural land is *inter alia* forcing agriculture into climatically more marginal areas associated with even more delicate sensitivities to climate and to economic risks,[3] implying that crop production per unit area in the higher agricultural production areas will need to be increased substantially.

Superimposed onto this already high-risk environment are the further considerable uncertainties and possible threats linked with as yet unknown regional impacts of an anticipated global climate change associated with the augmented greenhouse effect. With the many questions relating to the magnitudes and directions of climate change, CO_2 'fertilization' effects, possible system feedbacks, spatial shifts in agricultural belts, sensitivities to crop yields, and changes in vulnerabil-

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ity to crop failure, global climate change has ramifications which reach into food production, food supply, its distribution subsystems, inter-regional food dependence and international trade.

Any national or regional agricultural plan, food security strategy or resource management programme requires, as a prerequisite, a basic knowledge and interpretation of the intrinsic environmental production capacity of the region, its regional distribution patterns and its natural variability. This is necessary in general agricultural terms as well as in relation to the production potential of the region's staple food crop. If, on top of that, climate change poses an additional threat to food security and a region's economic viability, then there is a strong motivation to assess impacts of climate change over and above those of natural variability, particularly if it is surmised that the influences of a climate change on the inter-annual variability, and thus risks of yields, is likely to be more problematic than its consequences on average yields.

Objectives

To address the above problems relating to food security, a first step is to set up the infrastructure for, and then to apply, appropriate simulation models of production at an appropriate level of regional disaggregation of this physiographically and climatically diverse region. Climatic, edaphic, plant growth rate and agronomic data/information sets, to be used as inputs to these models, also have to be obtained.

This paper outlines the scientific foundations of a food security study by assessing, mapping and interpreting, for the southern African region, the distributions and inter-annual variabilities

- of net above-ground primary productivity, selected as an expression of the intrinsic environmental production capability of a region, and
- of maize yields (attained under both commercial and subsistence management conditions), with maize being selected because it occupies 58% of the cropland and is the staple grain crop of southern Africa,
- with distributions being mapped for both present and possible future climate scenarios,
- using a daily time step agrohydrological modelling system, *ACRU*, within which has been imbedded the CERES suite of crop growth/yield models.

To preface the results and their possible implications for regional food security, we first discuss the system infrastructure (eg regionalization, databases); the models which were developed and selected, namely *ACRU*[4] and CERES[5] and their interlinkages; the concepts of primary productivity; the assumptions made in the maize yield model; and the proposed climatic perturbations associated with an enhanced greenhouse effect.

System infrastructure

Regional disaggregation

Because of southern Africa's altitudinal range (0 to 3000 m) and diverse rainfall climate (mean annual precipitation (MAP) less than 50 to over 3000 mm), South Africa has been delineated into 712 relatively homogeneous response zones of differing area according to local

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culture, Report to the Interdepartmental Co-ordinating Committee for Global Environmental Change (ICC) Task Group on the Terrestrial Environment. Department of Environment Affairs, Pretoria, 1992.
[2] *Ibid.*
[3] N.B. Human, Report to the Interdepartmental Co-ordinating Committee for Global Environmental Change (ICC) Task Group on the Terrestrial Environment, Department of Environment Affairs, Pretoria, 1992.
[4] R.E Schulze, *ACRU: Background, Concepts and Theory*, Report 154/1/89, Water Research Commission, Pretoria, 1989, p 235.
[5] International Benchmark Sites Network for Agrotechnology Transfer (IBSNAT) Project, Decision Support System for Agrotechnology Transfer Version 3.0 (DSSAT V3.0), Department of Agronomy and Soil Science, College of Tropical Agriculture and Human Resources, University of Hawaii, Honolulu, HI, 1993. In print.

variations of *inter alia* MAP, altitude, relative relief, aspect and the intensity of agricultural production as criteria.[6] The map of 712 relatively homogeneous response zones was captured into a Geographic Information System (GIS). The GIS was then linked with appropriate geocoded vegetation, soils and climate information bases.

Climate data and information bases

The climate data and information bases for each zone consist of the following.

Rainfall. A representative rainfall station for each zone was selected from the national rainfall databases. The main criterion for station selection was a minimum record length of 40 years of reliable daily data, with any missing data filled synthetically by Dent *et al*[7] using recognized techniques for southern Africa developed by Zucchini and Adamson.[8]

Air temperature. A representative temperature station was assigned to each zone so that reliable monthly means of daily maximum and minimum temperatures could be obtained. An altitudinal correction factor, based on mean regionalized adiabatic lapse rates for maximum and minimum temperatures as determined by Schulze and Maharaj,[9] was used to adjust the mean monthly temperature data for differences between the average elevation of the zone and the elevation of temperature station. Daily values of maximum and minimum temperatures are derived internally within the *ACRU* model from the monthly means using Fourier analysis.[10]

Reference potential evaporation. For the assessment of primary productivity, the USWB Class A evaporation pan was selected for determining reference potential evaporation E_r.[11] Because of the lack of a uniformly dense network of A-pans from which to interpolate E_r, monthly A-pan equivalent evaporation estimates were derived from monthly air temperature data using the Linacre E_r equation.[12] The Linacre equation, a temperature-based surrogate of the Penman technique,[13] has been modified for southern African conditions to improve E_r estimates by applying a day-length correction factor to its radiation-related term and by making regional and seasonal adjustments to the wind term.[14] Daily values of E_r are determined within *ACRU* from the monthly totals using Fourier analysis. Each daily E_r amount is further perturbed by enhancing it by 5% on non-rain days and suppressing the evaporation by 20% on each rain day with > 5 mm rainfall.[15]

Solar radiation. The CERES model uses a version of the Priestley and Taylor equation[16] to estimate a reference potential evapotranspiration. This equation requires daily input of incoming solar radiation, which has been measured for long durations at only a few meteorological stations in southern Africa.[17] However, solar radiation can be estimated from sunshine duration using the Ångström equation,[18] and sunshine duration is measured reliably at several hundred sites in southern Africa. Reid[19] determined regional solar radiation:sunshine duration relationships for southern Africa from which he produced 12 monthly isoline maps of incoming solar radiation. These isolines were geocoded into a GIS to obtain representative monthly values for each of the 712

[6]M.C. Dent, R.E. Schulze and G.R. Angus, *Crop Water Requirements, Deficits and Water Yield for Irrigation Planning in Southern Africa*, Report 118/1/88, Water Research Commission, Pretoria, 1988, p 183.
[7]*Ibid.*
[8]W. Zucchini and P.T. Adamson, *The Occurrence and Severity of Droughts in South Africa*, Report 91/1/84 and Appendix, Water Research Commission, Pretoria, 1984.
[9]R.E. Schulze and M. Maharaj, *Regional Adiabatic Lapse Rates in Southern Africa for Maximum and Minimum Temperatures*, Department of Agricultural Engineering, University of Natal, Pietermaritzburg, 1993, mimeographed.
[10]Schulze, *op cit*, Ref 4.
[11]*Ibid.*
[12]E.T. Linacre, 'A simple formula for estimating evaporation rates in various climates using temperature data alone', *Agricultural Meteorology*, Vol 18, 1977, pp 408–424.
[13]H.L. Penman, 'Natural evaporation from open water, bare soil and grass', *Proceedings of the Royal Society*, London, Vol A193, 1948, pp 120–146.
[14]Dent *et al*, *op cit*, Ref 6.
[15]*Ibid.*
[16]C.H.B. Priestley and R.J. Taylor, 'On the assessment of surface heat flux and evaporation using large scale parameters', *Monthly Weather Review*, Vol 100, 1972, pp 81–92.
[17]P.C.M. Reid, 'Energy aspects of water use efficiency', Technical Report No 111, Department of Environment Affairs, Pretoria, 1981, p 217.
[18]A. Ångström, 'Solar and terrestrial radiation', *Quarterly Journal of the Royal Meteorological Society*, Vol 50, 1924, pp 121–126.
[19]Reid, *op cit*, Ref 17.

Table 1. Generalized vegetation input parameters for the *ACRU* modelling system, derived from minimum temperatures.

Monthly mean of daily minimum temperature (°C)	Crop coefficient	Fraction of roots in topsoil horizon	Interception (mm per rainday)
< 5	0.20	1.00	0.40
5–6	0.30	1.00	0.60
6–7	0.40	0.95	0.80
7–8	0.50	0.90	1.00
8–9	0.65	0.85	1.30
9–10	0.80	0.80	1.60
> 10	0.85	0.75	1.70

Source: R.E. Schulze and S.D. Lynch, 'Distributions and variability of primary productivity over southern Africa as an index of environment and agricultural resource determination', *ICID International Symposium on Impacts of Climatic Variations and Sustainable Development in Semi-Arid Regions*, Fortaleza, Brazil, 1992, p 16.

climate zones. *ACRU* converts the monthly incoming solar radiation to daily values for each zone by Fourier analysis.

Vegetation. To determine the vegetation water use in each of the 712 zones, vegetation parameters such as crop coefficients, rooting distributions and rainfall interception values are required as input into the *ACRU* modelling system. Crop coefficients are used to determine the maximum soil water evaporation and transpiration loss by vegetation. Vegetation interception rates are input to determine *inter alia* effective rainfall amounts, while rooting distributions within the various soil horizons are used in *ACRU* for estimating soil water uptake rates by plants.

Since there is currently no generalized land cover map (other than for natural vegetation) for southern Africa which can be used in the primary productivity component of this study, these vegetation parameters were generated using minimum temperatures. Thus a new season's potential growth commenced, proceeded and senesced according to a set of minimum temperature thresholds (Table 1). A natural vegetation of grassland and deciduous shrub was assumed and values were based on experience of the authors, of ecologists and grassland scientists. The temperature thresholds of the vegetation parameters applicable to the *ACRU* model are summarized in Table 1.

