Working Paper

CLIMATE CHANGE AND GLOBAL AGRICULTURAL POTENTIAL PROJECT:

A CASE STUDY OF KENYA

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WP-96-71
September, 1996

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DISCLAIMER

Any part of the hereìn presented AEZ model and model parameters, as well as the clìmate change scenarìos used, may be modified or replaced in the lìght of ìmproved knowledge and/or changed objectìves.

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ACRONYMS AND ABBREVIATIONS

AEZ	Agro-Ecologica1 Zoning
C_3	Plants with a 3-carbon organic acid photosynthesis pathway
C_4	Plants with a 4-carbon organic acid photosynthesis pathway
CAM	Crassulacean Acid Metabolism
CIMMYT	Centro de Investigacion y Mejoramiento de Maiz y Trigo
DEM	Digital Elevation Model
ECU	Environmental Change Unit (Oxford, UK)
FAO	Food and Agriculture Organization of the United Nations (Rome, Italy)
GSA	GISS quasi-transient Scenario A
GCM	General Circulation Models
GCM-E	General Circulation Models - Equilibrium Scenario
GCM-T	General Circulation Models - Coupled Ocean-Atmosphere Transient Scenario
GDP	Gross Domestic Product
GFDL	Geophysical Fluid Dynamics Laboratory (Princeton, USA)
GFTR	GFDL Transient Scenario
GIS	Geographical Information System
GISS	Goddard Institute of Space Studies (New York, USA)
GRID	Global Resource Information Database (UNEP)
IGBP	International Geosphere-Biosphere Programme: A Study of Global Change
IIASA	International Institute for Applied Systems Analysis (Laxenburg, Austria)
IPCC	Intergovernmental Panel on Climate Change
KARI	Kenyan Agricultural Research Institute (Nairobi, Kenya)
KENSOTER	Kenya SOTER pilot project
LAI	Leaf Area Index
LGP	Length of Growing Period
LUT	Land Utilization Types
MPI	Max Planck Institute for Meteorology (Hamburg, Germany)
MPTR	MPI Transient Scenario
OECD	Organization for Economic Cooperation and Development (Paris, France)
PAR	Photosynthetically Active Radiation
SOTER	Soils and Terrain Digital Databases
TSU	IPCC Working Group II Technical Support Unit
TZ	Thermal Zones
UKMO	United Kingdom Meteorologica1 Office (Bracknell, UK)
UKTR	UKMO Transient Scenario
UNEP	United Nations Environment Programme (Nairobi, Kenya)
USEPA	United States Environmental Protection Agency (Washington DC, USA)
USLE	Universal Soil Loss Equation
UTM	Universal Transverse Mercator
WUE	Water-Use Efficiency

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SUMMARY OF RESULTS

Kenya is endowed with a wide range of agro-ecologica1 conditions, varying from hot arid lowlands to cool humid highlands. As expected, the results of the impact analysis of climate change and increases of atmospheric carbon dioxide, therefore show a wide spectrum of impacts on land resources make-up and agricultural production. At the sub-national level results of impacts on agricultural productivity vary substantially both in terms of magnitude and direction.

At present, agricultural production in the low altitude areas in Kenya is mainly constrained by water availability, highland areas are constrained by low temperatures and locally by water availability, while in parts of central and western Kenya rainfall in excess of optimal levels occurs.

Rising temperatures, without corresponding increases in precipitation to balance the increased plant water requirements due to higher evapotranspiration may lead to dramatic reductions in agricultural production potential, especially in eastern and southern Kenya, i.e., in parts of Eastern province, North-Eastern province and Coast province. In central and western Kenya temperature increases would result in larger extents of lands with cultivation potential, because some higher altitude areas would become suitable for cropping. This, together with potentials for higher cropping intensities in these highland areas, more than outweighs effects of diminished misture conditions, even in scenarios assuming no change in precipitation. Under such conditions in the presently humid areas (>270 days of growing period), diminished wetness, in instances, could reduce the potential impact of pest and disease constraints.

Results of the impact assessment suggest that the national level food productivity potential of Kenya may well increase with higher levels of atmospheric CO_2 *and climate change induced increases in temperature, provided this is accompanied by some increase in precipitation as predicted by several global circulation models. If no balanced increase in precipitation were to take place then the impact on agricultural productivity in the semi-arid parts of Kenya could be devastating.*

Although land productivity in Kenya as a whole appears most likely positively affected by climate change, impacts vary considerably depending on location. Negative

impacts are expected to occur in Coast province and North-Eastern province. The inain reasons being:

- *Exceeding optimal temperature ranges for photosynthesis and growth;*
- *Shortening of cereal growth cycles and periods of yield formation;*
- *Iizcreased water stress.*

For Central province, Nairobi area, important parts of Eastern province, Nyanza province and Western province the impacts are mostly positive. However, some negative irnpacts in western Kenya may occur due to pest and disease damage and worsening of workability conditions due to increased wetness. The high-potential agricultural lands in centra1 and western Kenya will dominate the agricultural production potential even more under projected climate change coizditions. The main reasons of positive impacts appear to be:

- *Temperature increase in the mid/high altitudes, enlarging the area with crop production potential;*
- *Iizcreased cropping intensity potentials;*
- *CO_2 fertilization.*

In Rift Valley province, comprising of a wide range of thermal and moisture conditioizs, iinpacts are mixed. Negative iinpacts are. for instance, expected in Laikipia and Narok while positive iinpacts are anticipated in Nakuru and West Pokot.

Despite of overall positive effects for Kenya as a whole, impacts of climate change on land productivity nzay intensify regional disparities. Therefore, preparedness is critical in order to:

- *take advantage of potential blessings of climate change and increased atmospheric CO_2 concentrations ;*
- *mitigate likely negative impacts in low-lying and semi-arid areas;*
- *cope with the socio-economic consequences of changing patterns of land productivity.*

These observations are consistent with short and medium term considerations for sustainable development, emphasizing the critical need for careful planning and protectioiz of high potential areas.

CHAPTER 1
INTRODUCTION

1.1 Background

There is ample scientific evidence that global climate is gradually changing, and not the least as result of increasing levels of atmospheric greenhouse gases due to human activities, notably fossil fuel burning (IPCC, 1996a). It has also become clear that the expected changes in climate will alter agricultural potentials in various agro-ecologica1 regions of the world. The projected increase of atmospheric carbon dioxide CO_2 will result in enhanced potential agricultural productivity and improve the efficiency of water-use by various crops. The effects of global warming will extend agro-ecologica1 potentials polewards and into higher altitudes. These positive effects, however. may be undercut by altered temperature conditions. amounts and distribution of precipitation, evaporation patterns, radiation regimes, and indirect effects on land productivity such as increased impacts of pests, diseases and weeds. In the long term, these changes of climate pattems will significantly alter land potentials for producing food and other agricultural and forest products.

A number of initiatives on climate change have begun to compile assessments of climate change and its potential impact on agriculture. For example, the Intergovernmental Panel on Climate Change (IPCC) has been conducting a review of available data and more in-depth studies are being carried out by the Commission of the European Union, the United States Environmental Protection Agency (USEPA) and the Organization for Economic Cooperation and Development (OECD). Further work on impacts of climate change is being conducted by the International Geosphere-Biosphere Programme: A Study of Global Change (IGBP). Country case studies on the potential impacts of climate change on agriculture have been compiled for a growing number of countries, e.g., Australia, the Commonwealth of Independent States, Egypt, Finland, Indonesia, Malaysia, the Netherlands, New Zealand, Norway, Thailand, the United Kingdom, the United States of America, and Vietnam.

These initiatives differ markedly in their baseline data, methods of analysis, and scenarios of climate change. The majority of these studies have been based on climate change experiment with general circulation models (GCM), but often do not apply the same scenarios and do not share a common implementation strategy. Most of these studies have relied on both field-level results of crop model experiments and regional shifts in agro-climatic indices. Although results have enabled regional changes in vegetation zones to be mapped, the equivalent changes to agro-ecologica1 potential on a more global scale has yet to be compiled.

In addition, there are a few key areas related to a shifting agricultural potential that have not been addressed at a global scale. For example, few of the country studies have systematically mapped the possible shifts in agricultural potential for a wide variety of crops and analyzed the implications for national development planning. Although these studies have contributed to a more detailed understanding of the sensitivity of specific crops to climate change, a more rigorous sensitivity on such factors as technological growth and development have received far less attention. In addition, few global studies have directly addressed the potential for adaptive responses such as crop switching, the development of new varieties, expansion of the crops under cultivation, and changes of cropping intensity. In general, the interplay between climate change and other environmental factors that affect sustainable development have often been omitted.

In the next few years new scenarios of climate change can be expected that will incorporate more realistic land-cover models, ocean-atmosphere interaction and improved modeling of the hydrological cycle. It is hoped that a next generation of GCM scenarios will provide greater insight into critica1 variables for agriculture such as the frequency of occurrence of extreme events (drought, frost or heat), rainfall intensity and distribution, and solar radiation(accounting for changed cloudiness and aerosols).

This present '*Climate Change and Global Agricultural Potential Project*' intends to formulate methodologies that allow incorporation of climate related factors in land productivity assessments. The methodologies and applications to existing data bases, should allow scientists and policy makers to better assess present agricultural production conditions and should enable them to improve identification of future agricultural scenarios on national, regional, and global scales. As part of this project, a methodology is being applied and tested using existing land resources databases for Bangladesh, Kenya, Nigeria and for the World.

1.2 *Agro-ecological zones approach*

FAO has developed a methodological framework for assessments of land productivity which originally was designed for use in agricultural development planning and natura1 resources management.

Agro-ecologica1 zoning (AEZ) involves the inventory, characterization and classification of the land resources which are meaningful for assessments of the potential of agricultural production systems. This characterization of land resources includes components of climate, soils and landform, basic for the supply of water, energy, nutrients and physical support to plants.

Crops require heat, light and water in varying amounts. The geographic distribution of crops is mainly governed by these climatic elements. Temperature, water and solar radiation are key climatic parameters which condition the net photosynthesis and allow crops to accumulate dry matter according to the rates and patterns which are specific to individua1 crop species. Crops have specific temperature requirements for their growth and development, and prevailing temperatures set the limits of crop performance when moisture (and radiation) requirements are met. Vice versa, when temperature requirements are met, the growth of a crop is largely dependent on how well the length of its growth cycle matches the period when water is available. In the AEZ approach, this has led to the concept of the length-of-growing-period (LGP) which is defined as the period (in days) during the year in which water availability and prevailing temperature can sustain crop growth.

Crop performance depends as well on the availability of nutrients in the soil, the capacity to store water, and mechanical support for crops. Therefore, agro-ecologica1 zoning also includes an inventory of relevant soil and landform characteristics. The specific combinations of climatic, soil and terrain inventories (i.e., land resources inventory/database) form the basic units of analysis, and are referred to as agro-ecological cells (AEZ cells).

Technical specifications (including management) within a socio-economic setting under which a specific crop is grown have been defined as land utilization types (LUT). Crop suitability assessments, in essence, are based on matching of crop specific adaptability characteristics and crop/LUT ecological requirements with the attributes of individua1 AEZ cells.

The choice of using the AEZ methodology as the point of departure for developing a climate impact assessment methodology is based on the fact that AEZ is an environmental approach which provides a geographic dimension for establishing spatial inventories and databases on land resources and crop production potential. The data requirements are limited and it uses readily available data to the maximum. Moreover, it is comprehensive in terms of coverage of factors affecting agricultural production. The approach promises to be relevant for assessments of potential agricultural responses to scenarios of climate change.

For selected countries FAO has embarked on country case studies in the context of the present '*Climate Change and Global Agricultural Potential Project*'. Chapter 4 contains technical details of adaptations made to the AEZ methodologies to enable assessment of agricultural potentials for various climate change scenarios applicable for the Kenya climate change impact case study.

For the Kenya case study, existing AEZ inventories and databases (FAO/IIASA, 1993) were updated and computer procedures expanded and enhanced, resulting in the following activities with regard to the main steps of AEZ procedures:

- Selection of GCM outputs for the formulation of relevant climate change scenarios for Kenya for ca. 2030,2050 and beyond *(new);*
- Selection and definition of crop types/LUTs *(reviewed);*
- Compilation of crop ecological adaptability inventory *(updated);*
- Compilation of soil and terrain resources inventory and database *(updated, expanded);*
- Applications of various selected climate change scenarios *(new);*
- Application of AEZ water balance model at grid cell level to determine location specific length, type and quality of growing periods *(new);*
- Calculation of potential net biomass and yield *(enhanced with additional variables);*
- Assessment of crop suitability *(enhanced for application with updated and expanded land resources database);*
- Formulation of criteria for selection of optimum crop combinations and rotations *(reviewed);*
- Assessment of land productivity under various scenarios of climate change and atmospheric CO_2 concentrations *(new).*

1.3 Socio-econornic setting

The socio-economic setting which describes both the study area (Kenya) and the exposure unit (agriculture) is the context in which the climatic impact assessment methodology is applied and tested. The setting is fully described in Onyeji *et al.* (1996). Below some of the salient features are summarized.

Kenya is largely an agricultural economy. The country is denominated into eight administrative provinces including Nairobi. Each province. except Nairobi, is made up of districts divided further into smaller administrative units (e.g., division, location and sub-location). Kenya's agricultural economy is dominated by small holder farms, particularly in the Central, Eastern, Nyanza, Western, Rift Valley and Coast provinces. In 1961, agricultural population accounted for 89% of the total population. By 1990 this share has declined to 76%. Similarly, agriculture's contribution to gross domestic product (GDP) has steadily declined over the years, and so has the share of the agricultural labor force in the total labor force. With the gradual decline of the share of agriculture population, rural Kenya is also gradually urbanizing. Kenya's urban population is projected to increase from 3.8 million in 1989 to 6.4 million in 2000 at an annual rate of 4.8% (Republic of Kenya 1994a, 1994b). Inevitably, this increase in urbanization creates competition over land between agriculture and human settlements. Among other problems of Kenya agriculture are topsoil losses and degradation of vegetation due to low input, subsistence agricultural management practices; climate change is expected to bring on added consequences — some positive, some negative.

Sustainable agriculture and food production is a major agricultural development policy of the Government of Kenya. This policy, set out in various Kenya government documents, stresses the importance of the agricultural sector which in 1990 accounted for 24% of Kenya's total GDP, about 77% of total employment in the economy, and also earned a substantial amount of foreign exchange. To attain self-sufficiency in food by the year 2000, food commodity requirements are projected by the Kenyan Government as follows: rice production should grow at an annual rate of 12.5%; wheat by 7.8% and beans by 6.8%; maize, sorghum/millet as well as milk production are each required to grow by almost 5.0% annually.

The present study assesses the agricultural potential under climate change conditions beyond the current policy target year 2000. The employed methodology which is based on the agro-ecologica1 zones approach is particularly suited to this problems as it focuses on environmental resources that are modifiable by climate change and are essential for understanding its long term implications on the agricultural sector.

CHAPTER 2
CLIMATE CHANGE SCENARIOS

Scenarios of climate change were developed in order to estimate their effects on crop yields, extents of land with cultivation potential, and the number and type of crop combinations that can be cultivated. A climate change scenario is defined as a physically consistent set of changes in meteorological variables, based on generally accepted projections of CO, (and other trace gases) levels. The range of scenarios analyzed is intended to capture the range of possible effects and to set limits on the associated uncertainty.

A number of sensitivity and GCM-based climate scenarios were prepared for use in the AEZ-Kenya climate change study. Two kinds of climate scenarios were developed. First, several sensitivity experiments were defined, varying a single meteorological variable such as monthly temperatures or rainfall. Simulations were done exploring the potential consequences of temperature increases of between 1-5°C. Similarly, precipitation changes were tested in the range of -10% to +10% of baseline conditions. Secondly, several climate change scenarios were constructed based on available results of simulations with genera1 circulation models. Three types of GCM based scenarios were used in the study:

2.1 Doubled CO_2 equilibrium experiments

Equilibrium experiments determine the steady state of the simulated physical climate system under baseline and altered radiative conditions, usually equivalent to a doubling of current radiative forcing from greenhouse gases. Rates of future emissions of trace gases and the point in time when their effects will be fully realized are not certain. Because other greenhouse gases besides CO_2, such as methane (CH_4), nitrous oxide (N_2O), and the chlorofluorocarbons (CFCs), are also changing, an 'effective CO_2 doubling' has been defined as the combined radiative forcing of all greenhouse gases having the same forcing as doubled CO_2 (usually defined as –600 ppm). Doubled CO_2 experiments from three different GCMs were used in the Kenya study: the models are those from Goddard Institute for Space Studies (GISS) (Hansen *et* al., 1983), from Geophysical Fluid

Dynamics Laboratory (GFDL) (Manabe & Wetherald, 1987), and from United Kingdom Meteorologica1 Office (UKMO) (Wilson & Mitchell, 1987).

