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An approach to modelling spatial changes of plant carbon : nitrogen ratios in southern Africa in relation to anticipated global climate change

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Abstract. The carbon to nitrogen (C : N) ratio is the main factor determining the forage quality of a plant, with a low C : N ratio indicating relatively good plant digestibility and a high C : N ratio inferring relatively poor forage quality. Global atmospheric composition and climate change effects on plant carbon to nitrogen ratios are thus likely to be important when predicting possible second-order impacts of the enhanced greenhouse effect on rangeland forage quality and the resultant feeding habits of foraging animals and herbivorous insects. Equations relating the assimilation of total carbon and nitrogen rates to monthly air temperature, the ambient CO_2 level and soil fertility were used together with detailed spatial climatic and soil databases to simulate regional patterns of C : N ratios over southern Africa. Carbon to nitrogen ratios were estimated for both the present climate and for a possible future climate scenario defined by a general 2°C mean daily temperature increase over southern Africa (but with latitudinal, seasonal and diurnal adjustments made), an increase in atmospheric CO_2 concentration from 360 to 560 ppmv, but with no changes in precipitation patterns.

When C : N differences between future and present climates are examined, results indicate both relative increases and decreases over southern Africa in a regional context, ranging from −8 to +8%. Areas where the C : N ratios decreased indicate that for the future climate scenario which was assumed the relative increase in assimilated nitrogen would be greater than that for carbon. Similarly, areas where the C : N ratios increased indicate that the relative increase in assimilated carbon would be greater than that for nitrogen.

In this study, regions sensitive to climate change effects on C : N ratios in southern Africa have therefore been identified and with that, those areas where the consumption of plant matter may be expected to increase or decrease as a result of anticipated global climate change.

Key words. Climate change, carbon : nitrogen ratios, assimilation rates, southern Africa.

BACKGROUND

Plants respond directly to increasing levels of atmospheric CO_2 through changes in certain plant processes (e.g. photosynthesis and transpiration) and indirectly through changes in temperature and rainfall. However, it is the combined effects of increases in CO_2 levels and associated changes to other climate variables on certain plant processes which will determine how plants will ultimately respond to the enhanced greenhouse effect. Of the many influences of climate change on plant responses, this study focuses on possible climate change effects on plant carbon to nitrogen (C : N) ratios.

The C : N ratio determines, *inter alia*, the forage quality of a plant. For example, a low C : N ratio results in relatively good plant digestibility, whereas a high C : N ratio results in relatively poor forage quality. Hence, changes in C : N ratios resulting from possible changes in global atmosphere and climate may influence the feeding habits of foraging animals and herbivorous insects. Animal carrying capacity in African rangelands is more strongly influenced by forage quality than quantity (East, 1984). Both feedforward and feedback mechanisms are at play with the anticipated enhanced greenhouse effect. Elevated ambient CO_2 levels may boost the ratio of C : N, thus decreasing plant digestibility and increasing the consumption of plant matter by herbivorous insects. However, if enhanced CO_2 levels are associated with a warmer and drier climate, these climatic changes may produce more nitrogen relative to carbon, thus resulting in decreased C : N ratios.

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OBJECTIVES

The objective of this study is to simulate, map and interpret the spatial distribution of C : N ratios in southern Africa (defined as the Republic of South Africa together with the kingdoms of Lesotho and Swaziland and covering a surface area of 1,268,756 km^2) under present climatic conditions as well as for a likely future climate scenario, with the view to assessing regional changes in C : N ratios induced by the anticipated enhanced greenhouse effect. The approach determines total carbon and nitrogen assimilation rates, which includes both above- and below-ground production. In this study:

(a) the equations used to simulate carbon and nitrogen assimilation rates are first discussed;
(b) followed by a description of the detailed spatial, climatic, soil and vegetation data/information bases required for the simulation over southern Africa;
(c) together with the regional climate change scenarios which were used to
(d) quantify the possible climate change-induced effects on distributions of C : N ratios over southern Africa.