Soils. Soils information pertaining to southern Africa was obtained from the Institute for Soil, Climate and Water which has identified 84 'broad natural homogeneous' soil regions. The soils were classified, using the South African binomial system, into 41 soil forms, each made up of a vertical sequence of diagnostic horizons easily identifiable in the field, which in turn were further subdivided into a total of 501 soil series according to a variety of soil physical and chemical criteria.[20] Each soil form with its range of soil series has been correlated with the USDA Comprehensive System[21] and the FAO World Map Legend[22] to allow for international comparison. A computerized decision support system was developed to interpret the soil classification system hydrologically[23] to derive necessary information such as soil water retention constants, drainage rates and the respective soil horizon depths for each soil form and series. The information from the soils map was again geocoded into a GIS to obtain relevant soil parameter values for each of the 712 climate zones.

Climate change scenarios

To develop a perturbed climate input for southern Africa to simulate impacts of the enhanced greenhouse effect, a number of climatic change

[20]C.N. MacVicar, J.M. de Villiers, R.F. Loxton, E. Verster, J.J.N. Lambrechts, F.R. Merryweather, J. le Roux, T.H. van Rooyen and H.J. Harmse, *Soil Classification – A Binomial System for South Africa*, Department of Agricultural Technical Services, Soil and Irrigation Research Institute, Pretoria, 1977, p 150.
[21]Soil Survey Staff, *Soil Classification – A Comprehensive System* (*7th Approximation*), US Department of Agriculture, Washington, DC, 1960, together with supplements to the system dated March 1967 and September 1968.
[22]R. Dudal, *Definitions of Soil Units for the Soil Map of the World*, World Soil Resources Reports No 33, World Soil Resources Office, FAO, Rome, 1968.
[23]Schulze, *op cit*, Ref 4.

scenarios were derived from an extensive literature review.[24] The climatic change scenarios for southern Africa, which are summarized below, and which are based on GCM output, interpretation of past analogues, expert opinion and adaptions of overseas studies, have been adopted by the South African Global Change Committee and task groups of the Interdepartmental Co-ordinating Committee on Global Environmental Change (ICC) for use in impact studies in southern Africa.

Carbon dioxide

The 'present' base level of atmospheric CO_2 concentration for modelling purposes is taken to be 330 ppm, and this is perturbed to 555 ppm, a level assumed to be attained between 2030 and 2050. This approximates a doubling of the pre-industrial revolution (1850) CO_2 level of 280 ppm and is assumed in the models to change instantaneously when 'doubling of CO_2' scenarios are used.

Solar radiation

The incident solar radiation received at Earth's surface is a function of the extraterrestrial radiation; the atmosphere's ability to absorb, reflect and scatter the incoming solar radiation (ie atmospheric transmissivity); the degree of cloud cover; and finally on the portion of the incident shortwave radiation that is reflected back to the atmosphere by Earth's surface.

Extraterrestrial radiation, mainly a function of the Sun–Earth distance, seasonal and latitude relationships, is considered unaffected by a change in Earth's climate. Atmospheric transmissivity to incoming solar radiation is expected to change negligibly with global warming. Since precipitation changes are not considered in this impact assesment, cloudiness is assumed to remain unaffected by climate change. Therefore, for this study, incoming solar radiation has been taken to remain unaltered with climate change.

Temperature

The following basic premises were considered in developing temperature change scenarios for southern Africa:

- Global mean air temperature is predicted from GCMs to increase by 1.5 to 4.5°C for an effective doubling of CO_2, with a 'best estimate' around 2.5°C.[25] For southern Africa, high-resolution GCMs predict a 2°C rise.[26]
- The regional increase in temperature will be dependent on latitude (ϕ), increasing at higher latitude.[27]
- Diurnally, minimum temperatures are hypothesized to increase more than maximum temperatures.
- Seasonally, winter warming is likely to be greater than summer warming.[28]

Based on the above, and assuming a 2°C increase in mean temperature at 30°S latitude, the following temperature change algorithm for southern Africa, used in this study, was developed by Schulze and Kunz,[29] accounting for latitudinal dependence, diurnal differences between anticipated maximum and minimum temperature changes and seasonal temperature differences such that

$$\Delta T = \Delta T_{\phi}(0.9+F)$$

[24]R.E. Schulze and R.P. Kunz, *Climate Change Scenarios for Southern Africa: 1993*, Report to South African Global Climate Change Committee, Department of Agricultural Engineering, University of Natal, Pietermaritzburg, 1993, p 45.
[25]T.M.L. Wigley and S.C.B. Raper, 'Implications for climate and sea level of revised IPCC emissions scenarios', *Nature*, Vol 357, 1992, pp 293–300.
[26]J.F.B. Mitchell, *Simulated Climate Change over Southern Africa in a High Resolution Mixed-Layer Model Experiment*, Hadley Centre for Climate Prediction and Research, Meteorological Office, Bracknell, UK, unpublished paper, 1991.
[27]P.D. Tyson, *Recent Developments in the Modelling of the Future Climate of Southern Africa*, 13th Raymond Dart Memorial Lecture, University of the Witwatersrand, Johannesburg, 1992, mimeographed.
[28]Intergovernmental Panel on Climate Change, *The Supplementary Report to the IPCC Scientific Assessment*, J.T. Houghton, B.A. Callander and S.K. Varney, Cambridge University Press, Cambridge, 1992.
[29]Schulze and Kunz, *op cit*, Ref 24.

and

$$\Delta t \;= \Delta T_{\phi}(1.1+F)$$

where

ΔT = temperature change for maximum temperature
Δt = temperature change for minimum temperature
$\Delta T_{\phi} = \phi/30\Delta T_{30}$

where

ΔT_{ϕ} = latitudinally adjusted temperature
ΔT_{30} = temperature increase of 2°C at 30°S
ϕ = latitude south

and

F = seasonally adjusted temperature change

with

$$F = -0.045*12/S+\cos Z$$

where

$S = (12-I)$ when $(1\leq I\leq 6)$
$\;\;= I$ when $(6\leq I\leq 12)$
I = month of the year (1, . . ,12)
$Z = I\pi/6$

An example of the application of the above temperature change algorithm for southern Africa is illustrated in Figure 1.

Evaporation

A reference potential evaporation change of 3% per °C warming was adopted for southern Africa,[30] based on suggestions of a similar magnitude for Australia,[31] computations involving the Penman equation[32] and the fact that the capacity of air for water vapour increases by 5–6% per °C warming.[33]

Precipitation

To avoid introducing more uncertainty into this study it was decided, on the basis that the variable and somewhat contradictory GCM predictions of rainfall changes for southern Africa (reviewed by Schulze and Kunz[34]), and local climatologists' reporting that the present level of understanding of regional changes in rainfall over southern Africa cannot as yet justify any accurate quantification of rainfall changes,[35] that no changes in rainfall, amounts, intensities or temporal/spatial distributions over southern Africa would be input in model runs.

Primary productivity: concepts and estimation

Primary productivity is a quantitative expression of:

- Vegetative matter (eg harvestable yield)
- which can be produced (eg in tonnes)
- by the natural environment
- at a location
- per unit area (eg per hectare)
- over a given period of time (eg in a season or a year).

[30] *Ibid.*
[31] A.B. Pittock, 'Developing regional climate change scenarios: Their reliability and seriousness', Hawkesbury Centenary Conference, University of Western Sydney, 25–27 November 1991, mimeographed.
[32] Penman, *op cit*, Ref 13.
[33] N.J. Rosenberg, M.S. McKenney and P. Martin, 'Evapotranspiration in a greenhouse-warmed world: A review and a simulation', *Agricultural and Forest Meteorology*, Vol 47, 1989, pp 303–320.
[34] Schulze and Kunz, *op cit*, Ref 24.
[35] J.A. Lindesay, Climatology Research Group, University of the Witwatersrand, Johannesburg, personal communication, 1992.

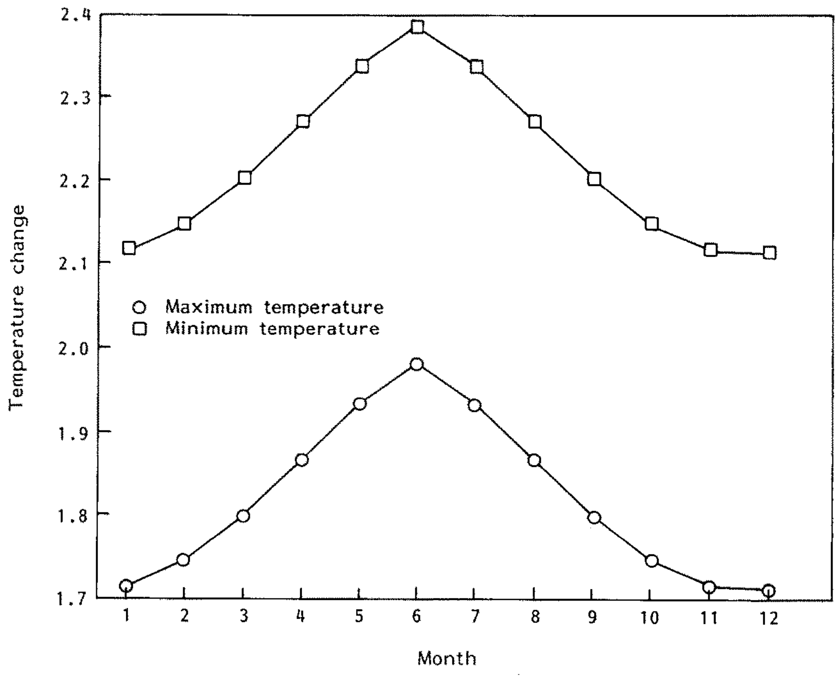

Figure 1. Example of the seasonal scenario changes in minimum and maximum temperatures used in southern Africa for a mean air temperature increase of 2°C at latitude 30°S.