2.2 Quasi-transient equilibrium experiments

The GISS Transient Scenario A (Hansen ***et*** al., 1988) consists of separate equilibrium GCM runs calculated for transient increased atmospheric CO_2 levels. In the experiment, CO_2 concentrations were set at 405 ppm, 460 ppm and 530 ppm, and have been associated respectively with year 2010, 2030 and 2050. We have termed these GCM calculations quasi-transient equilibrium experiments as they are quite different in their characteristics from the more recent experiments with coupled ocean-atmosphere models.

2.3 Transient GCM experiments

Transient climate change experiments aim to capture the time-dependent response of climate to time-dependent increases in greenhouse gases, using coupled ocean-atmosphere models. Because of the thermal inertia of the oceans, temperature increases obtained at the time of reaching a doubling of CO_2 in the atmosphere are much lower than for corresponding doubled CO_2 equilibrium experiments (4.0-5.2°C). Results from three GCMs were used, provided to Working Group II (see TSU, 1994) for preparation of the 1995 IPCC Second Assessment Report (IPCC, 1996b): from the GFDL group (Manabe ***et*** al., 1991), from the Max Planck Institute (MPI) (Cubasch ***et*** al., 1992), and from the UKMO (Murphy, 1995; Murphy & Mitchell, 1995).

Three climatic parameters from the GCM results were used to modify the baseline climate conditions of each grid-point of the land resources database. The difference in temperature, between a GCM climate change run and the respective GCM control experiment (assuming current ambient atmospheric greenhouse gas concentration levels) was added to the mean monthly maximum and minimum temperatures of the reference climate as described by the KARI/CIMMYT climate surfaces (see Chapter 4). Multipliers, i.e., the ratio between GCM climate change and control experiment, were used to impose changes in precipitation and incident solar radiation, respectively. Consequently, for each climate change scenario gridded surfaces of monthly values of four climate parameters were generated: mean monthly minimum and maximum temperature, monthly rainfall, and monthly solar radiation. Due to lack of reliable information, windrun was kept unchanged from reference conditions in all climate change scenarios. Relative humidity (RH) has been derived from regressions of actual RH data with the other climatic parameters of the baseline climate. For the different climate scenarios relative humidity is obtained through application of this regression equation with the altered climatic parameters.

In accordance with the soil and terrain resources inventory, a 2 km by 2 km grid size was used. Pixel values of climate change were spatially interpolated from the coarser grids used in GCMs. Each sensitivity test or GCM based climate scenario is also characterized by level of atmospheric CO_2 concentrations and assumed improvement in water-use efficiency. These parameters affect both the estimated reference evapotranspiration as well as parameterization of the biomass calculation procedures. Table 2.1 (see Tables section at the end of the report) presents for three-monthly periods the ranges of changes of temperatures ("C), precipitation (%) and solar radiation (%), scenario implied levels of atmospheric CO_2 concentrations (ppm)[1], and assumed leaf stornata resistance changes (%) for the various scenarios applied.

[1] Even in scenarios assuming a doubling of CO_2 equivalent concentrations carbon dioxide itself does not double since some of the other greenhouse gasses are expected to increase faster than CO_2.

CHAPTER 3

EFFECTS OF CLIMATE CHANGE AND INCREASED ATMOSPHERIC CARBON DIOXIDE CONCENTRATIONS ON CROP PRODUCTIVITY[2]

Plant species vary in their response to CO_2 in part because of differing photosynthetic mechanisms. C_3 plants use up some of the solar energy they absorb in a process known as photorespiration. In this process, which occurs only in the light, a considerable fraction of the carbon initially reduced from CO_2 and fixed into carbohydrates is reoxidized to CO_2. C_3 species tend to respond readily to increased CO_2 levels because photorespiration is suppressed in these conditions. Important crop plants with the C_3 photosynthetic pathway are wheat, rice, and soybean. In C_4 plants, on the other hand, CO_2 is trapped inside the leaf and then concentrated in the cells which carry on photosynthesis. These plants are more efficient photosynthetically than C_3 plants under present CO_2 levels, but in crop experiments were less responsive to CO_2 enrichment. C_4 plants of economic importance include maize, sorghum, millet, and sugarcane. Due to altered plant development in a CO_2-enriched atmosphere therefore, C_4 plants may be more vulnerable to increased competition from C_3 weeds.

Another important physiological effect of CO_2 enrichment is the closure of stomates, the small openings in leaf surfaces through which CO_2 is absorbed and water vapor released. Accordingly, a rise in atmospheric CO_2 may reduce transpiration even while promoting photosynthesis. This dual effect may improve water-use efficiency. Thus, by itself, increased CO_2 can increase yield and reduce water use per unit of biomass.

Temperature, solar radiation, water and atmospheric CO_2 concentration are the main climate and atmospheric vai-iables of importance to plant productivity. There are important differences in temperature requirements and responses to concentration of atmospheric CO_2 among C_3, C_4 and CAM[3] plants. Also, most of the crop plants presently used in agriculture have been selected and bred into different varieties for producing efficiently high yields under specific environmental and farming systems conditions. Nutrients and water may be augmented via fertilization and irrigation, while radiation and

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[2] Summarized and adapted from IPCC, WGII, Second Assessment Report (IPCC, 1996b) and Rozema *et* al. (1993).

[3] Crassulacean acid metabolism

temperature are more difficult to control, in particular in large scale agricultural operations.

Responses of plants to climate change have been studied in a large number of experiments and in detailed modeling of basic processes. Results of this research and knowledge of basic physical and biologica1 processes, together with research into the problems of up-scaling of research results obtained at micro level (e.g., individua] leaf) to macro-scales (e.g., farm field level for entire cropping seasons) have provided basic understanding of direct and indirect effects of climate change on agricultural productivity.

Climate change will most likely result in new combinations of soil, climate, atmospheric constituents, solar radiation and pests, diseases and weeds. Some of the interactions of temperature, moisture availability and increased CO_2 on plant growth have been investigated through crop response models. These models have been widely used to assess yield response to climate change at many different sites around the world and have produced valuable insights in these interactions (e.g., Rosenzweig & Parry, 1994; Fischer ***et*** al., 1996). However, details of the many different effects of climate changes and increased CO_2 on crop production, across widely varying conditions that exist in different agro-ecologica1 regions, have yet to be summarized.

3.1 *Effects of increased CO_2 levels*

There is generally agreement that an increase of atmospheric CO_2 levels leads to increased crop productivity. In experiments, C3 plants, like wheat and soybeans, exhibit an increased productivity at doubled CO_2 concentrations of about 30%. Response however depends on crop species as well as soil fertility conditions and other possibly limiting factors. C_4 plants, such as maize and sugarcane, show a much less pronounced response than the C3 crops, on the average in the order of 5-10%. In general, higher CO_2 concentrations also lead to improved water-use efficiency of both C_3 and C_4 plants.

Established trends of plant responses to increased CO_2 concentrations on the basis of experiments, in terms of plant growth, plant water-use efficiency, and quantity and quality of harvested produce are summarized below:

Plant growth

C3 plants (temperate and boreal) show a pronounced response to increased CO_2 concentrations.

C_4 plants (warm tropical) show only limited response to increased CO_2 concentrations.

C_3 plants with nitrogen fixing symbionts tend to benefit more from enhanced CO_2 supplies than other C3 plants.

Photosynthesis rate increases occur immediately following exposure to increased CO_2 concentrations.

Initial strong response is often reduced under long-term exposure to higher CO_2 levels; experimental evidence suggests that growth responses would be lower for perennials than for annuals.

Increased leaf area production, as a result of increased rate of photosynthesis, leads to an earlier and more complete light interception and therefore stimulates biomass increases.

Higher biomass requires higher energy supply for maintenance, expressed in higher respiration, partly compensated by lower specific respiration.

Leaf turn-over rate increases due to self shading and decrease of specific leaf surface, and both tend to reduce photosynthesis per leaf.

At higher CO_2 levels, plant growth damages inflicted by air pollutants, such as nitrogen oxides (NO_x), sulfur dioxide (SO_2) and ozone (O_3), are at least partly limited because of reduced stomatal opening.

Water use efficiency

Increased CO_2 levels reduce stomatal conductance and transpiration rate. However, water consumption on a ground area basis, i.e., canopy evapotranspiration, versus consumption on a leaf area basis is reporied to be much less affected.

The range in water-use efficiency (WUE) of major crops is fairly wide and most distinct for C_4 crops. Many studies report an increase in the water-use efficiency in terms of dry matter produced per unit of water transpired.

- As a consequence of reduced transpiration, leaf temperature will rise and may lead to a faster rate of plant development and considerable increase in leaf area development, especially in the early crop growth stages.
- Reduced transpiration and resulting higher leaf temperature leads to an accelerated aging of the leaf tissue.
- Overall effects of leaf temperature rise will depend upon whether or not optimum temperatures for photosynthesis are approached or exceeded.

iii. Harvest index and quality of produce

- Biomass and yield increased in almost all experiments under controlled conditions.
- Dry matter allocation patterns to roots, shoot and leaves have been observed to change differently for C3 an C_4 crops. Root/shoot ratios often increase under elevated CO_2 levels, favoring root and tuber crops (and also contribute to soil organic matter build-up).
- Increased CO_2 accelerates crop development due to increased leaf temperature resulting from reduced transpiration, reducing the efficiency of biomass or seed production.
- The content of non-structural carbohydrates generally increases under high CO_2 while the concentration of mineral nutrients and proteins is reduced. Food quality of leaf tissue may decline leading to an increased requirement of biomass by herbivores.

3.2 Effects of changes in climate variables

Current climate change scenarios predict a warming of between 1-4.5 degree Celsius and changing precipitation patterns with generally increasing rainfall levels. Changes in climatic variability are still uncertain, and discussion of its eventual effects on crop productivity would be rather speculative, and therefore has been omitted.

Trends of plant responses to changes of temperature, precipitation, humidity and (potential) evapotranspiration are summarized below:

i. Temperature effects

- Temperature effects depend strongly on interactions with other environmental effects such as elevated CO_2. There appears to be a clear temperature effect on CO_2

fertilization, especially for C3 plants, i.e., the processes responding to increased CO_2 tend to intensify with temperature.

Night-time temperatures are expected to increase more than average temperatures. This may result in higher respiration losses for C_3 and C_4 plants.

Higher temperatures have a positive effect on crops of the CAM type, strengthen the CO_2 fertilization effect, and improve water-use efficiency of C_3 and C_4 plants unless plants get overheated.

Higher mean temperatures during the cold season allow earlier planting, and cause earlier ripening of annual crops. Reduced length of the crop growth duration generally diminishes crop yields. On the other hand, the reduced growth cycle duration of crops in some cases might lead to more crops per year and extension of the growing season for perennials. For annual crops. shortening of the growing season is not fully compensated by a changed ontogenetic development and higher growth vigor at the higher temperature. Therefore a net yield loss is expected to occur. The duration of the vegetative growth and the light interception during the reproductive stages largely defines the occurrence of net yield losses.

Temperature influences the partitioning of dry matter and the growth rate of biomass.

Higher temperatures in mountainous areas will provide more plant growth at high altitudes. Improved heat provision will also benefit high latitude regions.

Higher temperatures might effect phenological development of crops or induce temperature stresses (e.g., risk of reversed vernalization in wheat, or the risk of increased spikelett sterility in rice).

Precipitation, humidity and evaporation

Climate change projections point to an intensification of the hydrological cycle; higher evaporation, humidity and precipitation. However, changes in seasonal precipitation distribution and intensity, in most instances, would affect crop productivity more than changes in annual precipitation and evapotranspiration do.

Under equal temperature conditions, increased CO_2 levels might decrease, potential evapotranspiration rates due to reduced crop transpiration. Actual evapotranspiration rates will partly compensate for improved WUE due to an increase in leaf area index (see change in water-use efficiencies under increased levels of atmospheric CO_2).

- Both positive and negative impacts are likely to be most pronounced in arid and semi-arid regions where the moisture balance is most sensitive to changes in precipitation and temperatures. Higher precipitation and humidity might improve moisture balances in some of these areas in favor of natura1 vegetation and crop yields. In humid and perhumid areas, however, increased precipitation and humidity might lead to extending of periods with excess moisture which could result in hampered field operations and increased incidence of pests and diseases; all of which may depress crop yields.

3.3 *Indirect effects through weeds, insect pests and diseases*

Weeds, insect pests and diseases are generally affected by climate and atmospheric constituents. Resultant changes in the geographic distribution, with vigor in current ranges, will most likely affect crop production.

i. Cornpetition of weeds

- Weeds compete with crops for resources essential for plant growth and unless controlled, weeds generally reduce potential crop yields in agro-ecosystems.
- Changes in CO_2 concentration, temperature, water and nutrient availability, differently affect the competition between weeds and crops.
- Differences in response of C3 and C_4 plants to increases in atmospheric CO_2 are of importance to weed-crop competition. In fact, most of the important food crops are C3 plants, while most weeds are C_4 plants.

ii. Crop insect pests

- Climate is a critical factor in determining habitats available to insect communities thus influencing insect survival rates. Changes in habitat generally leads to increased mortality but may also lead to higher reproduction rates, changes in diapause, migration, or even to genetic adaptation. Similarly, changes in seasonal and interannual climatic variation may influence life cycle duration, fecundity, diapause abilities and genetic adaptation of insects.

iii. *Croy diseases*

- Crop diseases are primarily related to climate and soil conditions. Evidences of changes in occurrence patterns of crop diseases related to climate change or increased CO_2 concentrations have, to our knowledge, not systematically been recorded or documented.

CHAPTER 4

AGRO-ECOLOGICAL ZONES METHODOLOGY FOR CLIMATE CHANGE IMPACT ASSESSMENTS

4.1 *Overview*

Figure 4.1 provides a general overview of the flow and integration of information as implemented in the Kenya Climate Change study. In the following explanation the numbers in brackets relate to the numbering used in Figure 4.1. Boxes shown in light gray indicate components of the AEZ-KENYA system that received a major update, components in dark gray have been newly implemented or added to expand the methodology for climate change impact assessments.

(1) ***Land utilization types (LUT):*** LUT descriptions comprise sets of alternative activities available to achieve specified objectives, i.e., usually production of crops, fodder or fuelwood. The first step in an AEZ application is the selection and description of land utilization types to be considered in the study. FAO (FAO, 1984) defines LUT as follows: '*A Land Utilization Type consists of a set of technical specifications within a socio-economic setting. As a miniinum requirement, both the nature of the produce and the setting inust be specified'*. The description has been organized in a hierarchical structure that defines:

***Level l*,** elements common to all land utilization types: These elements include the socio-economic setting of a 'homogenous' region for which a number of land utilization types may be defined.

***Level 2*,** elements common to groups of land utilization types: e.g., severa1 land utilization types may be defined for a particular farming system. Holding size, farm resources, etc. are to be presented at this level of LUT description.

***Level 3*,** elements specific to particular land utilization types: crop specific information such as cultivation practices, input requirements, crop calendars, utilization of main produce, crop residues and by-products, are to be described at this level. The variety of aspects that can be meaningfully included in the description as well as the amount and detail of quantitative information provided should match the needs and scale of a study. The Kenya study distinguishes 64 crop LUTs, 31 fuelwood LUTs and a compound grassland LUT[4], each at three levels of inputs. Similarly, 10 livestock systems are considered per input level.

(2) ***Crop, forage and fuelwood catalog:*** The term catalog refers to a computer representation of the quantitative aspects of the LUT description in a database format. As pointed out above, the level of detail regarding the representation of different crop, forage and fuelwood species and varieties in the database should reflect the study objectives as well as match the sophistication of its methodological components and the scale at which the study operates. For the Kenya study, the crop, forage and fuelwood catalog database includes parameters describing thermal requirements of crop types, reference crop cycle lengths, relative lengths of crop development stages (i.e., percentages of total crop cycle length), photosynthetic pathway, crop adaptability group, maximum leaf area index, parameters for biomass calculation, harvest index, development stage specific crop water requirement coefficients, moisture stress related yield reduction coefficients, food content coefficients (energy, protein), extraction/conversion rates, crop by-product/residue coefficients, commodity aggregation weights.