A Geographic Information System (GIS) was used both for the purposes of managing the spatial data bases, as well as for mapping.

METHODOLOGY

Estimation of total carbon assimilation rate

The assimilation of total carbon (C) by vegetation is a function of ambient CO_2 concentrations, irradiance, air temperature, leaf area, leaf stomatal conductance and photosynthetic enzyme activity. Under conditions where CO_2, temperature and soil water availability are not limiting to plant growth, the maximum carbon assimilation rate (C_{max}) approximates 200 g carbon (gC) per m^2 per month (Hall & Scurlock, 1993). In natural ecosystems, however, soil water availability and temperature are frequently limiting factors to growth. In order to determine these growth limiting effects on C_{max}, the following equation was applied:

$$C_a = C_{max} \cdot SWCF \cdot TCFC \cdot CO_2EF \qquad (1)$$

where

C_a = assimilated carbon rate (gC/m^2/month)
C_{max} = maximum carbon assimilation rate = 200 gC/m^2/month
SWCF = soil water constraint factor (0–1)
TCFC = temperature constraint factor for carbon (0–1)
CO_2EF = CO_2 enhancement factor ($2 \geq CO_2EF \geq 1$).

The soil water constraint factor (SWCF) incorporates the effects of stomatal resistance on plant growth (Fig. 1). Canopy stomatal conductance (g_c) is related to the ratio of actual transpiration (E_t) to maximum transpiration rates (E_{tm}), i.e. $g_c = E_t/E_{tm}$. The ratio varies with soil texture and with the soil water content of the topsoil horizon. Fig. 1 illustrates that if actual transpiration (E_t) occurs at the

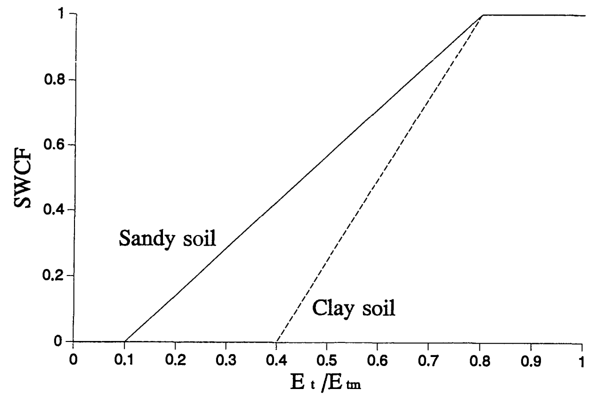

FIG. 1. Soil water constraint factor for carbon (SWCF) determined from the ratio of E_t/E_{tm}.

maximum rate (E_{tm}), then carbon assimilation is not constrained by stomatal closure. Below this level, C assimilation is reduced linearly.

The temperature constraint factor for carbon (TCFC) determines the growth-limiting effects of air temperature. Optimum assimilation of C for most natural vegetation is assumed to occur when the air temperature (T_m) is between 25 and 30°C. Sub-optimum growth takes place in a defined pattern for air temperatures outside this range (Fig. 2). For this paper monthly means of daily average temperatures were used as input for the TCFC.

The CO_2 enhancement factor enhances the carbon assimilation rate by a factor determined by anticipated future levels of atmospheric CO_2 concentration (in p.p.m.v.). Since the present ambient CO_2 level is approximately 360 p.p.m.v., this value has been used as the divisor of future atmospheric CO_2 levels in the CO_2EF equation, namely:

$$CO_2EF = 1.0 + 0.4 \cdot \ln([CO_2]/360) \qquad (2)$$

Estimation of total nitrogen assimilation rate

The assimilation of total nitrogen (N) in natural ecosystems is a function of the nitrogen mineralization rate of the soil, modified by soil temperature and the moisture content, and may be expressed as