Source: R.E. Schulze and R.P. Kunz, *Climate Change Scenarios for Southern Africa: 1993*, Report to South African Global Climate Change Committee, Department of Agricultural Engineering, University of Natal, Pietermaritzburg, 1993.

It may be conceptualized as a generalized expression of sustainable yield and agricultural productivity and is a quantification of the dryland (ie rainfed) biomass production expectation of a location. The concept is particularly useful and objective in assessing the intrinsic environmental production capability and in comparing the environmental resource potential of one location with others. As such, the concept of primary productivity can be used as a fundamental tool in overall resource, agricultural and sustainable development planning of a country or, alternatively, a region.

In a major contribution 25 years ago, Rosenzweig[36] used total evaporation (ie 'actual evapotranspiration' E) estimates derived from soil water budgeting techniques from 26 mature and undisturbed plant communities in widely ranging environments to derive a generalized equation for net above-ground (ie harvestable) productivity, measured as dry organic matter synthesized per area per unit time:

$$\log_{10}NAAP = 1.66(\pm 0.27)\log_{10}E - 1.66(\pm 0.07)$$

where

$NAAP$ = net annual above-ground productivity ($g.m^{-2}$)
E = annual total evaporation (mm)

Total evaporation in a natural environment synthesizes the two most variable photosynthetic resources, water and energy. It is a measure of the simultaneous availability of soil water and atmospheric evaporative demand of a plant community at a given stage of growth in a given period of time and it is the amount of water actually entering the atmosphere through the soil/vegetation complex. Being a quantifiable measure of the energy flow in a plant community, it is fundamentally a useful predictor of productivity.

[36]M.L. Rosenzweig, 'Net primary productivity of terrestrial communities: Prediction from climatological data', *American Naturalist*, Vol 102, 1968, pp 67–74.

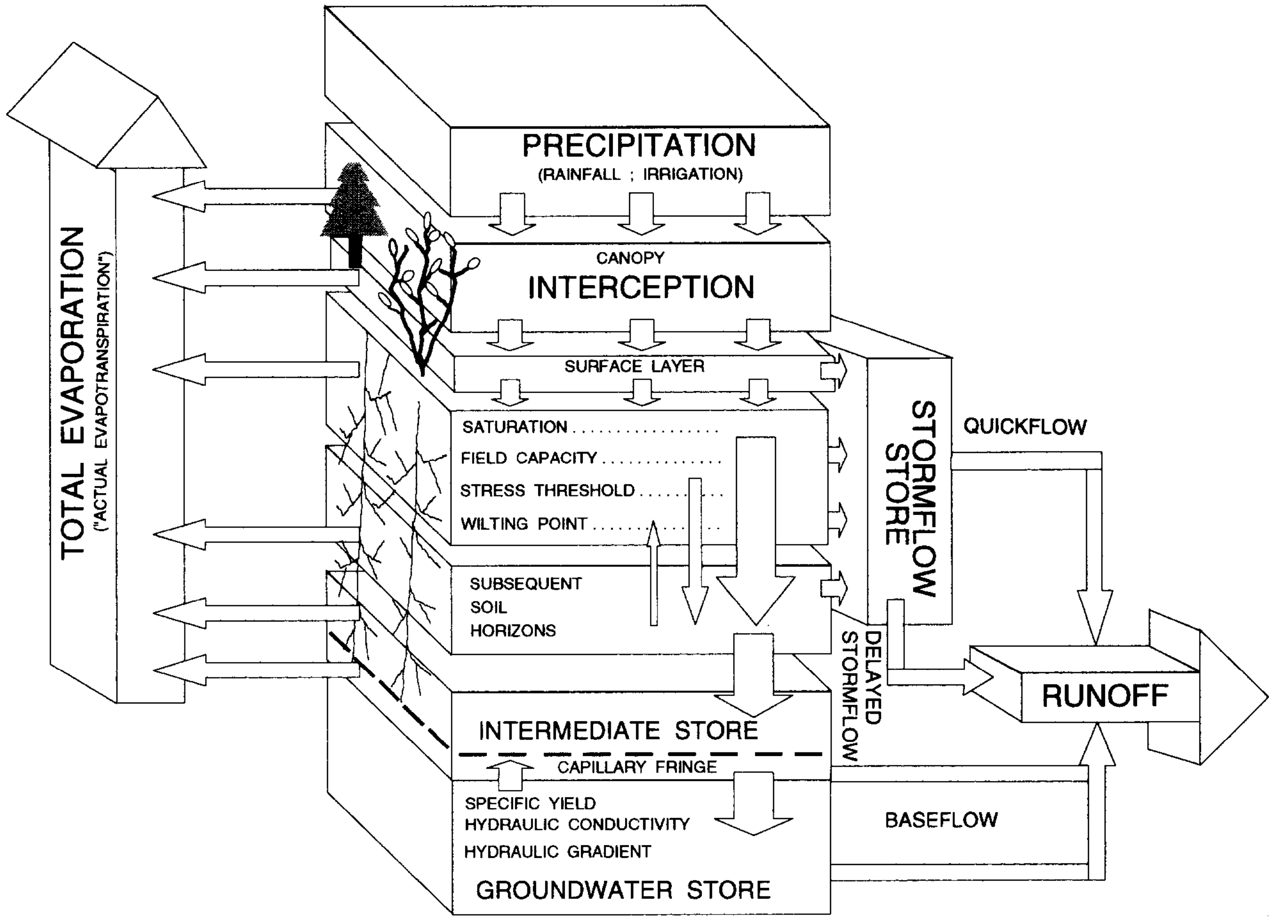

Figure 2. Structure of the *ACRU* agrohydrological modelling system.
Source, R.E. Schulze, *ACRU: Background, Concepts and Theory*, Report 154/1/89, Water Research Commission, Pretoria, 1989.

Simulation models

General features of the *ACRU* and CERES models, used respectively to simulate primary productivity and maize yields, are presented below.

The ACRU model

ACRU is a physical–conceptual and menu-driven integrated multi-purpose and multi-level modelling system revolving around daily time-step multi-layer soil water budgeting and containing decision support systems. In addition to runoff components, irrigation demand/supply, reservoir and crop yield options it outputs *inter alia* soil water status and total evaporation on a daily basis. The general structure of the model is illustrated schematically in Figure 2. When operated for multiple land uses within a catchment or for multiple subregions making up a larger, more complex region, *ACRU* operates on an interlinked cell-based structure.

The model partitions and redistributes soil water under saturated and unsaturated conditions and computes evaporation rates from plant intercepted water and the various soil layers according to seasonally varying Leaf Area Index, crop coefficients and root distribution and the relative wetness of respective soil horizons.

For the primary productivity study, the crop coefficient is generated from minimum temperature according to Schulze and Lynch,[37] implying more rapid vegetative growth after the dormant season in a warmer future temperature scenario (Table 1). In an assumed effective doubling of atmospheric CO_2, transpiration rates are suppressed in the model as a result of increased stomatal resistance associated with enhanced CO_2 concentrations. In *ACRU* a doubling of CO_2 induces a 33% transpiration suppression for C4 and 22% for C3 plants.

It is vital in primary productivity modelling to determine at what critical fraction, in the depletion of the plant-available soil water reservoir (PAW), plant stress may be assumed to set in, since stress implies a reduction in dry matter production. While this fraction varies according to daily atmospheric demand and the plant's critical leaf water potential, it was set at 40% of PAW, a value typical for many plants, for the primary productivity simulations. When plant stress occurs, the crop coefficient is reduced using an exponential decay function with time from onset of stress.[38] When plant stress is relieved after rainfall, the crop coefficient recovers linearly at a rate dependent on the daily mean air temperature.[39]

For the Rosenzweig[40] primary productivity function within *ACRU*, the daily *E* generated by the model was accumulated over a 1 July–30 June (ie southern hemisphere mid-winter to mid-winter) growing season to yield annual primary productivities over the period of climatic record. Various statistics could then be gleaned from the series of annual primary productivity values.

The CERES model

CERES Version 3.0 is a composite model created from earlier CERES crop models (Versions 2.1 and 2.5), simulating development and yield of maize, wheat, sorghum, millet and barley. The CERES Version 3.0 model is to be released with the Decision Support System for Agrotechnology Transfer (DSSAT) Version 3.0.[41] While many new features are available with CERES Version 3.0, it is not within the scope of this paper to give a full presentation of the new model.

The CERES model operates on a daily time-step with soil and climate inputs to simulate crop development and yield.[42] The model is a collection of specialized functions calculating various crop processes such as photosynthesis, evapotranspiration and phenological stages. In addition, the model stimulates daily water and nitrogen movement through the plant and soil.[43]

CERES Version 3.0 is useful in climate change research because of its responses to climate change inputs. The CO_2 concentration affects daily canopy photosynthesis by a scaling factor.[44] In addition, CO_2 effects on plant transpiration are simulated by altering stomatal conductance.[45]

Linkage of CERES and ACRU models

The *ACRU* and CERES models were linked together by using *ACRU*'s cell-based structure as a driver program while the CERES model was restructured as a sub-routine to execute within the *ACRU* daily loop. The combination of the two models allowed the sharing of rainfall, temperature, solar radiation and soils input information. Users can combine the soils and climate data from either model to simulate either crop growth and/or hydrologically related responses.