(3, 4, 5) ***Climate database:*** In the present study the historical records of rainfall and synoptic station data have been scrutinized and updated, now covering, where available, the period of the 1920's until 1992. In addition to these data, average climate data from the FAOCLIM database (FAO, 1995) for Kenya and neighboring countries. and gridded climate surfaces data developed within the KARI/CIMMYT Kenya Maize Data Base Project (Box 4), provide the basic spatial and temporal climate information used in the assessment. All climatic parameters are kept in a 'baseline' gridded database (Box 5).

(6) ***GCM-based climate scenarios:*** A number of sensitivity and general circulation models (GCM) based climate scenarios were prepared for use in the AEZ-Kenya climate change study. Scenarios were used from doubled CO_2 equilibrium experiments (GISS - Goddard Institute of Space Studies, GFDL - Geophysical Fluid Dynamics Laboratory, and UKMO - United Kingdom Meteorologica1 Office) and from coupled ocean-atmosphere transient experiments (GFTR - Geophysical Fluid Dynamics

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4 24 grass and 8 legume pasture species were rated in relation to temperature regime and moisture availability, and combined into a generalized grassland productivity assessment, assuming that for different ranges of environmental conditions respectively the most suitable and productive species would dominate, depending on level of inputs.

Laboratory, MPTR - Max Planck Institute of Meteorology, UKTR - United Kingdom Meteorologica1 Office).

(7) ***Scenario-derived climatic parameters:*** Three climatic parameters from the GCM results were used to adjust the baseline climate conditions of each grid-point of the climate surfaces. For this, indicators of climate change were spatially interpolated from the coarser grids used in GCMs. The *difference* in temperature, between a GCM climate change run and the respective GCM control experiment (assuming approximately current ambient atmospheric greenhouse gas concentration levels) was added to the mean monthly maximum and minimum temperatures of the baseline climate surfaces. Multipliers, i.e., the *ratio* between GCM climate change and control experiment, were used to impose changes in precipitation and incident solar radiation, respectively. Each sensitivity test or GCM-based climate scenario is also characterized by level of atmospheric CO, concentrations and assumed changes of water-use efficiency. These parameters affect both the estimated reference evapotranspiration as well as the parameterization of the biomass calculation procedures.

(8, 9) ***Lund resources inventories (GZS):*** The storage and manipulation of complex spatial information, i.e., various thematic maps such as soils, landform, slope, vegetation, present land use, social and economic characteristics, and administrative boundaries are facilitated by the application of Geographical Information Systems (GIS). Several layers of digital data were updated or added to the GIS database of the origina1 AEZ-KENYA system, including administrative boundaries (districts, divisions, locations), a 1:1M soil map recently updated at KARI in the KENSOTER project (Kenya Soil Survey, 1995), and a recent approximately 1 by 1 km resolution DEM (digital elevation model) available for Africa from the GRID Center in Sioux Falls, U.S.A.

(10) ***Climate data analysis*:** Monthly values of average daily reference evapotranspiration (ET_0) are calculated for each grid-cell according to the Penman-Monteith equation (FAO, 1992b). Details of the calculation procedure are described in Appendix 2. The methodology for the calculation of reference length of growing period (LGP) used in the AEZ-KENYA system is based on a simple water balance model, by comparing moisture supply from rainfall and soil storage with potential evapotranspiration. The algorithm determines the number and type of growing periods per year, starting and ending dates of each growing period and moisture excess and deficits during the growing periods. Further details are described in Appendix 3. Thermal zones (TZ) were obtained through classification of mean annual temperature and are defined for eleven classes in 2.5°C intervals, i.e., >30°C mean annual temperature, 27.5-30°C, 25-27.5°C, etc.

(11) ***Soil association composition database:*** Additional data related to the mapped information, e.g., a description of soil associations in terms of soil types, soil phases and texture classes, landform, slope, etc., is kept in the computerized system in the form of an attribute database file. The soil association attribute database of the AEZ-KENYA system was reviewed and updated by KARI with information from the KENSOTER project and reformulated in terms of the Revised Legend of the Soil Map of the World (FAO, 1988).

(12) ***Gridded land resources database:*** Combining overlaid spatial information with the contents of relevant attribute files (Boxes 5, 9, and 10 and 11) results in the creation of unique geo-referenced extents of land units, termed agro-ecologica1 cells, which form the basic unit of analysis used in AEZ applications. The collection of agro-ecologica1 cells, for given climate change scenarios, constitutes the land resources inventory. For the assessment of potential climate change impacts in Kenya, grid-cell level land resources databases were compiled from the ARC/INFO vector databases. Each grid-cell covers and area of 4 km^2, requiring a rectangular grid of 565 rows by 450 columns containing about 147,500 grid-points within Kenyan national boundaries.

(13) ***Biomass and yield calculation:*** The constraint-free crop yields computed in the biomass module reflect yield potentials with regard to temperature and radiation regimes prevailing in the respective grid-cells. Biomass accumulation is described in terms of photosynthetic characteristics and phenological requirements, enabling the calculation of site specific constraint-free maximum yields. The method of biomass estimation used in this AEZ-KENYA system accounts for different levels of atmospheric CO_2 concentrations. Details of the calculation procedures are given in Appendix 1.

(14) ***Edaphic requirernents:*** To assess the suitability of soils for individua1 LUTs, edaphic requirements of LUTs have been inventoried. In addition, these requirements must be understood within the context of limitations imposed by landform

and other features which do not form a part of soil but may have a significant influence on the use that can be made of the soil. Distinction is made between interna1 soil requirements of LUTs, such as soil temperature regime, soil moisture regime, soil fertility, effective soil depth for root development and other physical and chemical soil properties, and *external* requirements related to soil slope, occurrence of flooding and soil accessibility.

(15) ***Climatic requirements:*** Crops, grasses and fuelwood species have climatic requirements which have been inventoried for the climatic suitability assessment. These include, for instance, temperature limitations for cultivation, tolerance to drought or frost, optimal and margina1 temperature ranges for cultivation, and specific requirements at different phenological stages.

(16) ***Matching procedures:*** Matching rules and ratings for comparing requirements of crops, forages and fuelwood to the attributes of individual agro-ecologica1 cells have been stored in a database. The matching procedures include the applicaiion of agro-climate specific reduction factors (*agroclimatic constraints*), accounting for rainfall variability/moisture stress, pests and diseases, and workability constraints. As a result of the agro-climatic and agro-edaphic matching procedures, each agro-ecologica1cell is rated in terms of five suitability classes with respect to all LUTs relevant in that location.

(17) ***LUT suitability:*** The result of matching the LUT specific edaphic and climatic requirements to the attributes of individual agro-ecologica1 cells in combination with calculated potential biomass and yields (as in (13) above). provides specific estimates of attainable yields for LUTs at different levels of management and inputs.

(18) ***Sustainable land productivity***: On the basis of crop suitability, the productivity assessment captures sustainability factors that impact upon the production levels that can be attained. Production increases due to multiple cropping resulting from intensification of cultivation in space and time are taken into account in the analysis, as are productivity losses due to soil erosion. Since the productivity estimates should relate to production achievable on a sustainable basis, fallow requirements, to maintain soil fertility and structure and to counteract soil degradation caused by cultivation, are imposed depending on environmental conditions and LUTs, including level of inputs and management applied.

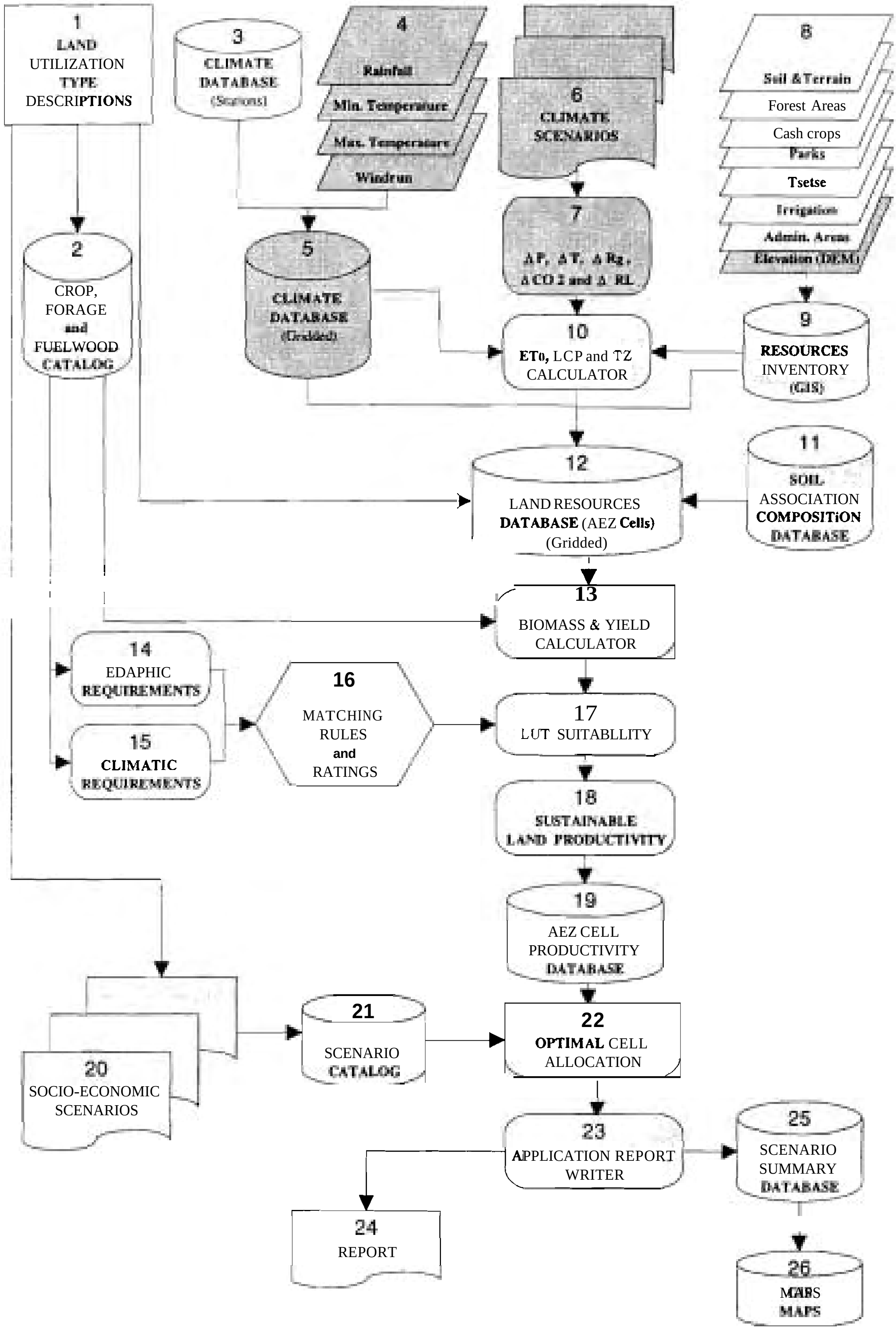
(19) ***AEZ cell productivity database:*** The productivity assessment records input level specific production of relevant and agro-ecologically feasible land utilization activities. The stored information includes a quantification of main produce and by-products, input requirements and estimates of associated soil erosion. The algorithm imposes a filter that eliminates activities that are ecologically unsuitable, too risky with respect to climatic uncertainties, environmentally unacceptable (i.e., producing soil degradation in excess of tolerable levels, or are much inferior to other possible activities in the particular land unit in terms of both expected economic benefit and nutritional value. At this stage of the analysis a database is created that contains for each agro-ecologica1cell quantified information on all feasible LUTs. This database allows for tabulating and mapping potential arable land by LUT and different levels of area aggregation. It provides the necessary geo-referenced agronomic data for district and national land-use planning scenarios, and allows for comparison of impacts on agricultural productivity of different climate change scenarios.

(20, 21, 22) ***Optimal AEZ cell allocation:*** Different sets of assumptions. e.g., in planning scenarios regarding population growth, availability and level of inputs, consumer demand, etc., are stored in a scenario catalog, i.e., a database of control parameter files used by the application programs. Planning scenarios in the AEZ application are specified by selecting and quantifying objectives and various constraints related to aspects such as demand preferences, production targets, nutritional requirements, input constraints, feed balances, crop-mix constraints, and tolerable environmental impacts. In the AEZ-KENYA climate change study, land productivity is defined rigorously by the capability of land to produce food energy and protein; i.e., the objective in the optimal AEZ-cell allocation procedure is to search for crop combinations that maximize total output from agriculture land in terms of a weighted sum of food calories and protein.

(23) ***Application report writer:*** The application report writer summarizes the scenario results by district, province and national totals.

(24, 25) ***Scenario summary database:*** Output from the AEZ application report writer can be kept in a scenario summary database and be linked to the geographical information system for visualization of the results.

Figure 4.1 AEZ climate change application: Information flow and integration



4.2 *Climatic resources*

The original AEZ climatic resources inventory of Kenya (FAO/IIASA, 1993) recorded both temperature and soil moisture conditions in a compiled form. The quantification of temperature attributes had been achieved by defining reference thermal zones. Temperature seasonality effects of latitude are minor in Kenya due to its location at the equator. Therefore thermal zones are closely related to altitude ranges. To cater for differences in temperature adaptability characteristics of crops, pasture and fuelwood species, nine thermal zones were distinguished in the original inventory, generally based on ranges of 2.5°C in mean annual temperatures, starting with areas of mean annual temperature >25°C, 22.5-25°C, 20-22.5°C, etc.

Quantification of soil moisture conditions was achieved through the concept of reference length of growing period (LGP). Reference LGP is defined as duration (in days) of the period when temperature permits plant growth and soil moisture supply exceeds half reference evapotranspiration; it includes the time required to evapotranspire up to a reference 100 mm of soil moisture storage (FAO, 1978-81). Growing periods which include a sub-period when precipitation exceeds reference evapotranspiration are termed *normal* LGPs as compared to *intermediate* LGPs with no such sub-period. The moisture regime had been inventoried by means of three complementary attributes (FAO, 1991):

- number of separate LGPs within a year, summarized as a historical profile of pattern of LGPs per year (LGP-pattern). Twenty-two such LGP-pattern classes were originally recognized;
- mean total dominant LGP, i.e., the sum of mean dominant and associated lengths of LGPs occurring during the year. Fifteen LGP zone classes, at thirty-day intervals were distinguished, and
- year to year variability of each LGP and associated moisture conditions.

For the present climate change impact assessment the historical records of rainfall and synoptic station climate data have been scrutinized and updated now covering where available the period 1920-1992. Together with these, additional data of the FAOCLIM database (FAO, 1995) for Kenya and neighboring countries and gridded climate surface data developed in a KARI/CIMMYT Maize Data Base Project have been used in the present assessment. All climate parameters are kept in a baseline gridded database with a grid-size of 2 by 2 km^2. From these datasets, thermal zones and LGP data have been evaluated in each grid-cell, to serve as baseline inventories in the present study. Also with each climate change scenario separate map layers of thermal and LGP zones are derived. Examples of thermal zones, LGP and LGP-pattern zones are shown in Figure 5.1.

4.2.1 GCM-derived data

The present generation of GCM experiments are based on recent projections of increases of concentrations of greenhouse gases in the atmosphere (IPCC, 1992). Apart from changes of atmospheric CO_2 concentrations, three climate attributes (for defined scenarios/time horizons) have been derived from the GCM results and interpolated to the 2 by 2 km^2 grid from the relatively coarse GCM grid-points falling within and immediately around Kenya. These are:

- change of temperature regimes ("C);
- change of amount and distribution of precipitation (%);
- change of incident solar radiation (%).

The *difference* in temperature, between a GCM climate change run and the respective GCM control experiment was added to the mean monthly maximum and minimum temperatures of the baseline climate surfaces. Multipliers, i.e., the *ratio* between GCM climate change and control experiment, were used to impose changes in precipitation and incident solar radiation, respectively. Adjustments were determined separately for each three-month period starting in December, i.e., December-January-February, March-April-May, etc., as well as annual changes in precipitation and radiation were calculated. These quarterly disturbance terms were scaled such that the application to monthly climate attributes matches the calculated annual changes. This method of generating climate scenarios captures the seasonal characteristics of GCM experiments but largely avoids unrealistic multipliers which could result from differences between GCM control experiments and actual baseline climate conditions. Consequently, for each climate change scenario gridded surfaces of monthly values of four climate parameters were generated: mean monthly minimum and maximum temperature, monthly rainfall, and solar radiation.