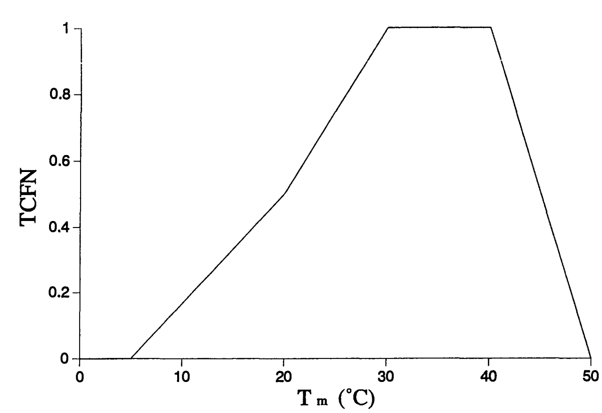

FIG. 2. Temperature constraint factor for carbon (TCFC).

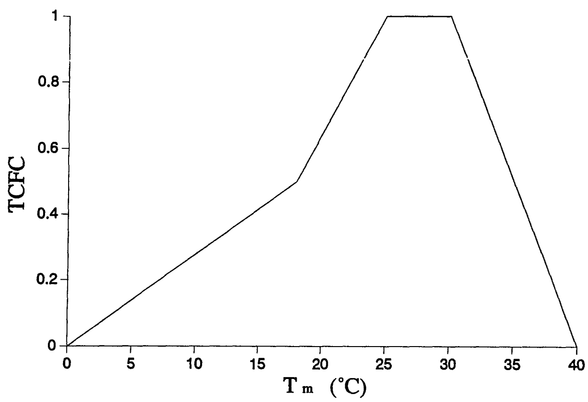

FIG. 3. Temperature constraint factor for nitrogen (TCFN).

$$N_a = N_{min} \cdot SWCF \cdot TCFN \quad (3)$$

where

N_a = assimilated nitrogen rate ($gN/m^2/month$)
N_{min} = nitrogen mineralisation rate ($gN/m^2/month$)
SWCF = soil water constraint factor (0–1)
TCFN = temperature constraint factor for nitrogen (0–1)

The soil water constraint factor for nitrogen has in this study been assumed the same as that for carbon (Fig. 1). However, the temperature constraint factor for nitrogen (TCFN) is different to that of carbon, with optimum conditions for N assimilation occurring when the air temperature is between 30 and 40°C (Fig. 3). Furthermore, with air temperatures below 5°C and above 50°C nitrogen assimilation is assumed to cease completely. Again, monthly means of daily average temperatures were used as input for the TCFN.

The nitrogen mineralization rate depends on the fertility of the soil and in our model can attain a maximum value of 5.0 $gN/m^2/month$ for highly fertile soils. N_{min} can be estimated using Equation 4:

$$N_{min} = N_{pot} \cdot F_s \quad (4)$$

where

N_{pot} = potential mineralization rate
= 5.0 $gN/m^2/month$
F_s = soil fertility score (0–10).

F_s is an index of soil fertility which ranges from a score of zero (i.e. no fertility) to a score of 10 (i.e. the highest possible fertility potential). In terms of nitrogen mineralization, soil fertility may be considered a function of the soil's clay content and its base status. The following algorithm (Equation 5) was used to estimate soil fertility from clay content and base status:

$$F_s = f_c \cdot f_b \quad (5)$$

where

F_s = soil fertility score (0–10)
f_c = fertility index based on clay content (cc)
= 0 if cc = 0% (e.g. rock)
= 1 if $0 < cc < 15\%$
= 2 if $15 \leq cc < 35\%$
= 3 if $35 \leq cc < 55\%$
= 3.3 if $cc \geq 55\%$
f_b = fertility index depending on base status
= 1 for dystrophic soils
= 2 for mesotrophic soils
= 3 for eutrophic or, alternatively, calcareous soils.

The fertility scores were based on the expert judgement of a soil scientist (M.V. Fey, pers. comm., 1993) and were specifically orientated towards nitrogen mineralization potentials.