The *ACRU*/CERES hybrid can be executed in two modes – discrete

[37]R.E. Schulze and S.D. Lynch, 'Distributions and variability of primary productivity over southern Africa as an index of environmental and agricultural resource determination', *ICID International Symposium on Impacts of Climatic Variations and Sustainable Development in Semi-Arid Regions*, Fortaleza, Brazil, 1992, p 16.
[38]A.D. Hughes, *Sugarcane Yield Simulation with the ACRU Modelling System*, unpublished MSc dissertation, Department of Agricultural Engineering, University of Natal, Pietermaritzburg, 1992, pp 32–38.
[39]*Ibid.*
[40]Rosenzweig, *op cit*, Ref 36.
[41]*Op cit*, Ref 5.
[42]J.T. Ritchie, 'The CERES-maize model', in C.A. Jones and J.R. Kiniry, eds, *CERES-Maize: A Simulation Model of Maize Growth and Development*, Texas A&M University Press, College Station, TX, 1986, pp 3–6.
[43]D.C. Godwin, C.A. Jones, J.T. Ritchie, P.L.G. Vlek, and L.J. Youngdahl, 'The water and nitrogen components of the CERES models', in *Proceedings of the International Symposium on Minimum Data Sets for Agrotechnology Transfer, Patancheru, India*, International Crops Research Institute for the Semi-Arid Tropics, Andhra Pradesh, 1984, pp 101–106; D.C. Godwin and C.A. Jones, 'Nitrogen dynamics in soil–plant systems', in J. Hanks and J.T. Ritchie, eds, *Modelling Plant and Soil Systems*, American Society of Agronomy, Madison, WI, 1991, pp 287–321.
[44]C. Rosenzweig, in J.B. Smith and D.A. Tirpak, eds, *The Potential Effects of Global Climate Change on the US*, US Environmental Protection Agency, Washington, DC, 1989, Appendix C.
[45]B. Peart, J.W. Jones, R.B. Curry, K.J. Boote and L.H. Allen, Jr, in J.B Smith and D.A. Tirpak, eds, *The Potential Effects of Global Climate Change on the United States*, US Environmental Protection Agency, Washington, DC, 1989, Appendix C.

Table 2. Genetic coefficients for maize used in the *ACRU*/CERES model.

Genetic parameter description	Parameter value
Degree days (base 8°C from seedling emergence to the end of juvenile stage (Σ°C_8–day)	270
Photoperiod sensitivity constant (dimensionless)	0.75
Degree days (base 8°C) from silking to physiological maturity (Σ°C_8–day)	710
Potential kernel number (kernels/plant)	730
Potential kernel growth rate (kernels/day)	7.3

and continuous. The discrete simulation mode starts the crop model on a specific day and ends immediately after harvest. The crop management dates are reset to the next year and *ACRU* continues execution alone until the following growing season's beginning date, when the crop model is executed once again. At the beginning of each discrete simulation, the soil water and nutrient variables are reset to user-prescribed initial conditions.

In continuous simulation mode, the crop model is started on a specific date and simulates all crop functions until harvest. After the crop has reached harvest maturity, the model continues to simulate only the soil water budget, with no crop growth routines executed, resulting in a 'fallow' period until the next seeding date. In this option, no soil water or nutrient values are reset to initial conditions at planting, but commence with 'actual' (simulated) values from the continuous simulation.

Management inputs

In southern African maize production, management practices range from highly mechanized to subsistence production. Climate changes in marginal production areas may have a more adverse effect on the smaller farmers.[46] One of the most important differences between the two groups is access to fertilizer inputs. In this study, two nitrogen fertilization schedules were analysed. The first schedule assumed optimum N availability (ie no N stress) to reflect the highly mechanized commercial agricultural practices. The second schedule assumed two nitrogen fertilizations of 8.0 kg/ha NO_3 to simulate nitrogen-limited subsistence production. The first fertilization occurred on 1 October, just before the seeding date, and the next occurred in the first week of January of the following year, midway through the cropping season.

Both management practices used the same method for determining a suitable planting date. The planting date was set by an automatic function within CERES[47] that calculates available soil water in the top 150 mm of soil. The *ACRU*/CERES hybrid was run in the discrete mode, beginning the simulation on 16 September and 'warming up' until the first possible planting date on 1 October. The window of opportunity for planting continued until 21 December. For continuity in the *ACRU* program, if the desired planting conditions were not met within the window of opportunity, then the crop was assumed to have been planted on 21 December. To reflect typical southern African cultural practices, the seeding depth was 50 mm with a row spacing of 1.5 m and a plant population of 21.1 plants/m^2.[48] All other management practices were the same in both present and future climate scenarios. Pest effects were not included in the simulations. One cultivar, a medium length of growing season maize variety, was used for all climate zones.[49] The genetic coefficients are listed in Table 2.

[46]T.E. Downing, *Climate Change and Vulnerable Places: Global Food Security and Country Studies in Zimbabwe, Kenya, Senegal and Chile*, Research Report No 1, Environmental Change Unit, University of Oxford, Oxford, 1992.
[47]R. Bowen, in International Benchmark Sites Network for Agrotechnology Transfer Project, Decision Support Systems for Agrotechnology Transfer Version 3.0 (DSSAT V3.0), Department of Agronomy and Soil Science, College of Tropical Agriculture and Human Resources, University of Hawaii, Honolulu, HI, 1993. In print.
[48]Sentraoes, *Prosedure vir Potensiaalbepaling van Droëlandmielies*, Report 114, Sentraoes Ko-öperatief Beperk, Ficksburg, 1984.
[49]W. Berry, Summer Grain Centre, Cedara Agricultural Research Institute, Cedara, personal communication, 1993.

Environmental inputs

In using the *ACRU*/CERES hybrid for climate change simulations in southern Africa, all environmental inputs were coordinated through the *ACRU* menu input system. Climate inputs for each response zone included daily rainfall, as well as monthly means of daily maximum and minimum temperature and solar radiation. To compensate for reductions in solar radiation on days when precipitation occurred, a simple perturbation was invoked based on southern African research findings on evaporation fluctuations by Dent *et al*, namely: if the daily rainfall was greater than 5 mm then the mean daily solar radiation value was reduced by 20%, otherwise the mean daily radiation value was enhanced by 5%.[50]

Daily potential evapotranspiration was calculated within the CERES model by using a modified Priestley–Taylor equation,[51] using daily solar radiation inputs. Rainfall was not altered for future climate change scenarios, as was the case with primary productivity simulations, and temperatures were changed as described previously.

Soil inputs

Soil information from standard *ACRU* files for the 712 climate zones supplied all but three of the necessary CERES soils inputs. The values for the SCS curve number, the upper limit of stage one soil water evaporation and the soil albedo were estimated using *ACRU* soils input for the 712 regions in conjunction with the assumptions presented by Ritchie *et al.*[52] The soil profit in each zone was checked for a minimum depth of 0.75 m. For the maize yield simulations soil profiles less than this minimum depth were assigned a 0.75 m depth on the premiss that only the deeper soils within a zone would be cultivated.

Initial soil water and nitrogen levels were reset each year on the simulation starting date of 16 September, two weeks before the first possible planting date, on which date the soil moisture levels were also initialized at 50% available water capacity for all layers. The soil nitrogen levels for ammonium and nitrate were both set at 2.0 g elemental N/Mg soil. The two-week period following the simulation starting date allowed the soil water conditions to be adjusted by the local climate conditions occurring for that specific year of simulation.

Results from simulations

This paper has considered a vegetative response impact analysis which has concentrated directly on estimating the primary effects of environmental variables on crop yields. The approach used has been to quantify the effects of increasing atmospheric CO_2 concentration, and resultant expected increases in air temperature, on crop response and primary productivity. No precipitation changes were considered because of the large uncertainty surrounding the quantification of such changes. The approach assumes an instantaneous change in climate state and estimates the 'before-and-after' yield effects.

Annual primary productivity under present climate conditions

Results show that primary productivity estimated using the Rosenzweig primary productivity equation imbedded within *ACRU* ranges from less than 2 tonnes/ha/season in the dry and arid western regions to over 14 tonnes/ha/season along the wet and humid eastern seaboard of southern

[50]Dent *et al*, *op cit*, Ref 6.
[51]C.A. Jones, J.T. Ritchie, J.R. Kiniry and D.C. Godwin, 'Subroutine structure', in C.A. Jones and J.R. Kiniry, eds, *CERES–Maize: A Simulation Model of Maize Growth and Development*, Texas A&M University Press, College Station, TX, 1986, pp 57–58.
[52]J.T. Ritchie, J.R. Kiniry, C.A. Jones and P.T. Dyke, 'Model inputs', in C.A. Jones and J.R. Kiniry, eds, *CERES–Maize: A Simulation Model of Maize Growth and Development*, Texas A&M University Press, College Station, TX, 1986, pp 37–48.