At baseline and scenario conditions relative humidity has been estimated through regressions with selected climate parameters, distance to the coast and altitude. Due to lack of reliable information, the windrun data has been kept unchanged from baseline values for all climate change scenarios, both GCM-based and sensitivity scenarios.

Each sensitivity test or GCM-based climate scenario is also characterized by level of atmospheric CO_2 concentrations and assumed changes of water-use efficiency. These parameters affect both the estimated reference evapotranspiration as well as the parameterization of the biomass calculation procedures.

In the AEZ biomass model the photosynthetic active radiation (PAR) is required to be adjusted according to actual global radiation (R_g) or sunshine duration relative to day-length. Further the model requires average daily as well as day-time temperatures. Both actual radiation and temperatures are read or calculated from the climatic data sets.

4.2.2 Reference evapotranspìratiòn

From the baseline and scenario climate data sets potential evapotranspiration has been estimated by using the modified Penman-Monteith equation, as recommended by FAO (FAO, 1992b). In the estimation of reference evapotranspiration, the interactions between increased CO_2 concentrations and stomatal resistance which influence the crop canopy resistance (r_c) has been accounted for. The canopy resistance is related to stomatal resistance and leaf area index (LAI) as follows (Allen *et* al., 1989):

$$r_c = R_l / 0.5\ LAI$$

where:

R_l = average daily stomata resistance of a single leaf [s m-l] ≈100

LAI = leaf area index

Stomatal resistance at doubling of ambient CO_2 concentrations has been reported to increase up to 50% (de Bruin & Jacobs, 1993). With such information and estimates of expected CO_2 concentrations for scenarios/time horizons to be considered, reasonable estimates of reference evapotranspiration can be made.

4.2.3 AEZ climatic resources inventory

Subsequently in combination with 'scenario' precipitation, through the AEZ growing period calculation procedures, 'scenario' LGPs have been calculated and gridded LGP and LGP-pattern inventories have been compiled. Similarly, 'scenario' thermal zones inventories have been compiled.

The three layers, LGP, LGP-pattern and thermal zones, make-up 'scenario' (AEZ) climatic resources inventories which function in applications of AEZ crop suitability and land productivity assessments. From the monthly climate variables, the LGP analysis generates pseudo-daily values through spline-interpolation. These can be used to assess growing conditions during different crop stages as well as among different growing seasons.

4.3 Biomass and yield

The model for the estimation of potential net biomass and yields (Kassam, 1977) is based on data of radiation and temperature regimes, and crop eco-physiological characteristics. A summary description of the procedures is given in the Appendix 1.

4.3.1 Photosynthesis

For the AEZ biomass and yield model, a division of crops into five adaptability groups is used, based on the difference between crop species in their photosynthesis pathways and the response of photosynthesis to temperature and radiation, because these differences determine productivity when climatic phenological requirements are met.

The two major photosynthesis pathways are the C3 pathway and the C_4 pathway. In the former, the first product of photosynthesis is a 3-carbon organic acid (3-phosphoglyceric acid), while in the latter the first products are 4-carbon organic acids (malate and aspartate). At current levels of atmospheric CO_2 concentrations, crop species with a C3 assimilation pathway have relatively much lower rates of CO_2 exchange at a given radiation level than C_4 species.

However, both pathways are adapted to operate at optimum rates over ranges of temperatures that are specific to the pathways. In case of C3 species, one group is adapted to operate under conditions of moderately cool and cool temperatures (10-20°C), e.g., wheat, barley, white potato. Another group is adapted to operate under conditions of moderately warm to warm temperatures (25-30°C), e.g., rice, cotton, groundnut. These C_3 species constitute adaptability groups I and II of the AEZ system.

In the case of C_4 species, one group of cultivars or ecotypes is adapted to operate under conditions of warm to very warm temperatures (25-35°C), e.g., lowland maize, lowland sorghum, sugarcane, and another group of cultivars or ecotypes is adapted to operate under conditions of moderately cool to moderately warm temperatures (15-25°C), including, for instance, highland maize and highland sorghum. These C_4 groups of crop ecotypes constitute adaptability groups III and IV of the AEZ system.

One further group of species has the Crassulacean acid metabolism (CAM). The biochemistry of photosynthesis in the CAM-species has several features in common with C_4 species, in particular the synthesis of C_4-carbon organic acids. CAM-species are adapted to operate under moderately warm and warm temperature conditions (20-30°C), including crops such as pineapple and sisal. The CAM species constitute adaptability group V in the AEZ system.

Climate change and increase of atmospheric CO_2 concentrations affect rates of photosynthesis and range of optimum temperatures for photosynthesis differently for C3 and C_4 crops. As quoted from literature in the previous section, C3 species would benefit more from increased CO_2 concentrations than C_4 species (respectively 30% and 5%, on the average, at doubled CO_2 concentrations). It has become evident, however, that there is an interaction between temperature and relative increase in growth (photosynthesis). For a selection of C_3 species, Idso *et* al. (1987) have demonstrated that the CO_2 fertilization effect increases with temperature. From experiments in open-top CO_2 enrichment chambers the relative growth increase ranges, from slightly negative at temperatures below 19°C to more than 80% at more than 30°C (Kimball *et* al., 1993). A linear regression based on the experimental data suggests that relative growth increase is related to temperature in the following way:

$$f_y = -0.452 + 0.0824\,T \qquad (r^2 = 0.63)$$

where f_y is relative yield increase and T is temperature ("C).

Another important aspect is the observation that the temperature optimum for photosynthesis, specifically for C_3 species, shifts considerably to higher temperatures with increasing CO_2 concentrations (Allen ***et*** al., 1990, 1991).

Based on the above quoted experiments and evidence, it is believed that greater CO_2 growth stimulation at higher temperatures is real and thus would lead to different changes of maximum rates of photosynthesis (P,) for different temperatures. Below in Table 4.1, maximum photosynthesis rates by day-time temperatures for current atmospheric CO_2 concentrations, as used in the AEZ system, are reproduced for crop adaptability groups I, II, III and IV. To enable the AEZ biomass model to handle maximum photosynthesis rates at different concentrations of atmospheric CO_2, an alternative set of photosynthesis rates, Table 4.2, has been set up similar to Table 4.1. The values in Table 4.2 represent maximum photosynthesis rates at doubled atmospheric CO_2. Depending on the projections of increase of atmospheric CO_2 used for climate change scenarios, interpolations between the values of Table 4.1 and Table 4.2 are made in the study.

Table 4.1 Maximum photosynthesis rates (P, in kg CH_2O ha^{-1} hr^{-1}) by mean day-time temperatures for crop adaptability groups I to IV at present atmospheric CO_2 concentrations.

Crop Group	Mean Day-time Temperatures								
	5°C	10°C	15°C	20°C	25"C	30°C	35°C	40°C	45°C
I (C_3)	5	15	20	20	15	5	0	0	0
II (C_3)	0	0	15	32.5	35	35	32.5	5	0
III (C_4)	0	0	5	45	65	65	65	45	5
IV (C_4)	0	5	45	65	65	65	45	5	0

4.3.2 Respiration

Changes in growth and maintenance respiration, as far as related to changes of temperature, are accounted for in the AEZ biomass model (see Appendix 1). Changes of atmospheric CO_2 concentrations on respiration seem uncertain and therefore could not be included in the present stage of the model development.

4.3.3 Water-use efficiency

Elevated levels of CO_2 concentrations slow transpiration by inducing partial closure of leaf stomata. This appears to be important in particular for C_4 plants. For C_3 plants elevated CO_2 concentrations lead mainly to increase of photosynthesis, through efficiency enhancements. Table 4.3 shows the relative contributions to changes in net photosynthesis and transpiration to a CO_2 induced, approximately doubling of leaf water-use efficiency for C_3 and C_4 plants (generalized from Rogers & Dahlman, 1993).

Table 4.2 Maximum photosynthesis rates (in kg CH_2O ha^{-1} hr^{-1}) by mean day time temperatures for crop adaptability groups I to IV at doubled atmospheric CO_2 concentrations[5].

Crop Group	Mean Day-time Temperatures								
	5°C	10°C	15°C	20°C	25°C	30°C	35°C	40°C	45°C
I (C_3)	5	10	22	28	21	7	0	0	0
II (C_3)	0	0	13	37	50	56	52	8	0
III (C_4)	0	0	5	47	68	68	68	47	5
IV (C_4)	0	5	47	68	68	68	47	5	0

Table 4.3 Relative contribution (%) to changes in net photosynthesis and transpiration of a CO, induced approximately doubling of leaf water-use efficiency for C3 and C_4 plants.

Crop Adaptability Group	Photosynthesis	Transpiration
Group I and II (C3)	75	25
Group III and I V (C4)	30	70

Higher stomatal resistance, reducing transpiration rates leads to increased leaf temperatures, which influences the rates of plant development. In particular, this considerably increases leaf area development in early growth stages of plants. In this way the average leaf area over the growth cycle can increase substantially and will enhance biomass production.

4.3.4 Harvest index

There is extensive evidence that both quantity and quality of the yield (economically useful parts) of crops change under elevated CO_2 concentrations. However,

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[5] The values presented in Table 4.2 generalize present knowledge as discussed in previous sections.

there is not sufficient convergence of evidence that yield quantities in relation to total biomass would change. Therefore, in the present analysis, harvest indexes in the model have not been modified with regard to changes of atmospheric CO_2 concentrations.

4.3.5 *Growth cycle duration*

At higher temperatures annual determinate crops will exhibit shortened growth cycles. The changed ontogenetic development and higher growth vigor at higher temperatures will not fully compensate for the shortening of the growth cycle, therefore a net yield loss will occur. The duration of crop growth cycles is defined in the AEZ biomass model and those of annual determinate crops need to be adjusted according to the expected temperature changes. For this adjustment use is made of relationships between growth cycle durations and crop variety specific heat unit requirements (degree days).

4.4 *Climatic suitability*

In the present implementation, matching rules and ratings for comparing requirements of crops, forages and fuelwood to the climatic attributes of each grid-cell are assumed to remain valid also under a change of atmospheric CO_2 concentrations.

4.4.1 *Growth cycle curtailment*

The procedures accounting for shortfall of available length of growing period to crop growth cycle requirement may be affected through possible changes in crop specific yield response to water stress (k_y factor, see FAO, 1992a). This might change under the influence of changed crop water-use efficiencies. At present, there is insufficient evidence to consider adaptations to the crop and crop phenological stage specific k_y values.

4.4.2 *Agro-climatic constraints*

The agro-climatic constraints related to effects of pests, diseases and weeds, and workability ('b', 'c' and 'd' constraints as used in FAO, 1978-81 and FAO/IIASA, 1993) remain linked to the respective LGP and thermal zones as used in baseline conditions. It is assumed that these agro-climatic constraints will remain linked to corresponding agro-climatic conditions. For individual year assessments, length of growing period and soil moisture deficit is quantified according to climatic data. The agro-climatic constraints related to inter-annual rainfall variability ('a' constraints) are removed for individual year assessments and remain unchanged for long-term averages. Thus, it is assumed that rainfall variability remains similarly related to LGP as it is at present.

4.5 *Soil and terrain resources*

The original AEZ soil and terrain resources inventory (FAO/IIASA, 1993) was based on the 1:1 million scale Exploratory Soil Map of Kenya (Sombroek et al., 1982). This information, in particular the soil association composition database, has been updated at KARI in the frame of the KENSOTER project (Kenya Soil Survey, 1995). In addition, for the purpose of the present study, the soil classification has been reformulated in terms of the Revised Legend of the Soil Map of the World (FAO, 1988).

Apart from the soil and terrain layer, also the vegetation (forest areas), national parks and tsetse infestation area GIS coverages were updated with recent information from KARI. Other layers as used in the original AEZ-GIS inventory (cash crop zones and irrigation areas) remain unchanged. The administrative areas layer has been updated and refined; now including provinces, districts, divisions and locations. A recently available approximately 1 by 1 km^2 resolution DEM (Digital Elevation Model) available for Africa from the GRID Center in Sioux Falls, U.S.A. was converted to UTM projection and added to the database.

4.5.1 *Soil and terrain characteristics and climate change*

i. Changes to *soil* characteristics

There is insufficient systematic quantitative evidence in which way and how far soil characteristics would change as result of climate change and increase of atmospheric CO_2 (Brinkman & Sombroek, 1993). At present, climate change impacts that may affect soils in the longer-term have not been taken into account in the simulations.

ii. Changed *crop/soil relationships*

There is as yet also no quantitative evidence to support any modification to the edaphic crop suitability classifications as result of climate change or increased atmospheric CO_2 concentrations. Therefore, the edaphic suitability assessment has, in principle, remained unchanged in the present study.

4.5.2 *Soil and terrain suitability classifications*

The soil and terrain suitability ratings and rules have been reviewed and updated, in particular in view of the newly introduced soil classification of the Revised Legend of the Soil Map of the World (FAO, 1988).

Until sufficient evidence becomes available it is assumed in the AEZ system that increased atmospheric CO_2 and CO_2 x Temperature interactions will enhance growth of crops only when soils are not suffering severe nutrient deficiencies or toxic substances. Hence, enhanced biomass production due to increased atmospheric CO_2 levels is applied in relation to edaphic suitability. The full effect (100%) of CO_2 fertilization has been applied where soils do not impose limitations to productivity of the defined LUTs (S1 rating). At S2, S3, S4 and N soil ratings respectively 75%, 50% 25% and 0% of the potential enhancement due to CO_2 fertilization have been assumed.

4.5.3 *Land productivity*

i. Multiple cropping increments

The total effect of changed crop component suitability and changed growth cycle duration is accounted for in the AEZ model. There is no conclusive data or indications of some evidence available on changed crop-crop interactions in sequential, relay or intercropping systems as would result from climate change or increased atmospheric CO_2 concentrations. Therefore, the interaction effects as established in the agro-ecologica1 land resources assessment study of Kenya remained unchanged.

ii. Sustainability criteria

The AEZ-KENYA system uses an implementation of a modified version of the Universal Soil Loss Equation (USLE) to quantify erosion impacts (FAO/IIASA, 1993). The USLE factors accounting for rainfall erosivity (R) and related to crop cover and management (C*) are calculated within the AEZ programs and will change as result of altered amount and distribution of rainfall and changes in cropping patterns and crop component leaf area parameters. Thus, these effects have been included in the calculations. There is, however, no evidence that soil erosion/productivity loss relationships with or without consideration of soil conservation measures would significantly change.

Fallow period requirements would be affected by changed nutrient cycling. There emerges some evidence that increased levels of atmospheric CO_2 would enhance nutrient cycling and increase soil organic matter status. This could, for example, lead to diminished fallow period requirements. In the present analysis this has not been taken into account but can be implemented in the system as quantitative estimates become available.

CHAPTER 5
CLIMATE CHANGE IMPACTS

In this section the results of various sensitivity and GCM-based climate change scenarios (as described in Chapter 2) are discussed in terms of: (i) changes of climatic resources, and (ii) changes of potential crop production and land productivity. Further, the factors underlying the changes of potential productivity are discussed, i.e., changes of crop yield levels, changes of extents of land with cultivation potential, and changes of cropping patterns and cropping intensities potentially induced by climate change.

The results are presented primarily for the national level in a number of tables, charts and small-scale maps. A selection of indicators, i.e., potential productivity of maize and wheat, and an overall measure of potential land productivity is presented by province and district (Appendix 4).

5.1 Changes of climate resources

Temperature changes have a direct effect on the spatial distribution of individual thermal zones. Table 5.1 shows extents of thermal zones for both reference conditions and a range of climate scenarios. Figure 5.1 presents small-scale maps of thermal zones for reference conditions and for four selected scenarios (T-Sensitivity T20, GSA 2030, GFTR-D2 and GFTR-D3).

As shown in Table 5.1, depending on climate scenario, extents in thermal zones TZ 3 to TZ 11 decrease quite substantially, while zones TZ 1 and TZ 2 generally increase. This is a necessary consequence of a 'pyramid effect', i.e., the fact that (i) average temperatures and thus thermal zones are highly correlated with altitude, and (ii) extents of individua1 zones decrease with altitude (see Table 5.1). Hence, extents ‘lost’ from any particular zone because of global warming to warmer thermal zones are not fully compensated for by extents 'gained' from previously cooler regions. In fact, thermal zone TZ 1, indicating hot and agronomically unfavorable conditions with average annual temperatures above 30°C, does not occur under baseline conditions but occupies as much as 85,000 km^2 in response to a warming of 2°C, however, falling mostly in the arid and dry semi-arid zone.