Since the ratio of assimilated carbon to that of assimilated nitrogen (i.e. $C_a : N_a$) is sought, the effect of soil moisture on plant growth, which is taken into account through the soil water constraint factor (SWCF) is annulled because the SWCF has, in this subcontinental scale study, been assumed identical for both C and N assimilations at individual locations (Equations 1 and 3). Hence, this approach considers only temperature and soil fertility effects on C : N ratios. The method used to develop regional temperature and soil fertility data bases for southern Africa is described next.

Development of a regional temperature data base for southern Africa

Because the current network of temperature recording stations in southern Africa is relatively coarse, a method was sought to estimate temperature at unmeasured points from certain physiographic and geographic factors. Schulze & Maharaj (1991) have identified thirteen homogeneous temperature zones in southern Africa and for each zone, equations for monthly means of daily maximum and minimum temperatures were developed from observed data regressed against latitude, longitude, altitude, rainfall, a physiographic position index (i.e. whether or not in a valley and the level of 'constriction' of the valley) and a continentality index (distance from sea), using stepwise multiple regression techniques.

For the southern African region estimates of, *inter alia*:

(a) altitude;
(b) median monthly rainfall;
(c) the physiographic position index; and
(d) continentality (distance from sea),

have been determined for each of the 423,700 one minute of a degree latitude/longitude grid points ($1' \times 1' \sim 1.6 \times 1.6$ km) making up the region. The gridded temperature data bases were obtained month-by-month by applying the relevant physiographic/locational variables to the temperature regression equations at each grid point of each of the thirteen zones. Where temperature estimates had to be extrapolated to grid points with altitudes beyond the range used in the development of the equations, zonal temperature lapse rate adjustments were made on a monthly basis before gridded point temperature values were estimated. At the boundary of two or more temperature zones, estimated grid values of temperature were averaged around a 15-minute of a degree 'grey zone' overlapping into each respective zone.

Results obtained from this approach were highly successful. For example, in Zone 6 (Southwest Cape Interior) a total of 108 temperature recording stations were used to develop temperature equations, with 91% of simulated January (midsummer) temperatures within 5% of observed values and 79% of simulated July (midwinter) temperatures within 5% of the observations (Schulze & Maharaj, 1991). The next section describes the development of a possible future temperature climate for southern Africa.

Determination of a perturbed temperature scenario associated with climate change

A review of the international literature on climate change was undertaken in order to derive a series of climate change scenarios on temperature, evaporation and precipitation applicable to southern Africa for an effective doubling of pre-Industrial Revolution CO_2 concentrations to approximate 560 p.p.m.v. CO_2, as anticipated in the next four to six decades.

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

(a) Global mean air temperature is predicted from GCMs to increase by 1.5–4.5°C for an effective doubling of CO_2, with a 'best estimate' around 2.5°C (IPCC, 1992). For southern Africa, high-resolution GCMs predict a 2°C rise (Mitchell, 1991).
(b) The regional increase in temperature will be dependent on latitude (θ), increasing at higher latitude (Sinha, Rao & Scaminathan, 1988).
(c) Diurnally, minimum temperatures are hypothesized to increase more than maximum temperatures, a fact largely confirmed by observations in southern Africa (Mühlenbruch-Tegen, 1992).
(d) Seasonally, winter warming is likely to be greater than summer warming (IPCC, 1992).

Based on the above, the following temperature change algorithm for southern Africa was developed (Schulze, Kiker & Kunz, 1993), which accounts for latitudinal dependence, diurnal differences between anticipated maximum and minimum temperature changes and seasonal temperature differences, such that:

$$\Delta T = \Delta T_{\phi}(0.9 + F) \quad (6)$$

and

$$\Delta t = \Delta T_{\phi}(1.1 + F) \quad (7)$$

where

ΔT = temperature change for maximum air temperature (°C)
Δt = temperature change for minimum air temperature (°C)
$\Delta T_{\phi} = \phi/30 \Delta T_{30}$ (°C)

with

ΔT_{ϕ} = latitudinally adjusted change in temperature (°C)
ΔT_{30} = anticipated temperature increase at 30°S (°C)
ϕ = latitude south (degrees)

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 = $I\pi/6$

The above algorithm was used to determine a possible future climate scenario by perturbing each monthly mean of daily maximum and minimum temperature estimate in the southern African regional grid for each month of the year. An example of the application of the above temperature change algorithm for southern Africa is illustrated in Fig. 4. The following section describes the determination of soil fertility scores for the southern African region.