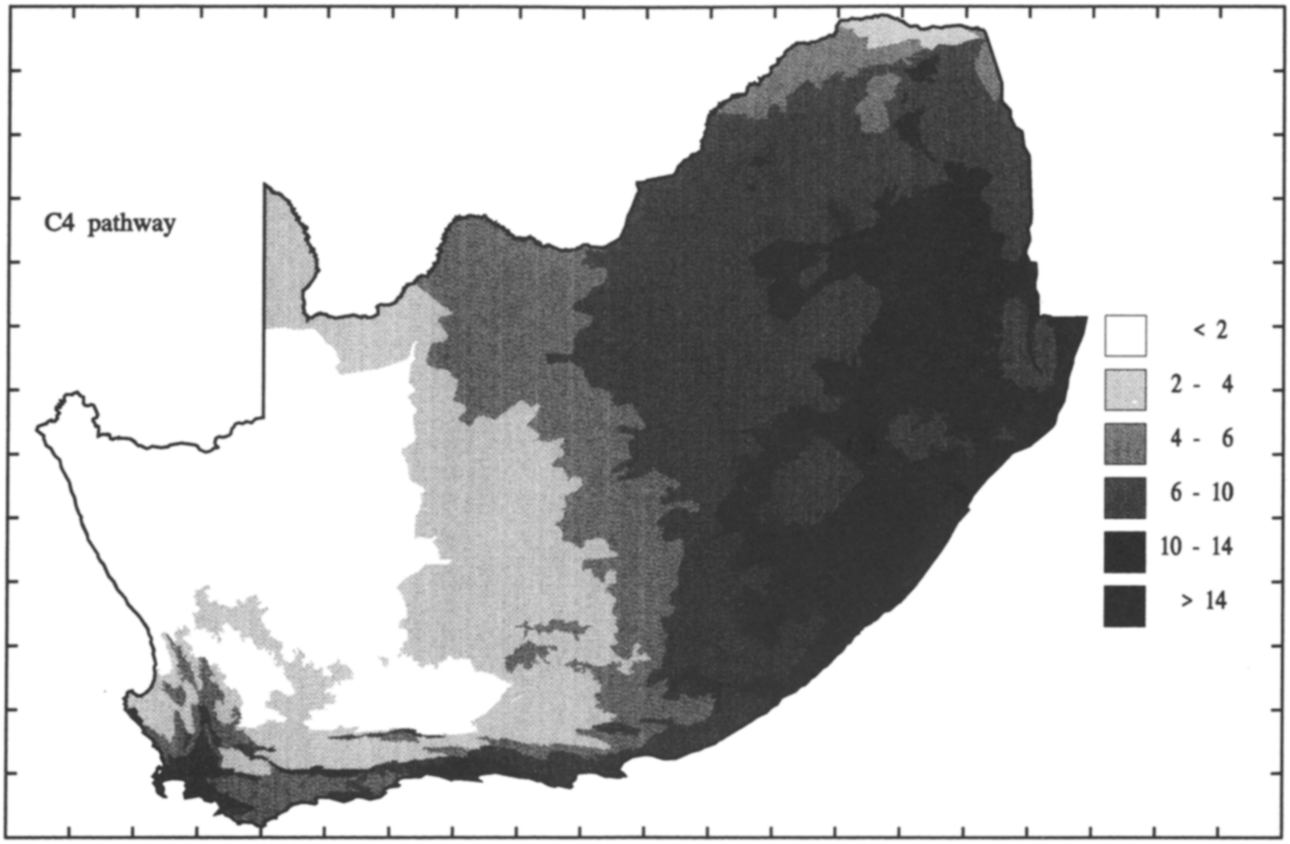

Figure 3. Simulated mean annual primary productivity (tonnes/ha/season) over southern Africa for present climatic conditions.

Africa (Figure 3). The increase in primary productivity from low to high potential is generally in phase with increasing rainfall and decreasing reference evaporation from the west to east coast across southern Africa.

The distribution of inter-annual variability of primary productivity (Figure 4), expressed as the percentage coefficient of variation, shows that the arid west and the northern boundaries of southern Africa are characterized as extremely high-risk areas, whereas the eastern and southern regions, while still high-risk by most major crop production standards, display lower inter-annual variability.

Changes in primary productivity under a possible future climate

Figures 3 and 4 illustrate that soil water availability exercises the overriding control on primary productivity of most South African ecosystems. Net soil water availability is influenced by supply (rainfall) and demand (evaporation). Therefore, all else being equal, if the rainfall remains the same but temperatures rise, plants should experience lower soil water availability, higher stress frequencies and production should decease proportionately.[53] More rapid plant development at higher temperatures on the one hand, and the 'fertilization' effect of increased CO_2 concentrations on the other, could however bring into effect feedback.

Since 95% of the natural vegetation of southern Africa consists of C4 grasses,[54] primary productivity for a possible future climate with a

[53]R.J. Scholes, *The Impact of Global Change on Terrestrial Ecosystems*, Report to the Interdepartmental Co-ordinating Committee for Global Environmental Change (ICC) Task Group on the Terrestrial Environment, Department of Environment Affairs, Pretoria, 1992.
[54]R.P. Ellis, J.C. Vogel and A. Fuls, 'Photosynthetic pathways and the geographical distribution of grasses in South West Africa/Namibia', *South African Journal of Science*, Vol 76, 1980, pp 307–314.
[55]Human, *op cit*, Ref 3.

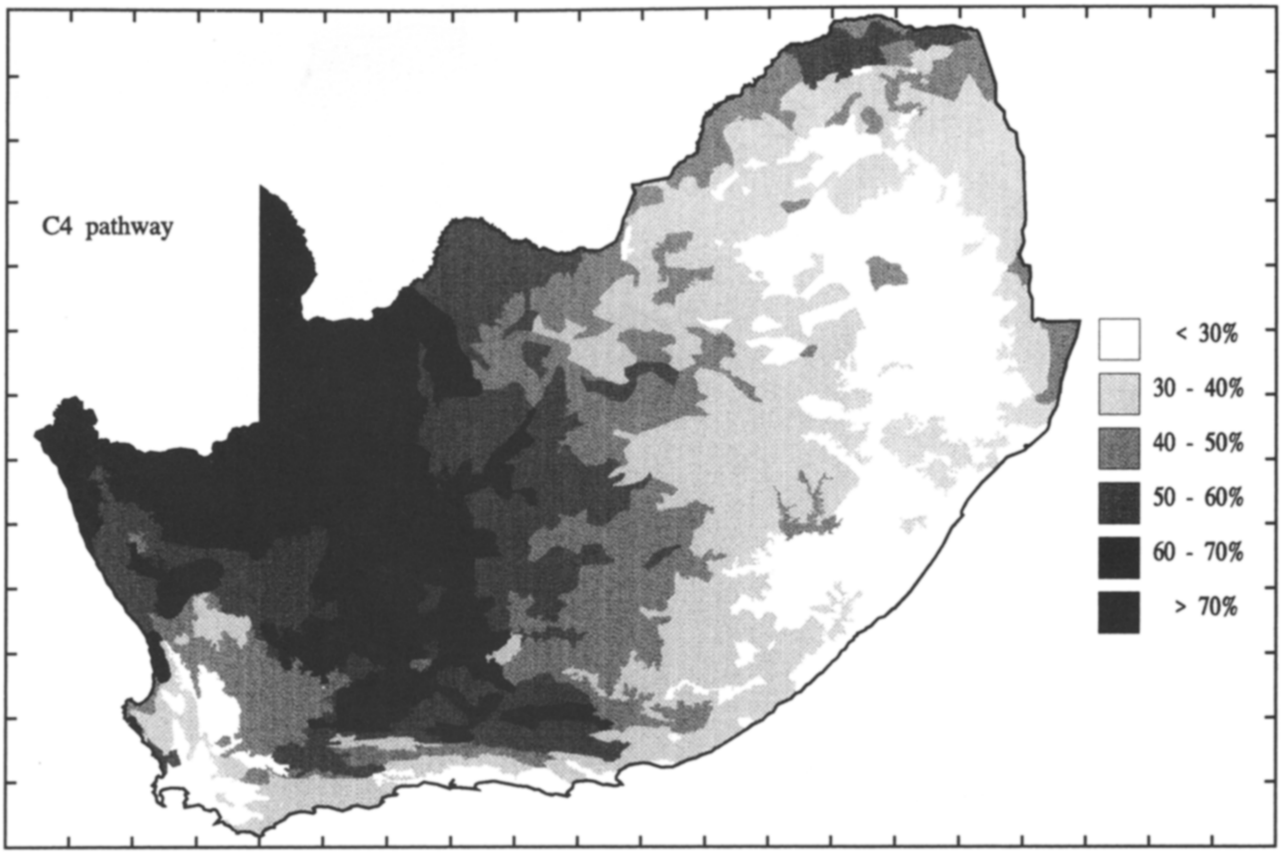

Figure 4. Inter-annual coefficient of variation (%) of primary productivity over southern Africa.

doubling of CO_2 was subjected to a transpiration suppression of 33% (typical for C4 plants in *ACRU*), with the temperature and reference evaporation perturbations in the model as outlined previously. The results (Figure 5) show similar spatial trends to the present climate except that primary productivity is simulated to decrease generally over southern Africa.

A comparison of the relative changes in primary productivity from present conditions to a possible future climate (Figure 6) reveals that the smallest relative decreases occur in the western regions and the largest relative decreases occur in the eastern regions. This analysis clearly identifies areas sensitive to changes in climate variables.

Maize yields under present climate conditions

Figure 7 displays the mean maize yields simulated for present climate and nitrogen-unlimited conditions. Yields in areas with MAP of less than 300 mm are not shown in this and subsequent figures relating to maize. The areas of highest maize production per ha are found on the eastern coast and northeastern highland plateau regions, where MAP exceeds 600 mm with relatively low variability from year to year. Yields in these regions average between 4.0 and 8.0 tonnes/ha. The more marginal production areas are found to the west of the main production areas. The decrease in MAP and its increased year-to-year variability results in lower mean yields, with higher incidences of crop failure due to severe water stress.