A number of parameters derived from the climate scenarios, i.e., temperature, sunshine duration and atmospheric CO, concentrations, affect estimations of reference evapotranspiration, ET_0. Changed ET_0 and changed rainfall regimes alter soil-water balances and, in turn, result in changes of growing period conditions: (i) of the number of growing periods per year; (ii) the types of growing periods (normal growing periods which fully meet crop water requirements, and intermediate ones which only partly meet crop water requirements), and (iii) the lengths of growing periods (LGPs).

Table 5.2 presents for some thirty-three climate scenarios the changes in extents of LGP zones, relative to the reference conditions. Table 5.3 summarizes changes of number and types of growing periods, comparing them to LGPs under reference conditions. Figure 5.2 presents small-scale maps of LGP zones for reference conditions and for four selected scenarios. Figure 5.3 shows small-scale maps of growing period pattern zones, also for reference conditions and four selected climate scenarios.

Due to generally favorable increases in annual rainfall most GCM-based climate scenarios result in improved moisture conditions and a substantial reduction of the hyper-arid zone. In addition, higher temperatures usually lead to a reduction of extents in the perhumid zone, although this covers only tiny parts under baseline conditions. Extents in the moist semi-arid and sub-humid zones, the most productive regions for agricultural activities, are in genera1 expected to increase under GCM-based climate change scenarios (see Table 5.2).

The prevalence of improved moisture conditions in climate scenarios based on transient GCM experiments can also be clearly detected in Table 5.3 where extents of intermediate growing period zones (i.e., zones with moisture stress during the growing period) generally decline, whereas extents of normal growing periods (i.e., growing conditions which include a sub-period when rainfall exceeds reference evapotranspiration) expand.

Changes of thermal zones and LGP zones affect the combinations of these. For reference conditions and three scenarios cross tabulations of thermal zones and LGPs are presented in Table 5.4.

The diagonal structure of Table 5.4 demonstrates the obvious correlation between altitude (i.e., thermal zone) and moisture supply. Secondly, when considering the most favorable agro-climatic conditions, say moist semi-arid and sub-humid zones in thermal zones TZ 3 to TZ 7, we find, for the selected climate scenarios, a complex pattern of both increases and declines within the corresponding sub-matrix in Table 5.4. More uniformly for these moisture zones, there is a substantial increase of extents in thermal zone TZ 2.

5.2 Changes of potential crop production and land productivity

Assessing altered production conditions requires understanding of severa1 complex and intertwined factors determining overall land productivity. These include changes of attainable yield levels and production potential of individua] crops, changes in extents and quality of land with cultivation potential, and alterations of type and multi-cropping intensity of available crop combinations. This section first highlights impacts on production potentials of two important food staples, maize and wheat, and then discusses implications for land productivity as emerging from a wide range of simulation experiments.

5.2.1 Potential crop production

The impacts of climate change on potential rainfed production of important crops in Kenya (maize, sorghum, pearl millet, wheat, beans and cassava) is presented in Table 5.5. Table 5.6 and 5.7 present the effects of climate changes on potential maize and wheat production by province. Figure 5.4 and 5.5 present maps of changes to maize and wheat potential productivity respectively, for four scenarios (T-Sensitivity T20, GSA 2030, GFTR-D2 and GFTR-D3) in comparison with potential production from reference conditions. Finally, Figures 5.6 and 5.7 (bar charts) present productivity changes for wheat and maize by provinces for four climate change scenarios.

Maize, being by far the most important food crop in Kenya, shows for the aggregate national level both decreases and increases depending on climate scenario, although positive impacts occur in the majority of GCM-based climate scenarios. Also, positive impacts appear to be more pronounced, i.e., larger in magnitude, than decreases. The situation of maize is complex as it occurs both in lowland and highland areas. Like maize, potential sorghum production is mostly increasing in response to GCM-based climate scenarios. There are, however, also some unambiguous crop responses to climate change to be observed. For instance, millet and cassava gain importance in *all* the analyzed climate scenarios, while wheat cultivation is likely to suffer strong negative impacts.

Table 5.6 summarizes the spatial distribution of gains and losses in maize production potential. We observe strong positive impacts in Central and Eastern provinces, for all climate scenarios including the climate sensitivity experiments. This is a clear indication that the impacts in these regions mainly result from beneficial temperature increases in higher altitude areas. Less pronounced, though generally positive, are percentage changes in Rift Valley province. This province is fairly heterogeneous so that both large positive and large negative impacts occur in individua1 districts of the region, partly canceling out in the aggregate. Coast and Nyanza provinces are likely to be negatively impacted by climate change. The widely varying results for Coast province in Table 5.6, derived from transient GCM experiments, require some further explanation. Taking a closer look, in general, the impact of climate change on potential maize productivity is negative. However, for Taita Taveta district maize growing conditions improve under the projected climate scenarios. Therefore, the exact strength and balance of these two antagonistic developments produce a wide range of estimates for the aggregate outcome in Coast province, even though individua1 district results change in a more consistent way. This again points to the fact that aggregate results of climate impact studies may be grossly misleading without being derived with careful interpretation.

A very interesting combination of temperature and moisture impacts plays out in the climate scenarios for Western province. According to the sensitivity experiments, temperature increases appear to be fairly beneficial. Moisture increases, however, as observed in most GCM based scenarios, are likely to cause conditions too wet for optimal maize cultivation so that overall effects on maize production may well be negative. Western province benefits from higher temperatures, as indicated by results of T-Sensitivity climate scenarios, but may be negatively affected by aggravated wetness under climate scenarios based on transient GCM experiments due to worsening of workability conditions as well as increased pests and diseases.

The results of changes in potential wheat production offer a straightforward interpretation. Large negative impacts on potential wheat productivity mainly result from the projected temperature increases. With very few exceptions, such as in Central province, this devastating impact on wheat potential occurs in most regions to the tune of complete loss of wheat production potential in Nyanza and Western provinces.

5.2.2 Land productivity

Land productivity encompasses a broad set of issues which are open to multiple interpretations if not defined precisely. In this study we concentrate on the capability of land to produce crops for human food consumption. Thus, land productivity is measured here in terms of a weighted sum of food energy and protein available from crop production after subtraction of harvesting losses and conversion to products suitable for human consumption.

In each of the approximately 145,000 grid-cells the best-performing (in terms of the defined food production objective) crop combinations are determined, thereby defining land productivity locally. The selection of 'optimal' cropping patterns has been repeated for all climate change scenarios. We. therefore, assume that farmers are 'smart' in the sense that they will adapt cropping activities optimally in response to climate change as possible with the set of available cropping options. Furthermore, to be able to separate climate impacts from results due to CO_2 fertilization and enhanced water-use efficiency, all GCM-based climate scenarios were simulated at both baseline and projected increased CO_2 concentration levels.

Tables A4.1 and A4.2 in Appendix 4 present the impacts on potential land productivity and extents with cultivation potential, respectively, by province and district, for the various climate change scenarios. The results in Table A4.2, for baseline conditions (REF) and percentage changes according to different climate change scenarios, refer to a weighted sum of land with cultivation potential in four land productivity classes. The weights used are 1.0, 0.77, 0.55, and 0.33 for classes C1 to C4, respectively. The multipliers were chosen in accordance with the definition of productivity classes C1 to C4. Figure 5.8 presents small-scale maps of changes to potential land productivity for four scenarios. Figure 5.9 comprises of bar charts indicating changes of potential land productivity by province for four climate change scenarios. Complementing these results, Figure 5.10 presents bar charts of changes of extents of land with crop production potential by province for four climate change scenarios. The full set of results is shown in Table

A4.3 in Appendix 4 providing estimates of potential arable land in Kenya and in each province by land productivity classes for the various climate change scenarios.

An overview of the changes to reference land productivity for Kenya and the individual provinces for all the climate change scenarios is contained in Table 5.8. At the aggregate national level, potential land productivity increases in all GCM-based climate scenarios. Note that this conclusion holds both with and without taking into account physiological effects of enhanced atmospheric CO_2 concentrations. Only in temperature sensitivity experiments, when increasing temperature and holding precipitation levels at ambient levels, overall negative impacts result for temperature increases exceeding 2°C. Note that potential land productivity, as defined in this AEZ application, assumes efficient use of land resources, i.e., full adaptation of cropping patterns to changing conditions. This may partly explain the overall positive response. Clearly positive impacts on land productivity potential can be observed for Central, Eastern and Rift Valley provinces. Other regions experience mixed outcomes. With the range of climate scenarios analyzed here, strong negative impacts may, however, result only for Coast and North-Eastern provinces.

Changes in climate also affect the relative contribution of individual crops to potential land productivity, i.e., with other words, the 'optimal' cropping pattern changes. Table 5.9 presents, by climate change scenario, the relative contribution of major crop groups to total potential land productivity. Cereal crops are shown in two classes corresponding to lowland and highland zones, respectively. The most drastic alteration occurs in the contribution of the highland cereals group which currently dominates potential food production. This group would become much less important in response to climate change, whereas lowland cereals, legumes and the other crops group could expand, with some variations depending on the moisture conditions in the different climate scenarios.

Table 5.10 analyzes the impacts of climate change on potential land productivity in terms of the main contributing factors, namely changes of extents of land with cultivation potential, changes of crop yields, and changes of cropping intensities. Figure 5.11 (bar charts) summarizes our findings in graphical format, showing the relative contribution to land productivity changes of changes in the above main contributing factors, with and without consideration of impacts due to increases of atmospheric CO_2 concentration.

Given the wide range of landform and climate conditions characterizing the baseline conditions of Kenya, it is not surprising to note that the response of land productivity to the analyzed climate change scenarios is rather complex. In all cases we observe an increase in average cropping intensity, i.e., the average number of crops that can be grown per year increases. In severa1 scenarios, although not in all cases, the estimated extents of land with crop cultivation potential increase as well. Average crop yields, however, generally decline in response to climate change. As noted earlier, the net effect at country level of combining these three factors is positive for *all* GCM-based climate change scenarios. The tables included in Appendix 4 are focused on providing province and district level results. We leave it to the reader to explore these results in detail. Evidently, there is a wide range of possible outcomes, both among provinces as well as between climate change scenarios.

CHAPTER 6
CONCLUSIONS

Kenya comprises of a diversity of landscapes: desert-like areas stretching in the north and north-east of the country, wide savannas in the semi-arid regions providing habitats to numerous beasts and attractions for curious tourists, lively coast lands, and fertile highlands producing high-value cash-crops such as coffee and tea. From the hot and dry to the cool and wet, a very broad range of environmental conditions can be found in Kenya. This makes Kenya an interesting and fascinating yet complex subject of analysis regarding climate change impacts.

Under such conditions. the revised and expanded agro-ecologica1 zones approach developed in this study appears most appropriate to capturing the diverse impacts that may affect the agricultural production potential in different ecologica1 conditions. The AEZ method is capable of quantifying both direct impacts in terms of single-crop yield changes and alterations of extents with cultivation potential as well as more subtle changes related to quality and length of growing conditions and resulting multi-cropping intensity.

The conclusions extracted from the analysis of climate change impacts on Kenyan agricultural production potential are multifaceted:

- Overall, land productivity in Kenya is likely to be positively affected by global climate change. However, impacts of climate change are likely to vary much depending on location.
- Negative impacts at provincia1 level occur in severa1 climate sensitivity tests and GCM-based climate scenarios, primarily in Coast province and North-eastern province. Main reasons for negative impacts are exceeding of optimal temperature ranges of crop photosynthesis, shortening of crop cycle and yield formation periods due to warming, and increased evapotranspiration requirements. In some instances, particularly in scenarios based on transient GCM results, negative impacts in western Kenya occur due to simulated pest and disease damage and worsening of workability conditions due to increased wetness.

- Irnpacts are usually positive for Centra1 province, Nairobi area, and Eastern province. The main reasons for simulated positive impacts can be attributed to temperature increases in mid/high altitude zones, increased multi-cropping index, and gains from CO_2 fertilization.
- Impacts are mixed (though often positive) for Rift Valley, Nyanza and Western provinces. Depending on location and scenario, negative impacts are observed (e.g., Laikipia, Narok, Kericho) as well as very positive ones (e.g., Nakuru, West Pokot, Elgeyo/Marakwet).
- Despite of overall positive results, impacts of climate change on land productivity are likely to intensify regional disparities and thereby may increase the potential for social conflicts.
- The high-potential agricultural lands in centra1 and western Kenya will dominate the agricultural production potential even more under projected climate change conditions. Utmost protection and care in developing these limited and precious land resources should be given highest priority in agricultural policy formulation.

The uncertainty associated with projections of climate change and assessments of impacts on agricultural potential calls for attentive preparedness, to readily take advantage of beneficial impacts of climate change and increased atmospheric CO_2, to mitigate negative impacts of climate change where they cause loss of productive capacity, and to cope with the technological and social challenges of changing patterns of land productivity. In essence, however, this will require addressing many problems which concern farmers and decision makers already today.

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TABLES

Table 2.1 **Kenya climate change scenarios**

CLIMATE SCENARIOS			CO_2 ppm	Δ Rl (%)	Δ T (°C) DJF	MAM	JJA	SON	Δ P (%) DJF	MAM	JJA	SON	Δ Rg (%) DJF	MAM	JJA	SON	Δ T avg.	Δ P avg.	Δ Rg avg.
GSA	1	GSA 2010	330	0	1.2	1.2	1.1	1.1	-1.7	6.8	5.6	-0.1	0.8	1.4	0.6	0.1	1.1	3.3	0.8
	2	GSA 2030	330	0	2.3	2.3	2.3	2.2	-1.8	5.4	-6.0	20.8	0.6	1.1	2.9	0.6	2.3	7.0	1.3
	3	GSA 2050	330	0	3.7	3.7	3.5	3.5	-0.5	7.4	0.8	19.9	2.1	1.8	2.8	0.7	3.6	8.7	1.8
	4	GSA 2010	405	5	1.2	1.2	1.1	1.1	-1.7	6.8	5.6	-0.1	0.8	1.4	0.6	0.1	1.1	3.3	0.8
	5	GSA 2030	460	10	2.3	2.3	2.3	2.2	-1.8	5.4	-6.0	20.8	0.6	1.1	2.9	0.6	2.3	7.0	1.3
	6	GSA 2050	530	20	3.7	3.7	3.5	3.5	-0.5	7.4	0.8	19.9	2.1	1.8	2.8	0.7	3.6	8.7	1.8
GCM-E	7	GISS 2E	330	0	3.9	3.7	3.7	4.0	6.4	8.2	-1.3	6.1	2.2	0.6	2.8	2.2	3.8	6.0	1.9
	8	GISS 2E	550	25	3.9	3.7	3.7	4.0	6.4	8.2	-1.3	6.1	2.2	0.6	2.8	2.2	3.8	6.0	1.9
	9	GFDL 2E	330	0	2.5	2.3	2.3	2.3	20.0	21.2	16.4	6.1	0.8	-1.0	-2.9	0.3	2.4	16.2	-0.7
	10	GFDL 2E	550	25	2.5	2.3	2.3	2.3	20.0	21.2	16.4	6.1	0.8	-1.0	-2.9	0.3	2.4	16.2	-0.7
	11	UKMO 2E	330	0	3.3	3.4	3.3	3.1	22.3	57.0	-3.7	-13.0	-0.7	-5.4	-1.6	-0.5	3.3	23.8	-2.0
	12	UKMO-2E	550	25	3.3	3.4	3.3	3.1	22.3	57.0	-3.7	-13.0	-0.7	-5.4	-1.6	-0.5	3.3	23.8	-2.0
GCM-T D2	13	MPTR 2	330	0	1.0	1.0	1.1	1.2	4.4	6.3	10.2	26.3	-1.5	-3.0	-2.8	-3.4	1.1	12.1	-2.7
	14	MPTR 2	460	15	1.0	1.0	1.1	1.2	4.4	6.3	10.2	26.3	-1.5	-3.0	-2.8	-3.4	1.1	12.1	-2.7
	15	GFTR 2	330	0	1.4	1.1	0.8	0.6	-11.6	18.8	7.6	30.0	4.3	-4.6	-4.0	-3.5	1.0	15.4	-1.9
	16	GFTR 2	460	15	1.4	1.1	0.8	0.6	-11.6	18.8	7.6	30.0	4.3	-4.6	-4.0	-3.5	1.0	15.4	-1.9
	17	UKTR 2	330	0	0.7	0.5	0.5	0.4	19.3	16.1	10.7	13.0	-1.3	-1.0	-2.1	-2.1	0.5	15.1	-1.6
	18	UKTR 2	460	15	0.7	0.5	0.5	0.4	19.3	16.1	10.7	13.0	-1.3	-1.0	-2.1	-2.1	0.5	15.1	-1.6
GCM-T D3	19	MPTR 3	330	0	2.4	1.9	2.0	2.3	-0.4	23.9	11.8	-6.3	1.9	-6.1	-4.8	1.0	2.1	9.9	-2.0
	20	MPTR 3	550	25	2.4	1.9	2.0	2.3	-0.4	23.9	11.8	-6.3	1.9	-6.1	-4.8	1.0	2.1	9.9	-2.0
	21	GFTR 3	330	0	2.3	1.9	2.1	1.9	-0.5	19.9	-1.1	27.0	0.6	-5.7	2.1	-2.2	2.0	15.7	-1.3
	22	GFTR 3	550	25	2.3	1.9	2.1	1.9	-0.5	19.9	-1.1	27.0	0.6	-5.7	2.1	-2.2	2.0	15.7	-1.3
	23	UKTR 3	330	0	1.2	0.7	0.9	1.3	55.7	39.9	13.1	22.4	-3.9	-4.4	-0.4	-2.2	1.0	34.1	-2.7
	24	UKTR 3	550	25	1.2	0.7	0.9	1.3	55.7	39.9	13.1	22.4	-3.9	-4.4	-0.4	-2.2	1.0	34.1	-2.7
T Sensitivity	25	T10 (+1°C)	330	0	1.0	1.0	1.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0
	26	T20 (+2°C)	330	0	2.0	2.0	2.0	2.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.0	0.0	0.0
	27	T30 (+3°C)	330	0	3.0	3.0	3.0	3.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.0	0.0	0.0
	28	T40 (+4°C)	330	0	4.0	4.0	4.0	4.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.0	0.0	0.0
	29	T50 (+5°C)	330	0	5.0	5.0	5.0	5.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5.0	0.0	0.0
P Sensitivity	30	P05 (+5%)	330	0	0.0	0.0	0.0	0.0	5.0	5.0	5.0	5.0	0.0	0.0	0.0	0.0	0.0	5.0	0.0
	31	P10 (+10%)	330	0	0.0	0.0	0.0	0.0	10.0	10.0	10.0	10.0	0.0	0.0	0.0	0.0	0.0	10.0	0.0
	32	PM05 (-5%)	330	0	0.0	0.0	0.0	0.0	-5.0	-5.0	-5.0	-5.0	0.0	0.0	0.0	0.0	0.0	-5.0	0.0
	33	PM10 (-10%)	330	0	0.0	0.0	0.0	0.0	-10.0	-10.0	-10.0	-10.0	0.0	0.0	0.0	0.0	0.0	-10.0	0.0