Development of a soil fertility map for southern Africa

In southern Africa, eighty-four 'broad natural homogeneous soil zones' have been identified by the Institute for Soil, Climate and Water. Each soil zone was classified using the South African binomial soil classification system into its dominant soil forms (made up of vertical sequences of diagnostic horizons easily identifiable in the field), with the forms further subdivided into major soils series according to soil physical and chemical criteria (McVicar *et al.*, 1977). For each of the eighty-four soil zones identified, the percentages of each soil form and series occurring within each zone were determined (Schulze *et al.*, 1990). Typical clay content values and base status index are given for all soil forms and series identified by the binomial classification system (McVicar *et al.*, 1977).

A soil fertility map for southern Africa was produced by assigning soil fertility scores (Equation 5) to each soil type identified in each of the eighty-four 'broad natural homogeneous soil zones' and a weighted average was then obtained for each entire soil zone. Fig. 5 shows the distribution of the soil fertility scores determined for southern Africa. For example, Zone 1 of the eighty-four zones consists of four dominant soil forms and series (Table 1) and an area-weighted soil fertility score (F_s) of 4.6 was determined. In this study, the assumption was made that rainfall would remain unaffected by climate change for the following reasons.

(a) GCM predictions of rainfall changes for southern Africa are variable and somewhat contradictory (Schulze *et al.*, 1993).

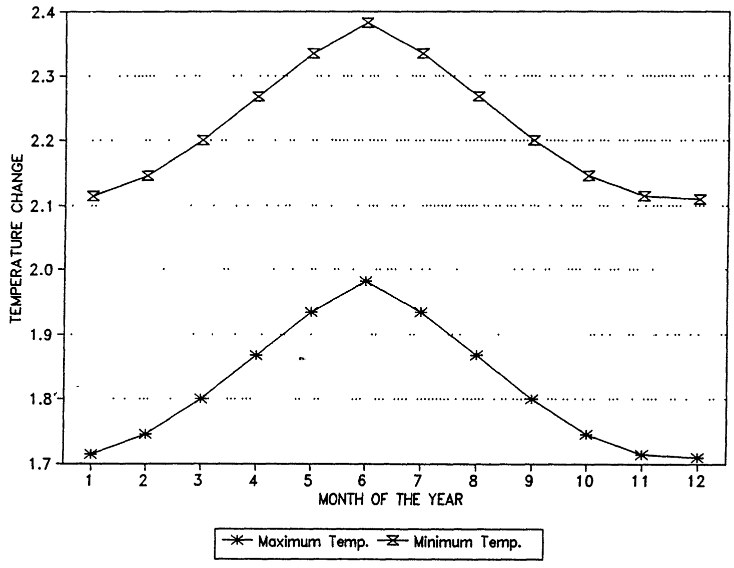

FIG. 4. Example of the seasonal scenario changes in daily means of minimum and maximum temperatures for each month of the year, as used in southern Africa for a mean air temperature increase of 2°C at latitude 30°S (after Schulze *et al.*, 1993).

(b) Meteorologists report that the present level of understanding of regional changes in rainfall over southern Africa cannot as yet justify any definitive quantification of rainfall changes (Schulze *et al.*, 1993).

Since no changes in rainfall amounts, intensities or temporal/spatial distributions over southern Africa were considered, it was assumed that the soil fertility scores (Equation 5) would remain unaffected by climate change.