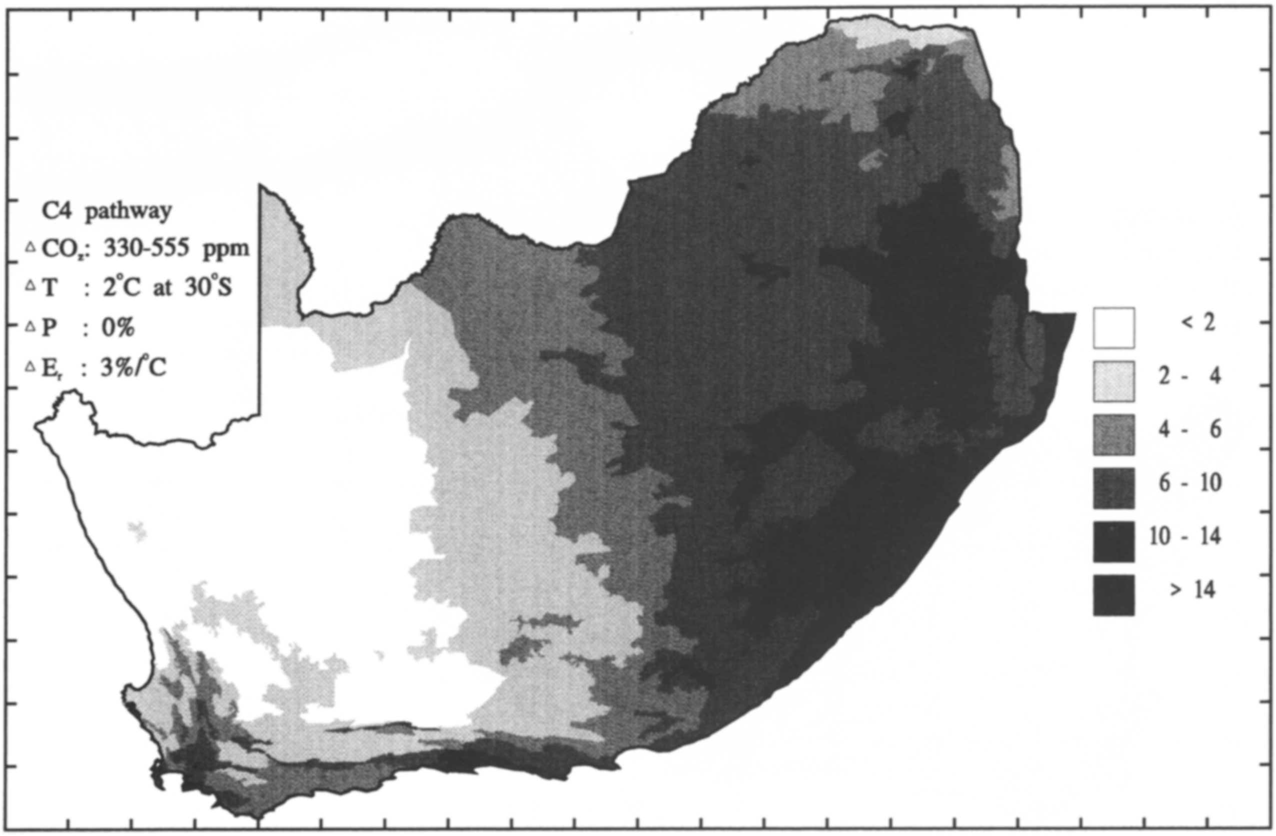

Figure 5. Simulated mean primary productivity (tonnes/ha/season) over southern Africa for a possible future climate scenario.

In the nitrogen-limited simulations, the spatial patterns of production follow the same geographical trends as those of nitrogen–unlimited production. However, the yields have been reduced significantly by nitrogen stress. In Figure 8, nitrogen deficiency alone has decreased the mean yields to less than one-third of the nitrogen-unlimited yields. This reduction is not uncommon when subsistence yields are compared with those from top commercial enterprises. The yield reduction is observed throughout all maize-producing areas with westward decreases again due to diminishing rainfall.

Changes in maize yields under a possible future climate

Figure 9 depicts the mean maize fields for nitrogen-unlimited simulations in a possible future climate. In areas previously producing mean annual yields of more than 8.0 tonnes/ha, the elevated temperature and CO_2 produces little change in yields, as seen in Figure 9. With no nitrogen stress and abundant rains the crops are, according to the model structure, therefore already growing in near-optimum conditions.

In more variable production areas (yields between 4.0 and 8.0 tonnes/ha) Figure 9 shows an expansion in the areas yielding up to 8.0 tonnes/ha and a westward expansion of increases into areas previously yielding below 4.0 tonnes/ha.

The difference between future and present climate scenarios is shown in Figure 10. The largest change in yields, over tonnes/ha, is found in the northeastern highveld region. In addition, south of the highveld in Lesotho, over 2.0 tonnes/ha changes are simulated.

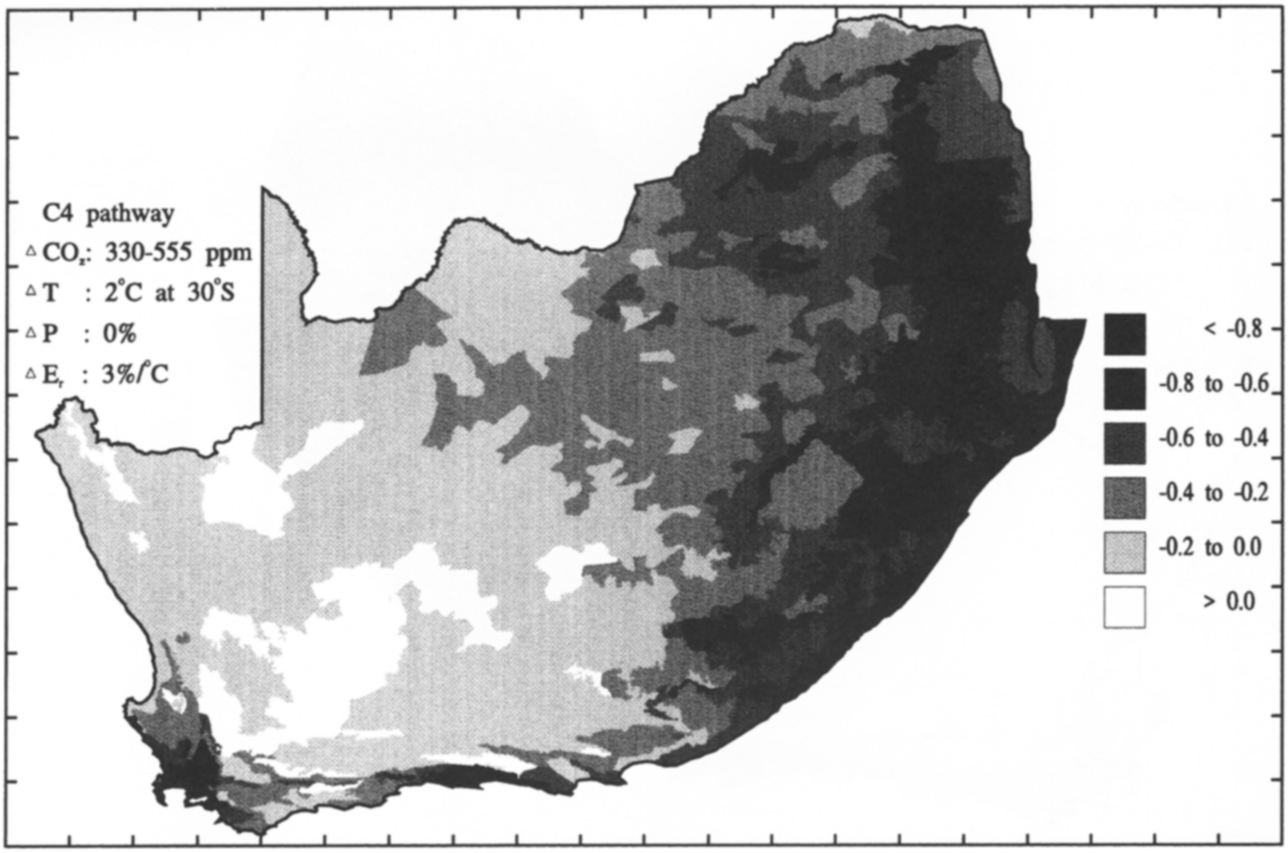

Figure 6. Differences (tonnes/ha/season) in simulated primary productivity over southern Africa resulting from a climate change scenario.

In areas with marginal rainfall for maize production, the climate change scenario has little absolute effect on the already low average yields. Some regions west of the main maize-production areas do show slight increases in simulated yields. However, in most low-yield areas Figure 10 displays increases of less than 1 tonne/ha.

The same trends are displayed in the nitrogen-limited simulations (distributions not shown in this paper) under possible future climate conditions, with again the increased water use efficiency leading to larger average yields in productive areas. However, the yield increases are smaller in magnitude due to the significant nitrogen stress.

From an overall food security perspective, therefore, the analysis using a generic primary productivity function indicates that if negative changes in production do occur, they are likely to be relatively minor, while the CERES Version 3.0 model in fact points to an overall increase in potential maize production.