Notes:

GSA:	Scenarios derived from GISS Transient Scenario A results	DJF	average change over December - January - February
GCM-E:	Scenarios derived from $2xCO_2$ equilibrium GCM experiments	MAM	average change over March - April - May
GCM-T D2	Scenarios derived from ocean-atmosphere coupled transient experiments decade 2	JJA	average change over June - July - August
GCM-T D3	Scenarios derived from ocean-atmosphere coupled transient experiments decade 3	SON	average change over September - October - November
T Sensitivity	Scenarios of arbitrary temperature changes for sensitivity testing	Δ P	Precipitation change (percent)
P Sensitivity	Scenarios of arbitrary precipitation changes for sensitivity testing	Δ Rg	Solar radiation change (percent)
Δ T	Temperature change (degrees Celsius)	Δ Rl	Leaf stomata resistance change (percent)

Table 5.1 **Impacts of climate change on the distribution of thermal zones (km^2)**

CLIMATE SCENARIOS		TZ 1 (>30°C)	TZ 2 (27.5-30°C)	TZ 3 (25-27.5°C)	TZ 4 (22.5-25°C)	TZ 5 (20-22.5°C)	TZ 6 (17.5-20°C)	TZ 7 (15-17.5°C)	TZ 8 (12.5-15°C)	TZ 9 (10-12.5°C)	TZ 10 (5-10°C)	TZ 11 (< 5°C)
Reference		0	155020	221763	63936	61229	46475	27826	10620	2056	888	92
GSA	GSA 2010	6784	272618	130371	64060	50954	39056	18892	5416	1116	584	52
	GSA 2030	121640	244006	69441	62280	47292	29992	11740	2456	668	356	32
	GSA 2050	271450	136923	64559	51634	39084	18968	5504	1140	420	212	8
GCM-E	GISS 2E	294184	120815	65316	50618	36338	16984	4124	952	384	180	8
	GFDL 2E	137928	231952	67561	61060	47000	29414	11576	2380	652	348	32
	UKMO 2E	242982	158197	62897	54367	41180	21328	6872	1384	456	228	12
GCM-T D2	MPTR 2	5684	263718	138477	65177	51648	38962	18920	5532	1144	588	52
	GFTR 2	4240	258746	142292	62632	52783	40416	20342	6500	1272	616	64
	UKTR 2	12	213112	181970	61388	56938	42122	23454	8564	1508	760	76
GCM-T D3	MPTR 3	95220	262410	76217	63526	47318	29852	11848	2448	672	360	32
	GFTR 3	98616	254348	75796	61985	47871	33258	13772	3048	780	396	32
	UKTR 3	8008	269074	128869	62262	54108	39580	19670	6348	1272	648	64
T Sensitivity	T10 (+1°C)	4632	260534	141404	63596	52150	39924	19736	6044	1216	608	60
	T20 (+2°C)	85618	265718	78190	62562	47749	32574	13392	2924	756	388	32
	T30 (+3°C)	213906	180635	62250	56356	42650	23426	8372	1500	524	264	20
	T40 (+4°C)	314076	104137	63838	49114	36306	16876	4052	960	360	176	8
	T50 (+5°C)	376767	63947	61248	46482	27806	10616	2056	612	276	88	4
P Sensitivity	P05 (+5% P)	0	155020	221763	63936	61229	46475	27826	10620	2056	888	92
	P10 (+10% P)	0	155020	221763	63936	61229	46475	27826	10620	2056	888	92
	PM05 (-5% P)	0	155020	221763	63936	61229	46475	27826	10620	2056	888	92
	PM10 (-10% P)	0	155020	221763	63936	61229	46475	27826	10620	2056	888	92

Table 5.2 **Impacts of climate change on the distribution of growing periods (% change)**

CLIMATE SCENARIOS			Hyperarid 0 days	Arid 1-59 days	Dry Semiarid 60-119 days	Moist Semiarid 120-179 days	Subhumid 180-269 days	Humid 270-365 days	Perhumid 365⁺ days
Reference (km²)			160370	119838	114678	103482	55487	36022	28
GSA	1	GSA 2010-330	-2.6	2.7	4.8	1.5	-0.8	-15.7	-85.7
	2	GSA 2030-330	0.9	-4.0	16.1	-8.9	6.1	-25.3	-100.0
	3	GSA 2050-330	0.9	6.3	19.4	-17.1	-3.4	-32.1	-100.0
	4	GSA 2010-405	-3.0	2.8	4.4	2.0	-0.6	-14.8	-85.7
	5	GSA 2030-460	-0.4	-4.2	15.4	-7.1	7.0	-23.3	-85.7
	6	GSA 2050-530	-1.2	6.8	19.3	-15.8	-2.3	-29.7	-100.0
GCM-E	7	GISS 2E 330	12.7	-1.3	12.9	-15.2	-8.4	-36.6	-85.7
	8	GISS 2E 550	10.4	-0.4	11.4	-12.5	-7.6	-33.5	-85.7
	9	GFDL 2E 330	-35.9	38.4	1.6	8.9	-7.8	13.4	71.4
	10	GFDL 2E 550	-38.1	38.4	0.4	11.6	-6.2	16.8	71.4
	11	UKMO 2E 330	-56.3	72.9	23.9	-0.4	-12.0	-48.3	-100.0
	12	UKMO-2E 550	-58.8	74.3	22.6	1.7	-11.6	-44.5	-100.0
GCM-T D2	13	MPTR 2 330	-26.6	-2.3	18.3	12.7	14.0	9.9	-85.7
	14	MPTR 2 460	-27.8	-2.9	18.1	14.1	14.9	12.3	-85.7
	15	GFTR 2 330	-35.5	0.7	26.4	14.8	3.7	23.6	-100.0
	16	GFTR 2 460	-36.7	0.5	25.9	16.2	4.5	25.8	-100.0
	17	UKTR 2 330	-11.4	0.2	-11.6	11.4	10.2	38.4	-100.0
	18	UKTR 2 460	-12.7	0.3	-12.0	11.9	12.1	41.0	-100.0
GCM-T D3	19	MPTR 3 330	-43.5	47.6	18.9	3.5	-7.7	-23.1	-85.7
	20	MPTR 3 550	-45.2	47.0	18.1	5.8	-6.3	-19.4	-85.7
	21	GFTR 3 330	-36.0	32.5	5.2	9.2	-5.8	18.1	-85.7
	22	GFTR 3 550	-37.6	31.8	4.5	11.7	-5.3	22.1	-85.7
	23	UKTR 3 330	-54.1	33.0	-18.1	13.7	48.7	74.6	-100.0
	24	UKTR 3 550	-55.4	32.2	-17.5	13.1	50.9	79.6	-85.7
T Sensitivity	25	T10 (+1°C)	6.6	1.2	4.9	-10.7	-5.3	-10.3	-71.4
	26	T20 (+2°C)	13.9	-0.2	9.1	-19.3	-8.4	-21.7	-85.7
	27	T30 (+3°C)	22.6	-3.9	12.1	-26.0	-11.1	-34.2	-85.7
	28	T40 (+4°C)	33.1	-8.3	10.9	-29.8	-16.3	-43.6	-85.7
	29	T50 (+5°C)	42.1	-8.5	6.9	-31.5	-25.1	-52.1	-100.0
P Sensitivity	30	P05 (+5% P)	-11.4	0.3	-0.2	11.0	4.0	12.6	14.3
	31	P10 (+10% P)	-22.1	-0.8	2.5	19.8	8.1	23.6	71.4
	32	PM05 (-5% P)	15.1	-3.0	-0.5	-12.8	-5.1	-10.9	-71.4
	33	PM10 (-10% P)	35.0	-11.9	-3.5	-23.3	-7.4	-26.9	-85.7

Table 5.3 **Impacts of climate change on number and type of growing periods (% change)**

CLIMATE SCENARIOS			No Growing Period (0 days)	One Growing Period (<365 days)		Two or more Growing Periods (<365 days)		Year-round Growing Period (365^{+} days)
				Intermediate	Normal	Inter mediate	Normal	
Reference (km^2)			160370	137163	88322	82306	121716	28
GSA	1	GSA 2010-330	-2.9	0.2	-3.1	5.0	2.4	-75.0
	2	GSA 2030-330	-1.0	-20.7	-27.2	46.1	13.1	-75.0
	3	GSA 2050-330	-0.6	-7.3	-36.8	36.4	11.1	-100.0
	4	GSA 2010-405	-3.3	0.1	-2.4	5.0	2.6	-75.0
	5	GSA 2030-460	-2.2	-21.4	-25.0	46.3	14.0	-75.0
	6	GSA 2050-530	-2.6	-8.2	-34.1	37.5	12.1	-100.0
GCM-E	7	GISS 2E 330	12.4	2.2	-38.1	21.8	-5.9	-75.0
	8	GISS 2E 550	10.1	2.5	-34.6	20.2	-4.7	-75.0
	9	GFDL 2E 330	-38.7	22.9	30.8	-8.6	8.9	50.0
	10	GFDL 2E 550	-41.0	22.2	35.2	-10.3	10.5	62.5
	11	UKMO 2E 330	-74.0	29.7	116.0	-57.3	18.9	-100.0
	12	UKMO-2E 550	-76.3	29.4	120.9	-58.5	19.6	-100.0
GCM-T D2	13	MPTR 2 330	-27.9	-11.6	-6.6	31.2	33.6	-75.0
	14	MPTR 2 460	-28.9	-12.2	-4.9	30.5	34.8	-75.0
	15	GFTR 2 330	-39.7	-12.3	4.5	13.6	53.9	-100.0
	16	GFTR 2 460	-40.8	-12.1	6.1	12.7	54.6	-100.0
	17	UKTR 2 330	-16.0	-9.2	38.5	-24.8	20.3	-100.0
	18	UKTR 2 460	-17.3	-9.0	40.9	-25.6	20.6	-100.0
GCM-T D3	19	MPTR 3 330	-47.9	24.8	53.0	-16.4	8.0	-75.0
	20	MPTR 3 550	-49.8	23.6	57.3	-17.8	9.7	-62.5
	21	GFTR 3 330	-38.9	-2.3	28.0	-20.6	47.6	-75.0
	22	GFTR 3 550	-40.5	-3.0	30.8	-22.1	49.5	-75.0
	23	UKTR 3 330	-57.5	0.7	126.8	-43.2	12.4	-87.5
	24	UKTR 3 550	-58.9	-0.2	132.8	-45.7	12.6	-87.5
T Sensitivity	25	T10 (+1°C)	6.6	2.2	-12.6	4.1	-4.8	-62.5
	26	T20 (+2°C)	13.9	3.3	-22.9	7.3	-10.3	-75.0
	27	T30 (+3°C)	22.5	2.8	-31.9	9.5	-16.1	-75.0
	28	T40 (+4°C)	33.0	0.7	-41.7	10.7	-21.4	-75.0
	29	T50 (+5°C)	42.0	0.3	-49.2	8.9	-26.1	-100.0
P Sensitivity	30	P05 (+5% P)	-11.5	-3.4	8.2	3.9	10.5	12.5
	31	P10 (+10% P)	-22.3	-8.4	14.7	10.0	21.4	50.0
	32	PM05 (-5% P)	15.1	-1.3	-8.1	-5.0	-9.3	-62.5
	33	PM10 (-10% P)	35.0	-4.5	-16.3	-16.6	-18.1	-75.0

Table 5.4 **Impacts of climate change of selected scenarios on the distribution of growing period zones by thermal zones (km^2)**

GROWING PERIOD ZONES	CLIMATE SCENARIOS	TZ 1 (>30°C)	TZ 2 (27.5-30°C)	TZ 3 (25-27.5°C)	TZ 4 (22.5-25°C)	TZ 5 (20-22.5°C)	TZ 6 (17.5-20°C)	TZ 7 (15-17.5°C)	TZ 8 (12.5-15°C)	TZ 9 (10-12.5°C)	TZ 10 (5-10°C)	TZ 11 (< 5°C)
Hyperarid (0 days)	Reference	0	115528	40184	4342	4	288	24	0	0	0	0
	GSA2030	94612	58966	6056	0	12	4	0	0	0	0	0
	GFTR-D2	4064	90188	7258	0	0	0	0	0	0	0	0
	GFTR-D3	62328	37138	528	0	0	0	0	0	0	0	0
Arid (1-59 days)	Reference	0	30832	74390	11112	1908	1596	0	0	0	0	0
	GSA2030	24424	73944	13182	1528	1544	160	0	0	0	0	0
	GFTR-D2	176	85286	33186	1746	0	0	0	0	0	0	0
	GFTR-D3	35008	104982	17820	168	8	0	0	0	0	0	0
Dry Semiarid (60-119 days)	Reference	0	8580	68464	18480	8518	8006	2442	188	0	0	0
	GSA2030	2604	80452	27130	9354	9224	3250	304	0	0	0	0
	GFTR-D2	0	67124	57636	9458	8138	2026	40	0	0	0	0
	GFTR-D3	1280	76260	26876	7254	7158	882	84	0	0	0	0
Moist Semiarid (120-179 days)	Reference	0	80	30261	29306	29145	9806	4476	408	0	0	0
	GSA2030	0	22932	22485	29956	12410	7298	1072	0	0	0	0
	GFTR-D2	0	16148	33104	38937	22120	8578	1402	0	0	0	0
	GFTR-D3	0	29428	28792	34318	14820	7238	960	0	0	0	0
Subhumid (180-269 days)	Reference	0	0	8464	392	7748	16631	17704	4512	36	0	0
	GSA2030	0	7712	568	13576	13930	16564	6472	520	8	0	0
	GFTR-D2	0	0	11064	4256	10362	19424	11708	1152	24	0	0
	GFTR-D3	0	6540	1780	8051	12215	18348	5256	380	0	0	0
Humid (270-365 days)	Reference	0	0	0	304	13906	10148	3180	5512	2020	888	64
	GSA2030	0	0	20	7866	10172	2716	3892	1936	660	356	28
	GFTR-D2	0	0	44	8235	12163	10388	7192	5348	1248	616	64
	GFTR-D3	0	0	0	12194	13670	6790	7472	2668	780	396	28
Perhumid (365$^+$ days)	Reference	0	0	0	0	0	0	0	0	0	0	28
	GSA2030	0	0	0	0	0	0	0	0	0	0	4
	GFTR-D2	0	0	0	0	0	0	0	0	0	0	0
	GFTR-D3	0	0	0	0	0	0	0	0	0	0	4