Determination of C : N ratios for southern Africa

Carbon to nitrogen ratios were determined by applying the respective assimilation equations at each of the 423,700 grid points in southern Africa for both present climatic conditions and for a possible future climate. For the future climate scenario, atmospheric CO_2 levels were increased from 360 to 560 p.p.m.v. A 2°C temperature rise at 30°S was used with latitudinal, seasonal and diurnal adjustments made, as specified in Equations 6 and 7. Since soil fertility scores (Equation 5) are taken to remained unaffected by climate change because no rainfall perturbations were included, this subcontinental scale study considers only the possible impacts of increasing temperatures and enhanced CO_2 concentration on simulated changes in C : N ratios.

RESULTS AND DISCUSSION

The atmospheric CO_2 increase from 360 to 560 p.p.m.v would enhance carbon assimilation rates by a factor of 1.177 using the CO_2EF equation (Equation 2). A temperature increase would raise the temperature constraint factors for mean air temperatures below 30°C and 40°C for carbon and nitrogen respectively, and decrease them above these levels.

Fig. 6 shows the percentage change in the C : N ratio from present to a possible future climate and illustrates the overall effect of the temperature and CO_2 change scenarios on the C : N ratios. Patterns display both relative increases and decreases in regional C : N ratios ranging from − 8 to + 8%. Areas where the C : N ratios decrease indicate that the relative increase in assimilated nitrogen would be greater than that for carbon. Similarly, areas where the C : N ratios increase indicate that the relative increase in assimilated carbon would be greater than that for nitrogen.

TABLE 1. Soil fertility score estimated for each of the dominant soil forms and series found in Zone 1 of the broad natural homogeneous soil zones.

Soil form and series code (with FAO correlation)	Area (%)	Clay content (%)	Base status	Fertility score (F_s)
Hu35 (rhodic and helvic ferralsols and arenosols)	30	06–15	Eutrophic	3.0
Av35 (plinthic luvisols, ferralsols and acrisols)	30	06–15	Eutrophic	3.0
Sd21 (chromic, ferric and rhodic luvisols)	20	35–55	Eutrophic	9.0
Ar40 (pellic and chromic vertisols)	10	55–99	Eutrophic	9.9
			Weighted mean	4.6