Discussion

Responses in simulated yields to climate change scenarios in southern Africa

The results of responses from the *ACRU*/CERES hybridized model to these simple climate change scenarios show a large dependence on rainfall and its intra- and inter-seasonal variation. This is evidenced by nitrogen-unlimited and nitrogen-limited scenarios displaying the same

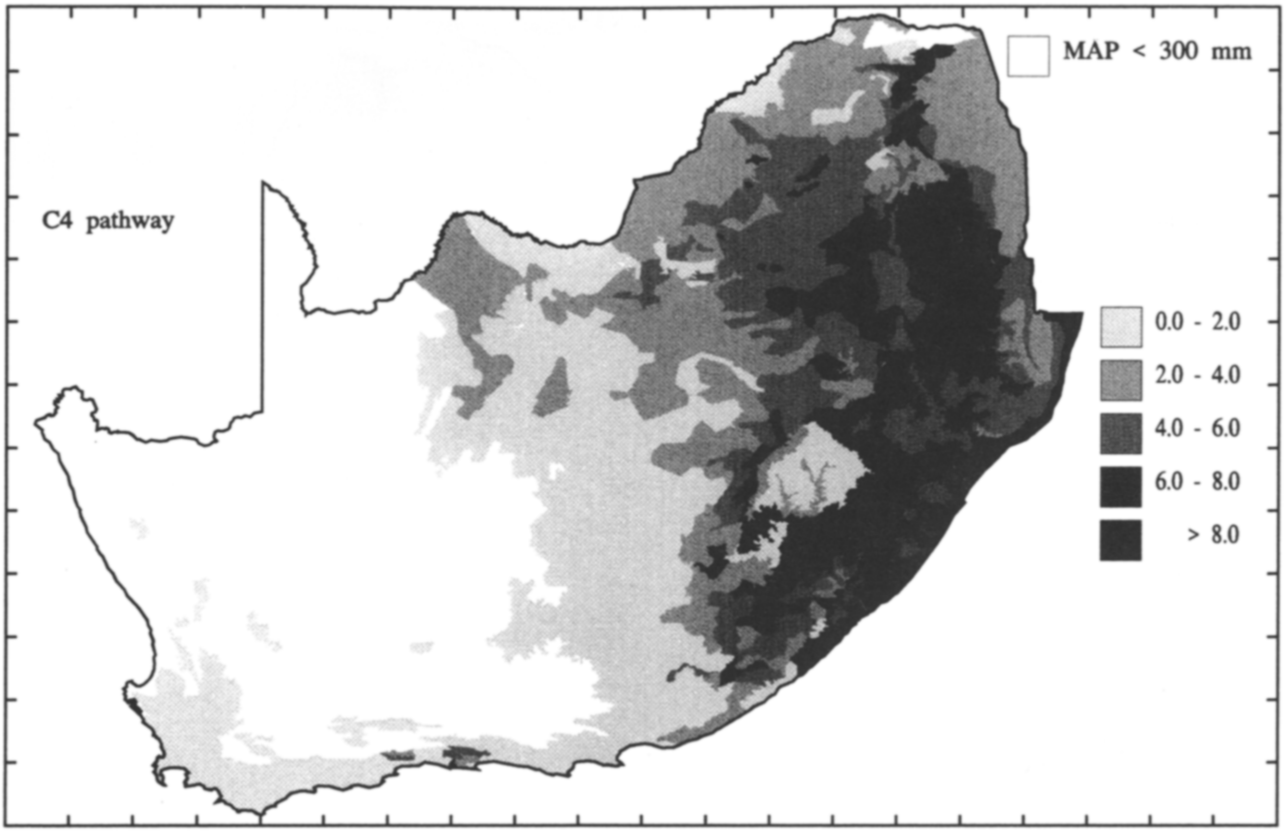

Figure 7. Simulated mean maize yields (tonnes/ha/season) over southern Africa for present climate and nitrogen-unlimited conditions.

trends in geographical distribution of maize yields, only with the respective values of yields being determined by nitrogen availability.

In these preliminary maize yield simulations, the overall effect of temperature increase and CO_2 doubling has been to increase water use efficiency by reducing plant transpiration. The 2.0°C rise in temperature, reduced in many high-production zones by latitudinal and seasonal effects, was more than counteracted by the CO_2 'fertilization' effect. The primary outcome of this higher efficiency is an increase in mean yields for many areas and thus a reduction in the number of crop failures. This simulated yield increase is seen primarily in regions with MAP between 400 and 800 mm. In the higher-rainfall zones, water is not a yield limiting factor to the same degree. As a result, the average yields change very little between simulations of present and future climates. In the lower-rainfall zones, the larger number of poor rainfall years coupled with higher average temperatures cancelled any water use efficiency increases caused by raised CO_2 concentrations. In all climate change scenarios, rainfall variability remains the most important single factor in determining either primary productivity or maize yields. While changes in average yields do give insights into the climate change question, greater effects on the population and on food security are induced by the impacts of season-to-season variability. This point is illustrated well in Figure 4.

The significance of model assumptions

If one major lesson can be learned from the development of the

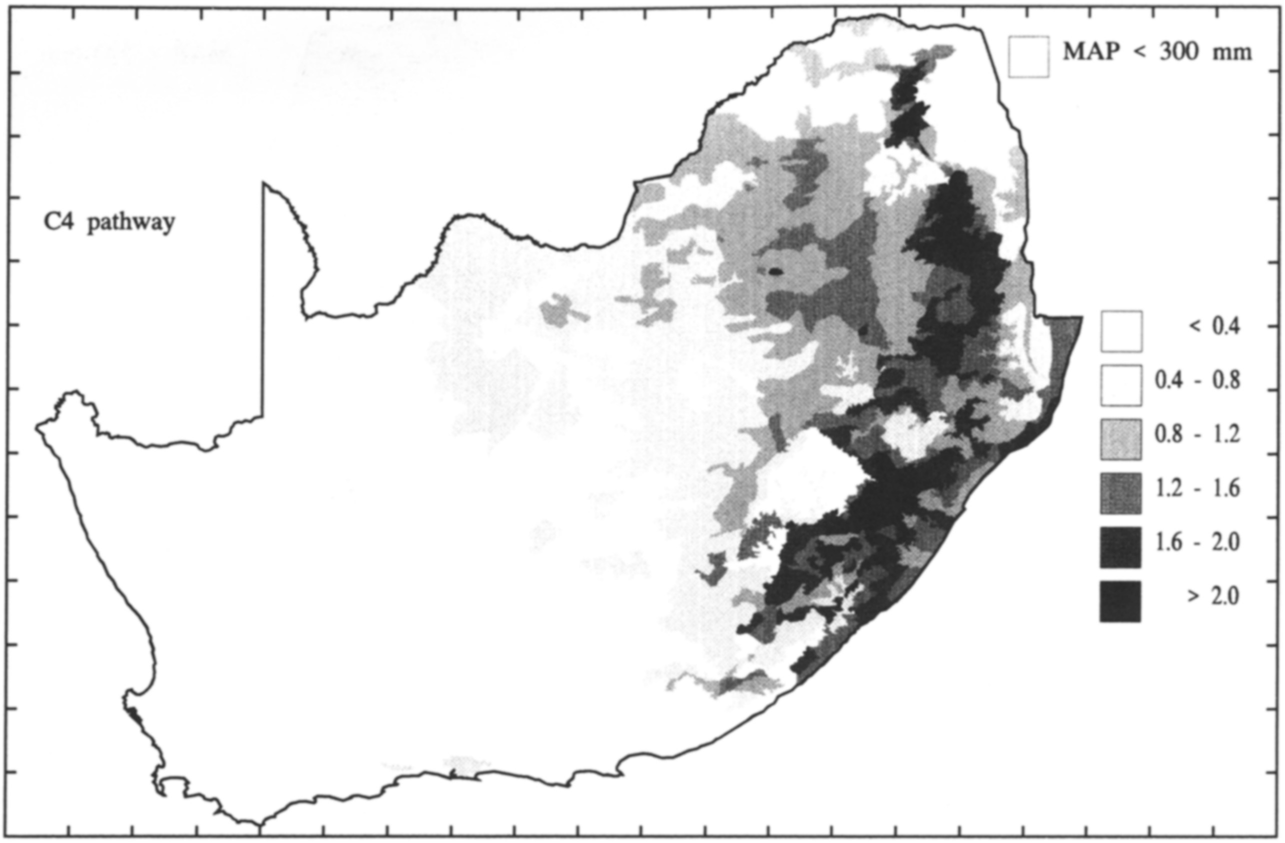

Figure 8. Simulated mean maize yields (tonnes/ha/season) over southern Africa for present climate and nitrogen-limited conditions.
N = 16 kg/ha.

ACRU/CERES modelling tool, it is that fundamental assumptions by the models play a direct role in the interpretation of simulation results. Two different scales are represented in the models used in the climate change analysis. Primary productivity is a corporate representation of the environmental capacity through the various climate–soil–vegetative interactions, and as such its distribution is a general index of sustainable agricultural productivity in southern Africa. The CERES model, on the other hand, simulates individual crops with specific genetic coefficients to delineate cultivar traits. In the primary productivity model, temperature increases create more rapid early season growth plus an expected elevated potential transpiration, which in turn would be expected to be converted to a higher potential yield by a cumulative transpiration to yield ratio. In suppressing transpiration by as much as 33%, however, to reflect reduced stomatal conductance with higher CO_2 concentrations, the potential yield is reduced by a lower cumulative transpiration. Assumptions for both CO_2 and temperature change have effects on yield as expected, but the feed-forward and feedback mechanisms are relatively simple and their respective magnitudes do not have the same 'sign' as the climate change impacts have with the CERES maize model.