Table 5.5 **Impacts of climate change on potential production of major rainfed crops (% change)**

CLIMATE SCENARIOS		Maize	Sorgh.	Millet	Wheat	Beans	Cassava
Reference	('000 tons)	9359	6292	2121	4172	3751	6549
GSA	GSA 2010-405	9	16	54	-13	0	50
	GSA 2030-460	-9	-1	79	-59	-28	95
	GSA 2050-530	-14	-1	116	-77	-43	130
GCM-E	GISS 2E 550	-5	12	147	-77	-43	131
	GFDL 2E 550	25	37	91	-28	14	145
	UKMO-2E 550	2	21	136	-66	-23	70
GCM-T D2	MPTR 2 460	10	13	49	-21	-4	83
	GFTR 2 460	-2	-8	19	-21	-9	71
	UKTR 2 460	26	23	34	5	20	43
GCM-T D3	MPTR 3 550	23	37	103	-25	10	107
	GFTR 3 550	-12	-14	52	-51	-22	152
	UKTR 3 550	73	74	121	6	65	115
T Sensitivity	T10 (+1°C)	0	5	33	-21	-9	40
	T20 (+2°C)	-2	5	61	-45	-19	71
	T30 (+3°C)	-8	1	85	-66	-34	74
	T40 (+4°C)	-19	-8	108	-81	-54	73
	T50 (+5°C)	-27	-15	123	-89	-72	64

Table 5.6 **Impacts of climate change on potential production of maize by province (% change)**

CLIMATE SCENARIOS		Central	Coast	Eastern	Nyanza	Rift Valley	Western	KENYA
Reference	('000 tons)	116	844	23	1186	6646	543	9359
GSA	GSA 2010-405	223	4	109	2	6	18	9
	GSA 2030-460	285	-19	178	-22	-13	12	-9
	GSA 2050-530	372	-38	204	-20	-19	15	-14
GCM-E	GISS 2E 550	375	-38	322	-12	-12	53	-5
	GFDL 2E 550	560	-26	370	-9	30	-18	25
	UKMO-2E 550	360	-27	357	-14	-3	47	2
GCM-T D2	MPTR 2 460	248	15	135	-11	12	-38	10
	GFTR 2 460	371	4	78	-36	2	-71	-2
	UKTR 2 460	355	-28	965	-25	40	-62	26
GCM-T D3	MPTR 3 550	449	-17	278	3	22	35	23
	GFTR 3 550	309	-32	209	-37	-8	-62	-12
	UKTR 3 550	1360	37	6422	-43	64	-62	73
T Sensitivity	T10 (+1°C)	112	-24	96	0	0	13	0
	T20 (+2°C)	272	-45	165	-3	-4	23	-2
	T30 (+3°C)	360	-61	200	-7	-13	36	-8
	T40 (+4°C)	331	-72	230	-15	-25	48	-19
	T50 (+5°C)	259	-80	287	-18	-34	55	-27

Table 5.7 **Impacts of climate change on potential production of wheat by province (% change)**

CLIMATE SCENARIOS		Central	Coast	Nyanza	Rift Valley	Western	KENYA
Reference	('000 tons)	229	56	118	3707	61	4172
GSA	GSA 2010-405	59	-36	-67	-15	-38	-13
	GSA 2030-460	-19	-61	-96	-59	-89	-59
	GSA 2050-530	-32	-88	-100	-79	-100	-77
GCM-E	GISS 2E 550	-26	-91	-98	-79	-100	-77
	GFDL 2E 550	34	-68	-99	-29	-92	-28
	UKMO-2E 550	-16	-82	-97	-68	-100	-66
GCM-T D2	MPTR 2 460	40	-34	-96	-21	-52	-21
	GFTR 2 460	94	-29	-99	-24	-75	-21
	UKTR 2 460	40	-21	-94	4	-74	5
GCM-T D3	MPTR 3 550	53	-59	-91	-27	-85	-25
	GFTR 3 550	-6	-68	-68	-51	-89	-51
	UKTR 3 550	157	-52	-100	-4	-82	6
T Sensitivity	T10 (+1°C)	16	-32	-67	-21	-36	-21
	T20 (+2°C)	0	-59	-86	-46	-75	-45
	T30 (+3°C)	-19	-77	-67	-68	-98	-66
	T40 (+4°C)	-34	-93	-83	-83	-100	-81
	T50 (+5°C)	-58	-100	-93	-91	-100	-89

Table 5.8 **Impacts of climate change on potential land productivity by province (% change)**

CLIMATE SCENARIOS			Central Province	Coast Province	Eastern Province	North-East Province	Nyanza Province	Rift Valley Province	Western Province	KENYA
Reference			22121	81330	29119	2537	92199	326207	51321	605081
GSA	1	GSA 2010-330	23	-5	0	3	13	4	25	7
	2	GSA 2030-330	18	-11	-4	9	-8	0	38	1
	3	GSA 2050-330	33	-35	-7	-13	1	0	46	0
	4	GSA 2010-405	27	-1	4	8	15	7	26	10
	5	GSA 2030-460	25	-4	9	18	-3	7	43	8
	6	GSA 2050-530	46	-26	11	-2	10	11	56	11
GCM-E	7	GISS 2E 330	37	-33	-5	-42	5	2	65	4
	8	GISS 2E 550	53	-23	20	-33	17	17	76	18
	9	GFDL 2E 330	74	-21	16	21	20	31	26	23
	10	GFDL 2E 550	95	-9	45	34	31	44	36	36
	11	UKMO 2E 330	24	-42	13	20	-11	2	55	0
	12	UKMO-2E 550	39	-35	34	36	-2	14	65	12
GCM-T D2	13	MPTR 2 330	23	20	8	80	15	13	8	14
	14	MPTR 2 460	32	30	19	94	20	19	13	21
	15	GFTR 2 330	34	12	7	92	-11	7	-10	5
	16	GFTR 2 460	45	20	14	104	-8	13	-5	11
	17	UKTR 2 330	48	-29	45	-46	-5	34	-17	16
	18	UKTR 2 460	66	-21	64	-41	0	40	-13	23
GCM-T D3	19	MPTR 3 330	45	-32	7	22	14	17	41	12
	20	MPTR 3 550	63	-22	27	38	25	28	49	24
	21	GFTR 3 330	25	-31	2	29	-4	10	5	2
	22	GFTR 3 550	41	-22	19	44	4	21	16	13
	23	UKTR 3 330	272	16	299	27	-1	64	-3	61
	24	UKTR 3 550	307	37	351	45	8	79	6	78
T Sensitivity	25	T10 (+1°C)	5	-23	-3	-21	12	1	22	1
	26	T20 (+2°C)	20	-44	-6	-42	10	2	37	0
	27	T30 (+3°C)	32	-55	-9	-54	7	-4	48	-4
	28	T40 (+4°C)	33	-64	-12	-65	4	-9	55	-8
	29	T50 (+5°C)	27	-71	-17	-73	3	-14	59	-12
P Sensitivity	30	P05 (+5% P)	10	19	8	28	-3	6	-5	6
	31	P10 (+10% P)	20	39	15	63	-6	12	-15	11
	32	PM05 (-5% P)	-8	-19	-7	-22	2	-7	6	-6
	33	PM10 (-10% P)	-17	-35	-14	-45	-3	-14	9	-14

Table 5.9 **Impacts of climate change on relative contribution of major crops to potential land productivity (% of total)**

CLIMATE SCENARIOS			CEREALS I (%)	CEREALS II (%)	LEGUMES (%)	ROOTS & TUBERS (%)	REST (%)
Reference			25	38	15	5	18
GSA	1	GSA 2010-330	30	31	18	3	19
	2	GSA 2030-330	34	18	22	3	23
	3	GSA 2050-330	40	10	25	3	22
	4	GSA 2010-405	30	31	19	4	17
	5	GSA 2030-460	35	18	24	4	20
	6	GSA 2050-530	40	10	28	3	18
GCM-E	7	GISS 2E 330	43	8	27	2	21
	8	GISS 2E 550	42	8	31	2	16
	9	GFDL 2E 330	36	21	22	3	19
	10	GFDL 2E 550	36	21	26	3	14
	11	UKMO 2E 330	41	12	23	2	22
	12	UKMO-2E 550	41	12	27	3	17
GCM-T D2	13	MPTR 2 330	28	27	19	3	22
	14	MPTR 2 460	29	28	21	4	19
	15	GFTR 2 330	26	29	20	4	22
	16	GFTR 2 460	26	29	21	5	18
	17	UKTR 2 330	24	35	18	3	20
	18	UKTR 2 460	25	35	19	4	16
GCM-T D3	19	MPTR 3 330	37	21	21	3	19
	20	MPTR 3 550	36	22	24	4	14
	21	GFTR 3 330	28	20	23	5	24
	22	GFTR 3 550	28	20	26	7	19
	23	UKTR 3 330	31	27	25	3	15
	24	UKTR 3 550	31	26	27	3	12
T Sensitivity	25	T10 (+1^{o}C)	29	32	18	4	18
	26	T20 (+2^{o}C)	35	22	20	3	20
	27	T30 (+3^{o}C)	40	15	22	3	20
	28	T40 (+4^{o}C)	42	9	25	2	21
	29	T50 (+5^{o}C)	43	7	29	2	20

Note:

Cereals I: Lowland Maize, Lowland Sorghum, Pearl Millet, Wetland Rice, Dryland Rice
Cereals II: Highland Maize, Highland Sorghum, Wheat, Barley, Rye, Oat
Legumes: Cowpea, Pigeonpea, Gram, Groundnut, Phaseolus Beans, Soybean
Roots & Tubers: White potato, Sweet Potato, Cassava
Rest: Banana, Sugarcane, Oilpalm, (Cotton, Coffee, Tea, Pineapple, Pyrethrum, Sisal), Grasses

Table 5.10 **Impacts of climate change on land productivity, arable land, yields, and cropping intensities (% change relative to reference conditions)**

CLIMATE SCENARIOS			Land Productivity	Arable Land	Yields	Cropping Intensity
GSA	1	GSA 2010-330	6.7	5.7	-0.4	1.3
	2	GSA 2030-330	1.0	-4.4	-8.5	15.4
	3	GSA 2050-330	0.1	-8.9	-9.1	20.8
	4	GSA 2010-405	9.6	4.2	3.1	2.0
	5	GSA 2030-460	7.7	-5.1	-2.3	16.1
	6	GSA 2050-530	11.0	-7.9	-0.3	20.8
GCM-E	7	GISS 2E 330	4.1	-6.6	-5.6	18.1
	8	GISS 2E 550	17.8	-3.9	3.8	18.1
	9	GFDL 2E 330	22.8	16.3	-6.9	13.4
	10	GFDL 2E 550	36.4	15.6	2.8	14.8
	11	UKMO 2E 330	-0.1	14.8	-15.3	2.7
	12	UKMO-2E 550	11.6	13.3	-4.7	3.4
GCM-T D2	13	MPTR 2 330	13.9	11.5	-6.0	8.7
	14	MPTR 2 460	20.9	9.8	0.0	10.1
	15	GFTR 2 330	4.6	12.6	-11.3	4.7
	16	GFTR 2 460	10.8	9.5	-5.1	6.7
	17	UKTR 2 330	15.8	18.6	-5.5	3.4
	18	UKTR 2 460	23.1	17.2	-0.3	5.4
GCM-T D3	19	MPTR 3 330	12.4	14.9	-4.8	2.7
	20	MPTR 3 550	23.7	13.8	4.5	4.0
	21	GFTR 3 330	2.2	8.2	-14.8	10.7
	22	GFTR 3 550	12.7	5.3	-4.5	12.1
	23	UKTR 3 330	61.0	46.0	-1.6	12.1
	24	UKTR 3 550	78.0	49.4	5.6	12.8
T Sensitivity	25	T10 (+1°C)	1.1	-2.7	1.2	2.7
	26	T20 (+2°C)	0.2	-7.4	-0.5	8.7
	27	T30 (+3°C)	-3.7	-11.6	-3.3	12.8
	28	T40 (+4°C)	-7.9	-17.9	-3.9	16.8
	29	T50 (+5°C)	-11.7	-23.4	-3.0	18.8
P Sensitivity	30	P05 (+5% P)	6.0	6.0	-1.9	2.0
	31	P10 (+10% P)	11.4	12.3	-3.9	3.4
	32	PM05 (-5% P)	-6.2	-7.4	4.0	-2.7
	33	PM10 (-10% P)	-13.5	-14.8	7.3	-5.4