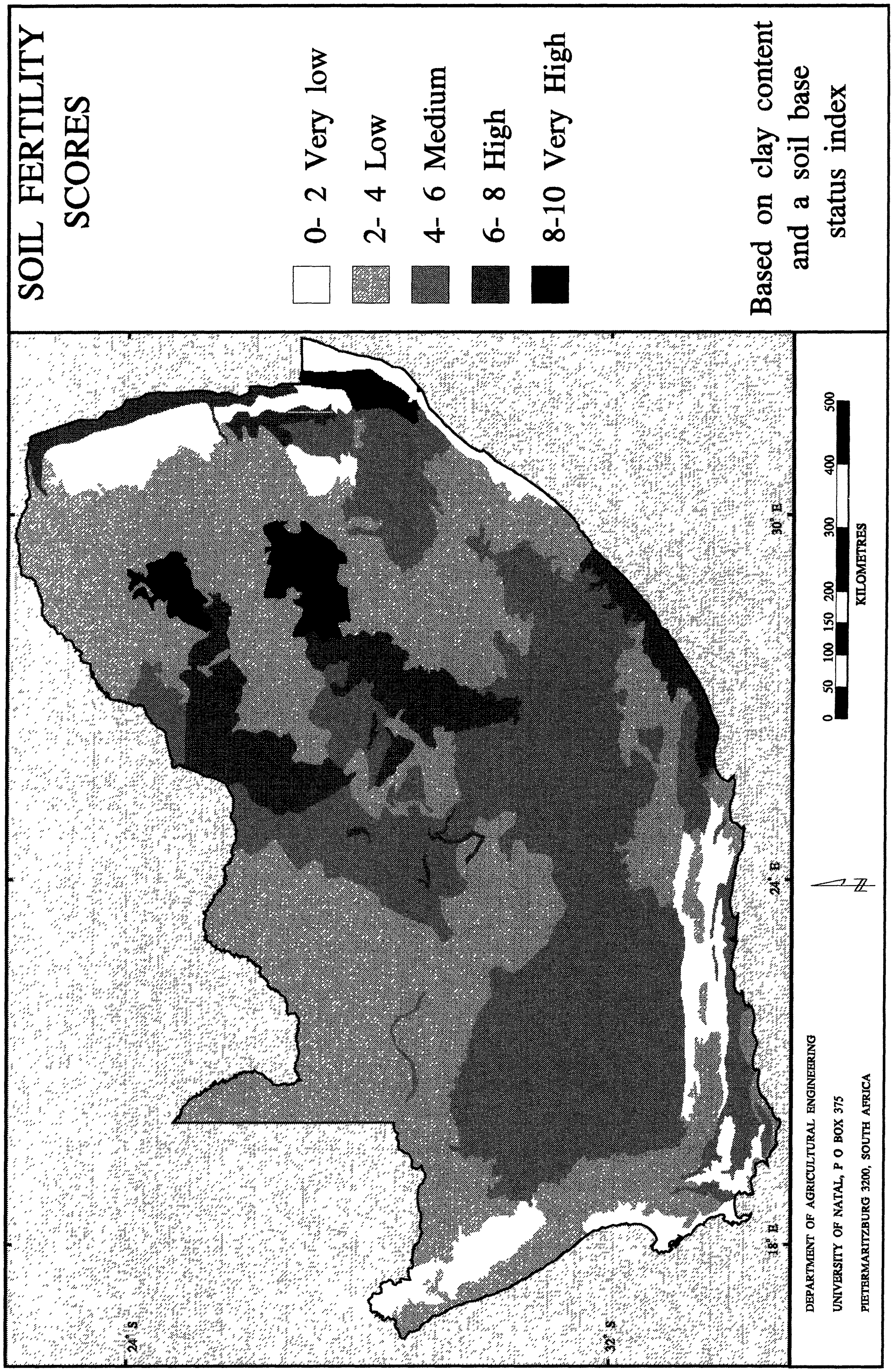

FIG. 5. Soil fertility scores for southern Africa based on clay content and base status.