The CERES model circumvents some of the above problems with its more mechanistic physiological basis. Daily canopy photosynthesis is increased by a factor related directly to CO_2 concentration while stomatal conductance is reduced according to crop and CO_2 concentra-

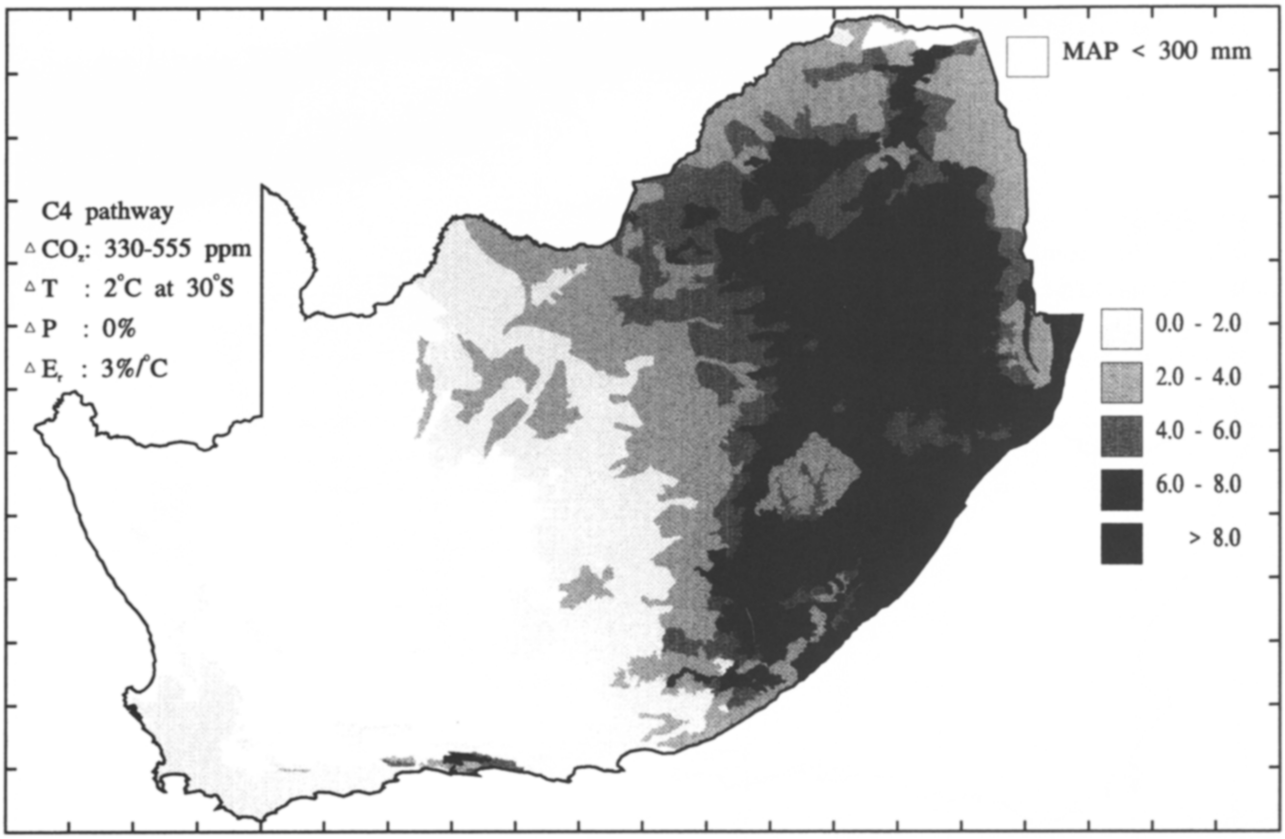

Figure 9. Simulated mean maize yields (tonnes/ha/season) over southern Africa for a possible future climate and nitrogen-unlimited conditions

tion. The interaction between the two processes is not yet understood fully – ie it is not yet known how much CO_2 increase is required to counteract a certain temperature increase and how the water balance is affected. Initial soil moisture and nitrogen conditions are fundamental in simulating environment responses over long periods. The relationship between these two variables is most important, but its significance is lost when initial conditions are reset at each year's beginning simulation date. At this point in the research, it seems as though all that can be done is to simulate responses to various 'accepted' climate change scenarios in an effort to improve understanding of the atmosphere–soil–plant continuum, and *not* to interpret the results of climate change scenario impacts at face value.

Clearly, a detailed sensitivity analysis involving both *ACRU* and CERES inputs would help to understand the strengths and the limitations of this powerful integrated tool in the applications that will be demanded of it.

Concluding remarks

The natural environment is a complex interactive system. Simultaneous multiple perturbations of this atmosphere–soil–plant system induce further complexities which are compounded by effects of scale and the unknowns of human adaptive responses and of future political developments. As natural and physical scientists, many important aspects of

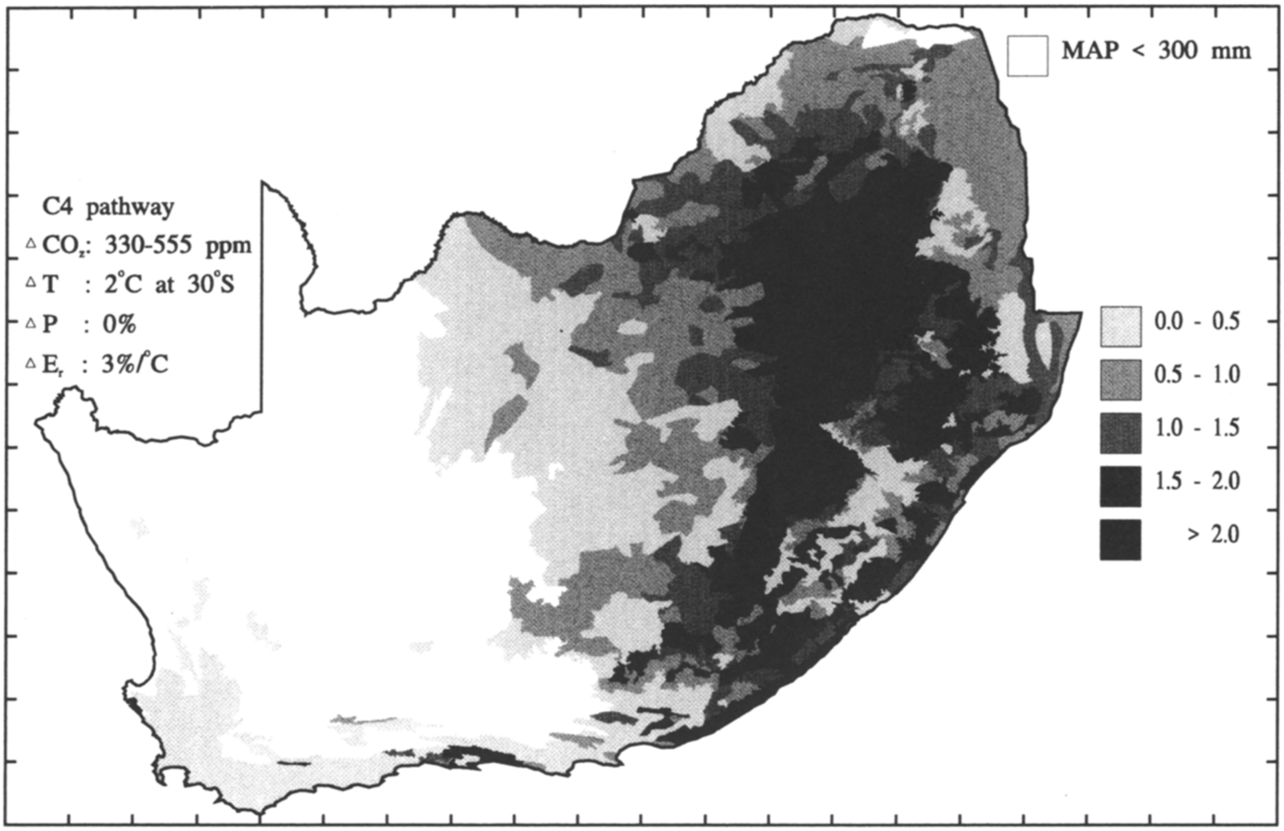

Figure 10. Differences (tonnes/ha/season) in simulated mean maize yields over southern Africa resulting from a climate change scenario.

food security are not within our 'control', and for us the challenges lie primarily in sharpening our modelling skills and predictive capabilities to provide the economic planner and politician with more certainties in answers to questions of climate change.

What do we not yet know?

A number of important modelling issues have already been addressed in the discussion. However, there remain many other fundamental gaps in our knowledge of a future environment and many further constraints in the models which we use to assess its impacts. A few limitations are listed below to illustrate that models are not yet 'dynamic' enough and there is a long road ahead in agricultural impact studies. For example:

- No changes in farmer perception of climate change and managerial response were incorporated in the models.
- Consequently, technological and cultivation practices affecting crop–climate relationships remained constant in time.
- Soil parameters such as soil water retention constants were assumed unaffected by changes in climate variables,
- as were root-to-shoot relationships and changing natural fertility through alterations in carbon to nitrogen ratios.
- Climate change scenarios at regional scale remain uncertain and speculative at this stage.
- No changes in pests and diseases were assumed, such as likely

increases in chilo borer incidence or diplodia root/stem rot in maize.[55]

Great caution therefore needs still to be exercised when interpreting the results of impact studies.

What, then, has been achieved?

What this paper has presented is not a series of off-the-shelf answers relating to climate change impacts and food security for southern Africa. We have set out to describe the development of a tool with which, given the strengths and constraints of the two models that have been hybridized, scenarios of climate change can be enacted, their responses can be compared and practical regional issues of food security can now be addressed for southern Africa from a sound scientific platform.

When combining two large modelling systems such as *ACRU* and CERES, the permutations for potential applications are numerous. A major advantage to the linkage of the models is a tool which combines catchment and field scales. Hydrological processes through the catchment can be linked with detailed field-scale process and *vice versa*.

The paper has, furthermore, presented a system infrastructure for southern Africa involving detailed climatic, edaphic and vegetative information based on a scientifically regionalized basis, coupled with the models and integrated with a GIS for purposes of display, comparison and interpretation. This linked modelling system for southern Africa will be used in forthcoming scientifically oriented research to indicate, for example,

- possible thresholds of climate for significant response to take place;
- sensitivities to variables changing, singly or in combinations;
- regions within southern Africa which may be more vulnerable than others to climate change;
- effects of nitrogen use and efficiency within present and future climate scenarios;
- pest and disease effects with respect to possible climate change;

The foundation has now been laid to couple the model output via GIS with issues relating more directly to food security in southern Africa, including

- analysis of present and possible future productivity and crop yields and their inter-annual variability based on areas actually under cultivation district by administrative district;
- analysis of production/variability according to population distribution, accessibility to rural population by road, distance from points of manufacture and export;
- possible management changes to reduce adverse climate change effects on various crops grown in southern Africa;
- analysis of anticipated political regionalization and land reform impacts on food production and distribution subsystems;

[55]Human, *op cit*, Ref 3.