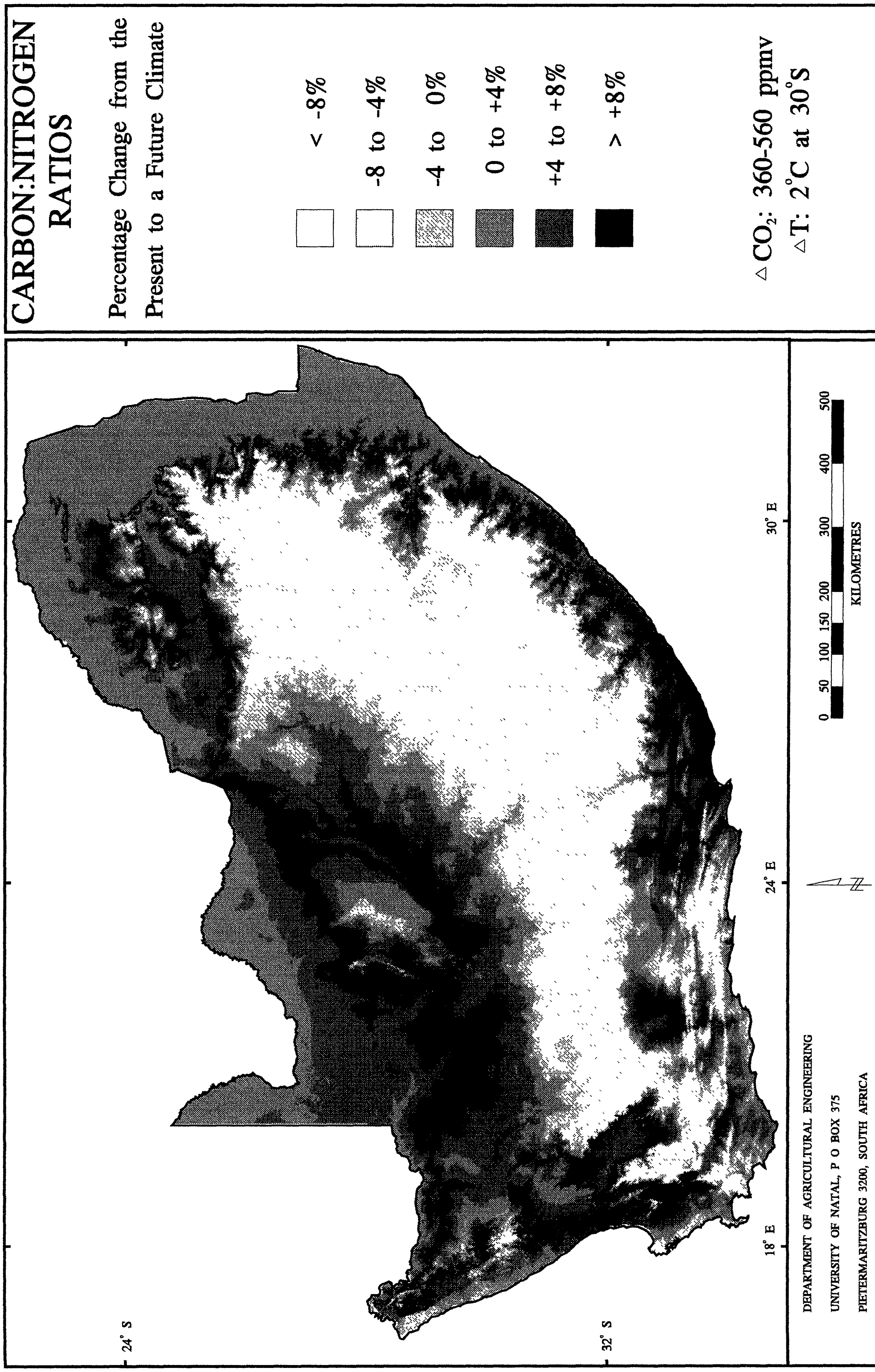

FIG. 6. Percentage change in the C : N ratios from present climatic conditions to a possible future climate scenario in southern Africa.

CONCLUSIONS

The future may be viewed as a valuable resource which scientists need to prepare for and learn to manage. With this in mind, the objectives of climate change impact assessments are to develop a stable scientific knowledge base describing interactions of climate, the environment and society and to provide managers, decision-makers and policy-makers with the necessary scientific information to enable them to predict future environmental impacts.

This study provides some insight into the possible effects of anticipated global climate change on carbon to nitrogen ratios in southern Africa, from which likely influences on plant forage quality and hence animal feeding habits may be inferred. The potential consequences of such changes on the spatial distribution of suitable grazing areas in southern Africa may be of considerable importance. For example, changes in land grazing quality may influence the spatial distribution of animal species as well as animal migration patterns in the pristine environment, and it may also alter present land-use through changes in areas suitable for livestock farming. Changes in plant–animal interactions may influence the population dynamics, migration patterns and the extent of damage caused by herbivorous insects to commercial crops.

The above-mentioned second order impacts of possible climate change are of greater importance than the first order impacts on carbon to nitrogen ratios *per se*. These second order impacts need quantification if scientists are to formulate suitable response strategies which will enable humanity to adapt to, or possibly avoid, unfavourable consequences of climate change. This study emphasizes the need for a holistic approach to climate change research in southern Africa since a possible impact in one system may have repercussions in another.

The results reported in this paper are preliminary. Present research includes computation of C : N ratios on an individual monthly basis to determine whether seasonal patterns differ markedly from location to location and future research will include calibration of the C : N ratio model using field data.

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