FIGURES

Figure 5.1a **Spatial distribution of thermal zones**

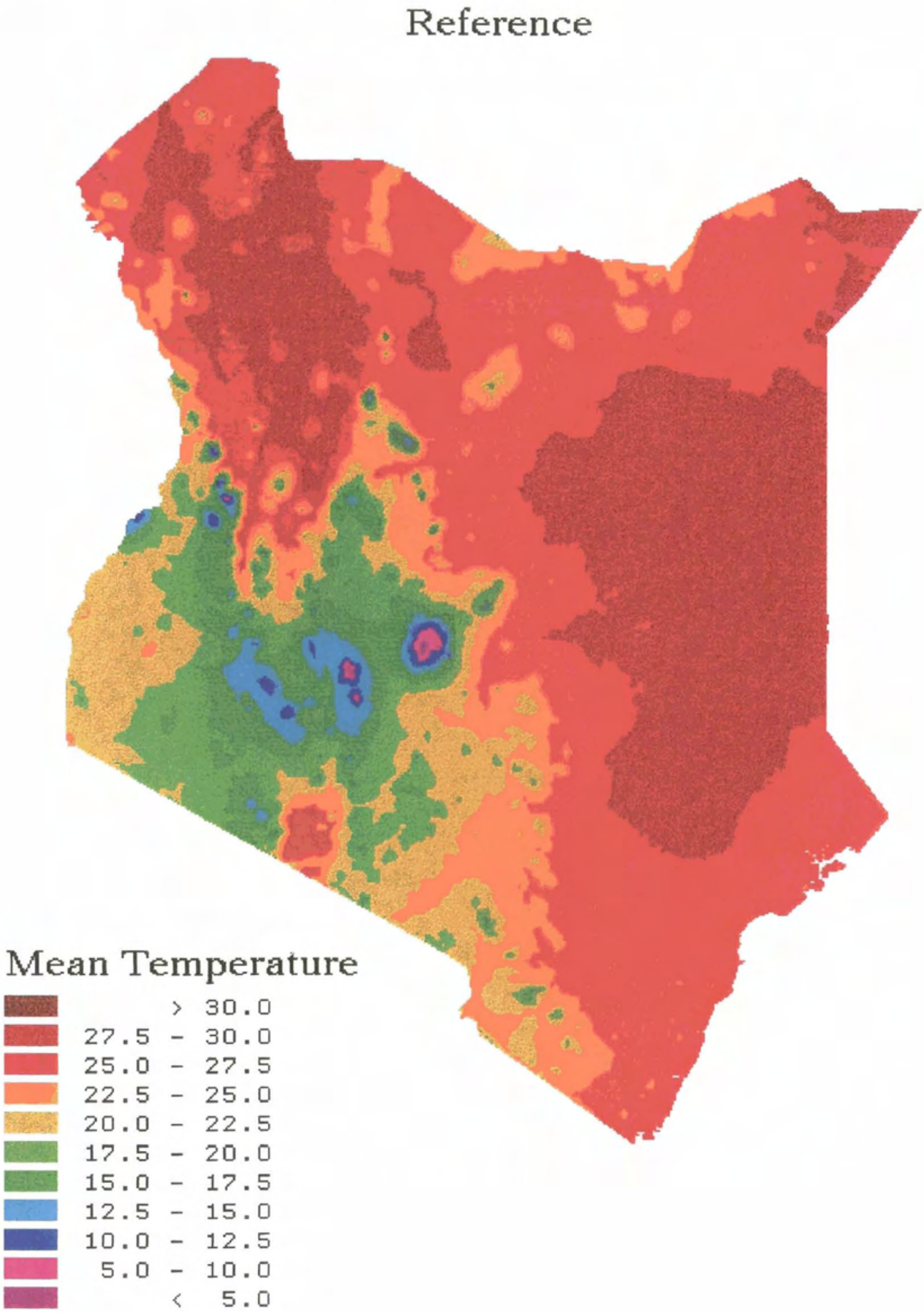


Figure 5.1b **Spatial distribution of thermal zones**

Figure 5.2a **Spatial distribution of growing period zones**

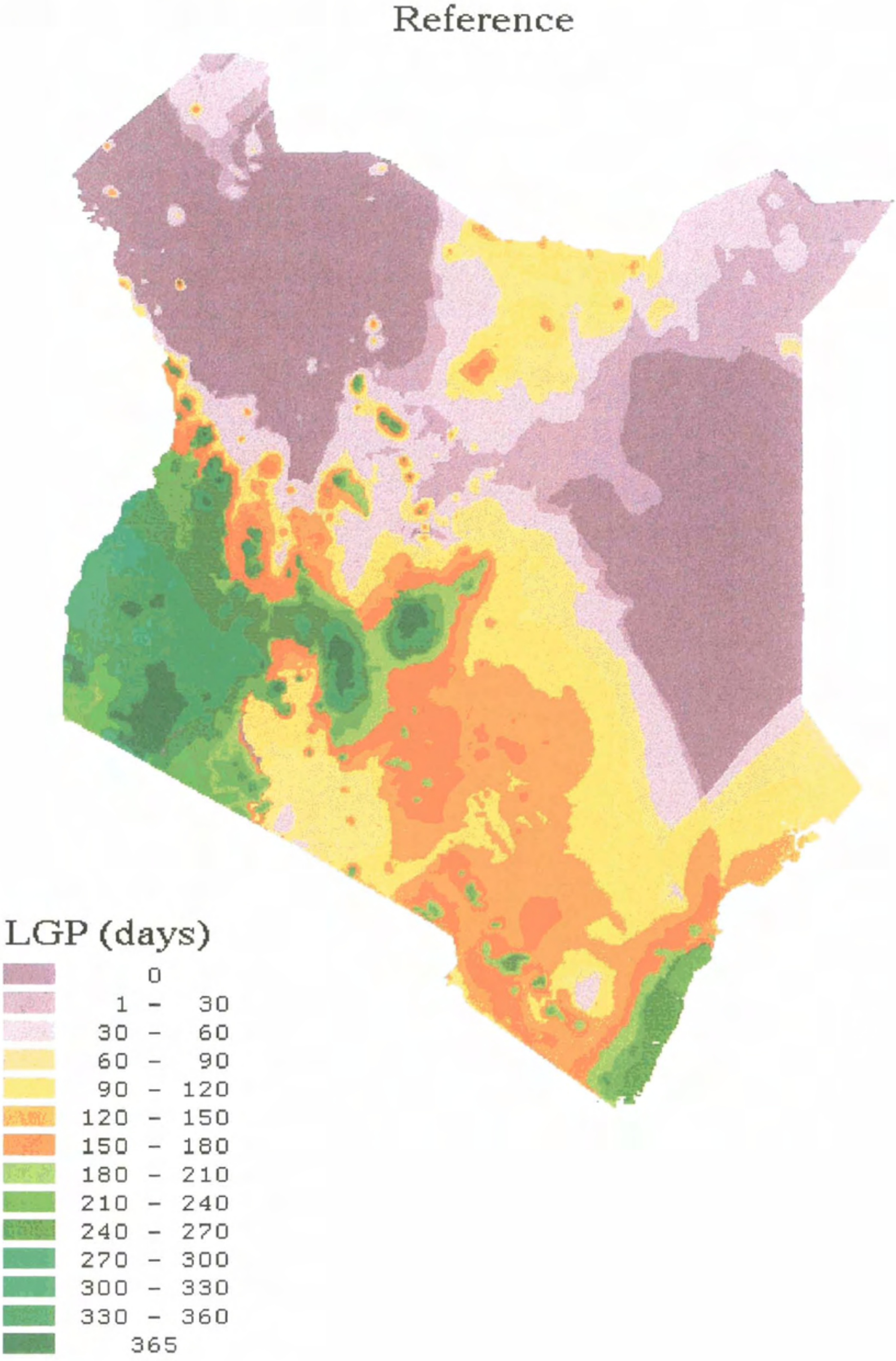


Figure 5.2b **Spatial distribution of growing period zones**

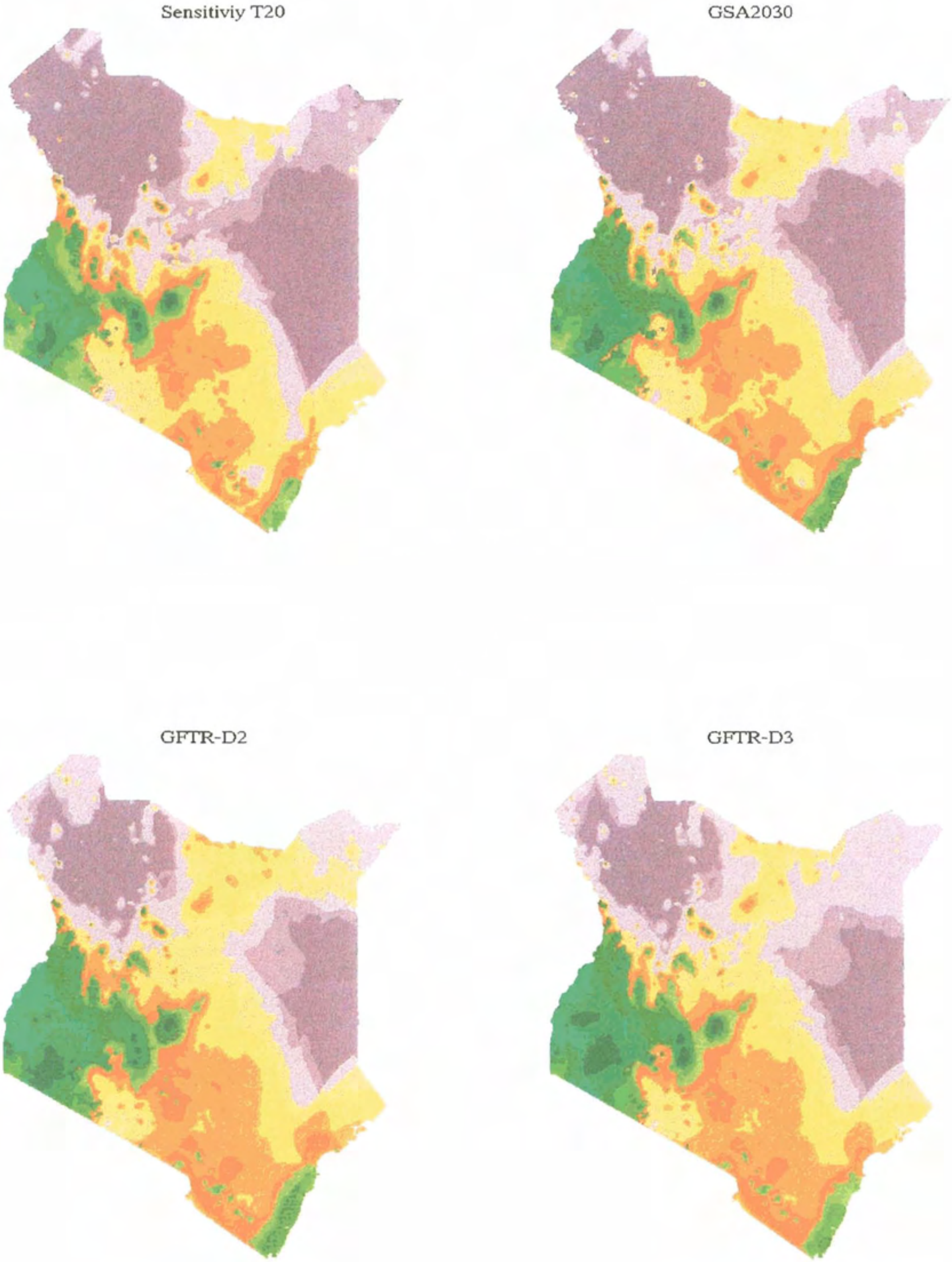


Figure 5.3a **Spatial distribution of growing period pattern zones**

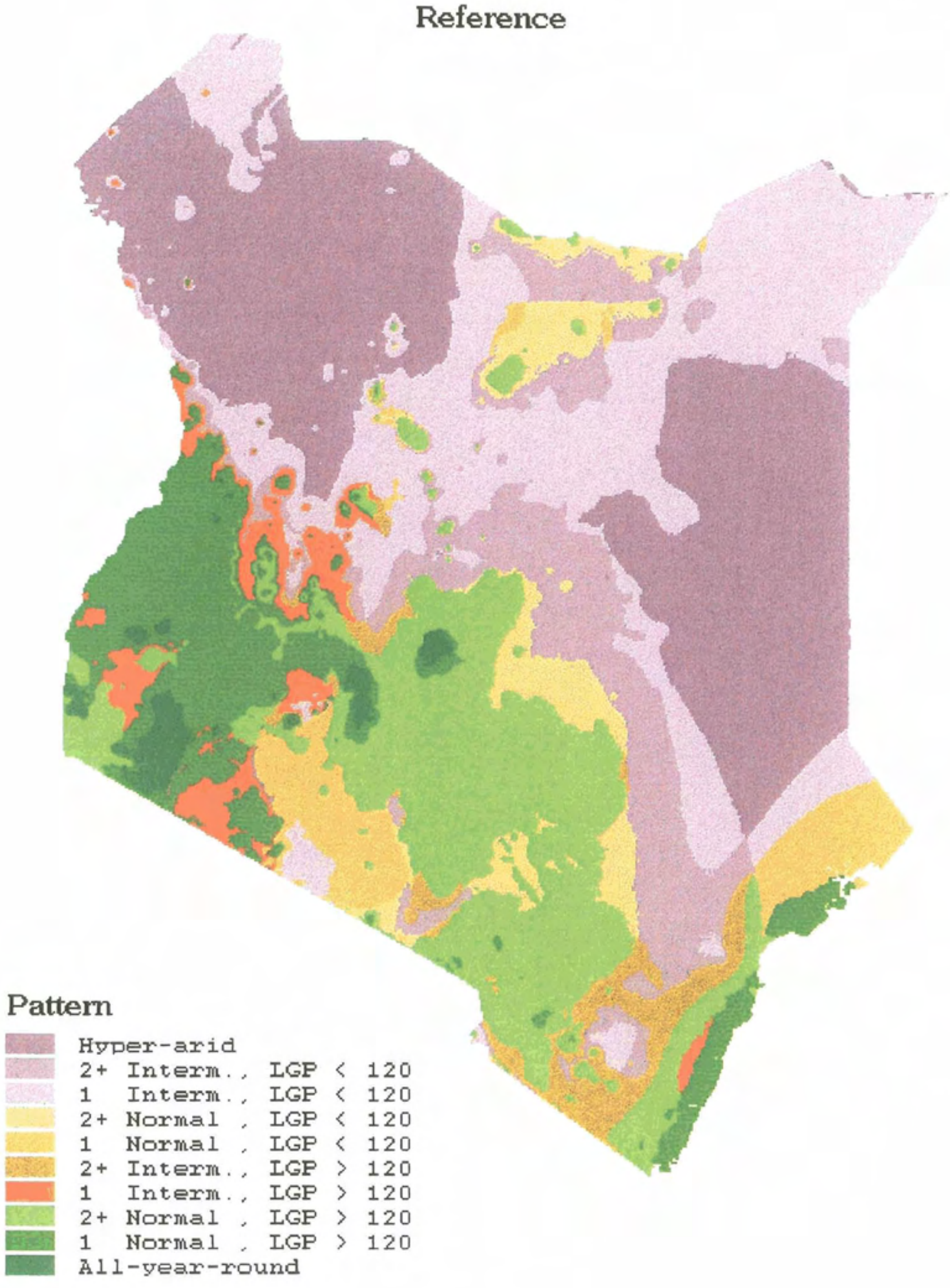


Figure 5.3b **Spatial distribution of growing period pattern zones**

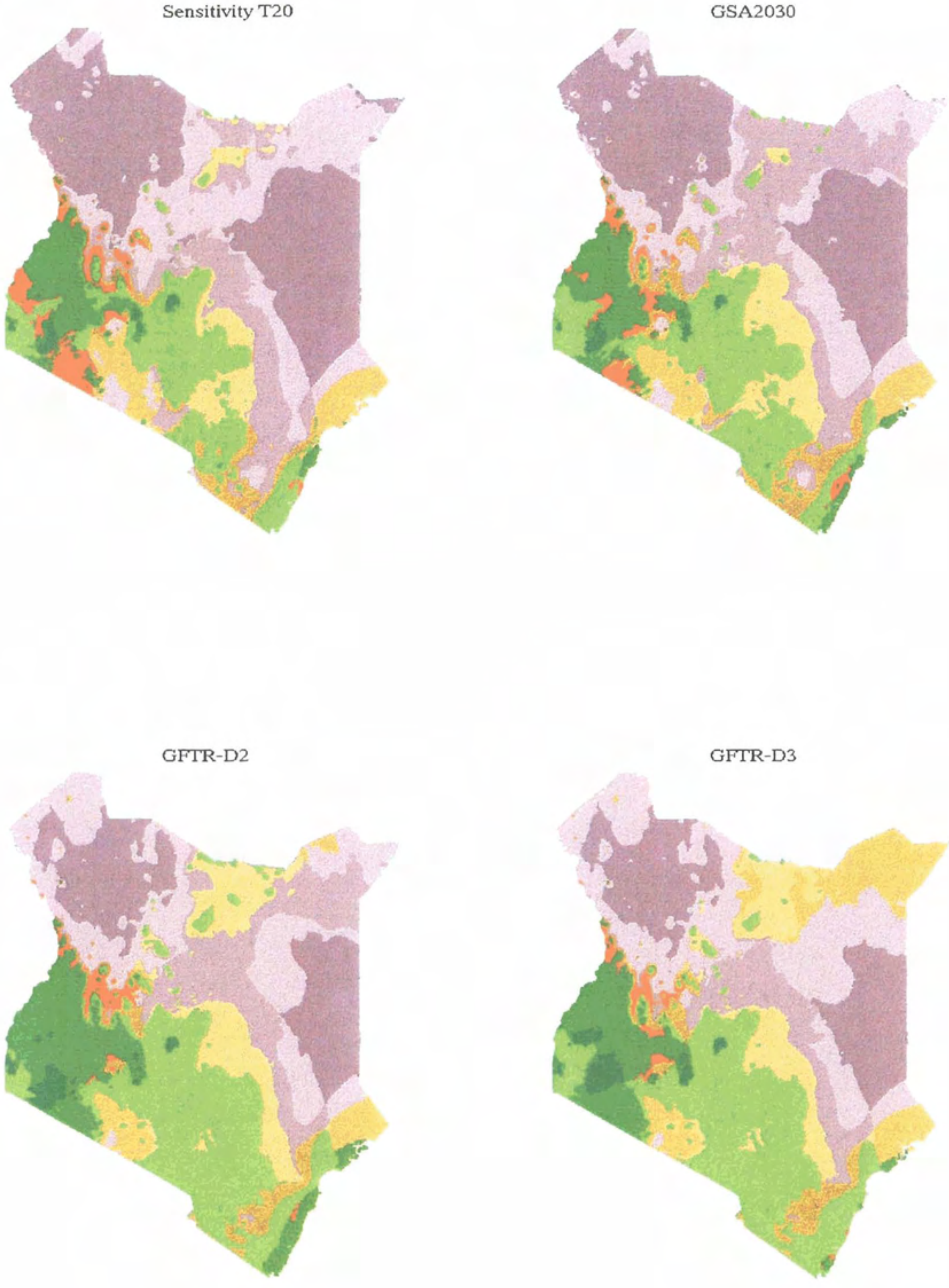


Figure 5.4 **Changes of maize productivity for four climate change scenarios, relative to reference conditions**

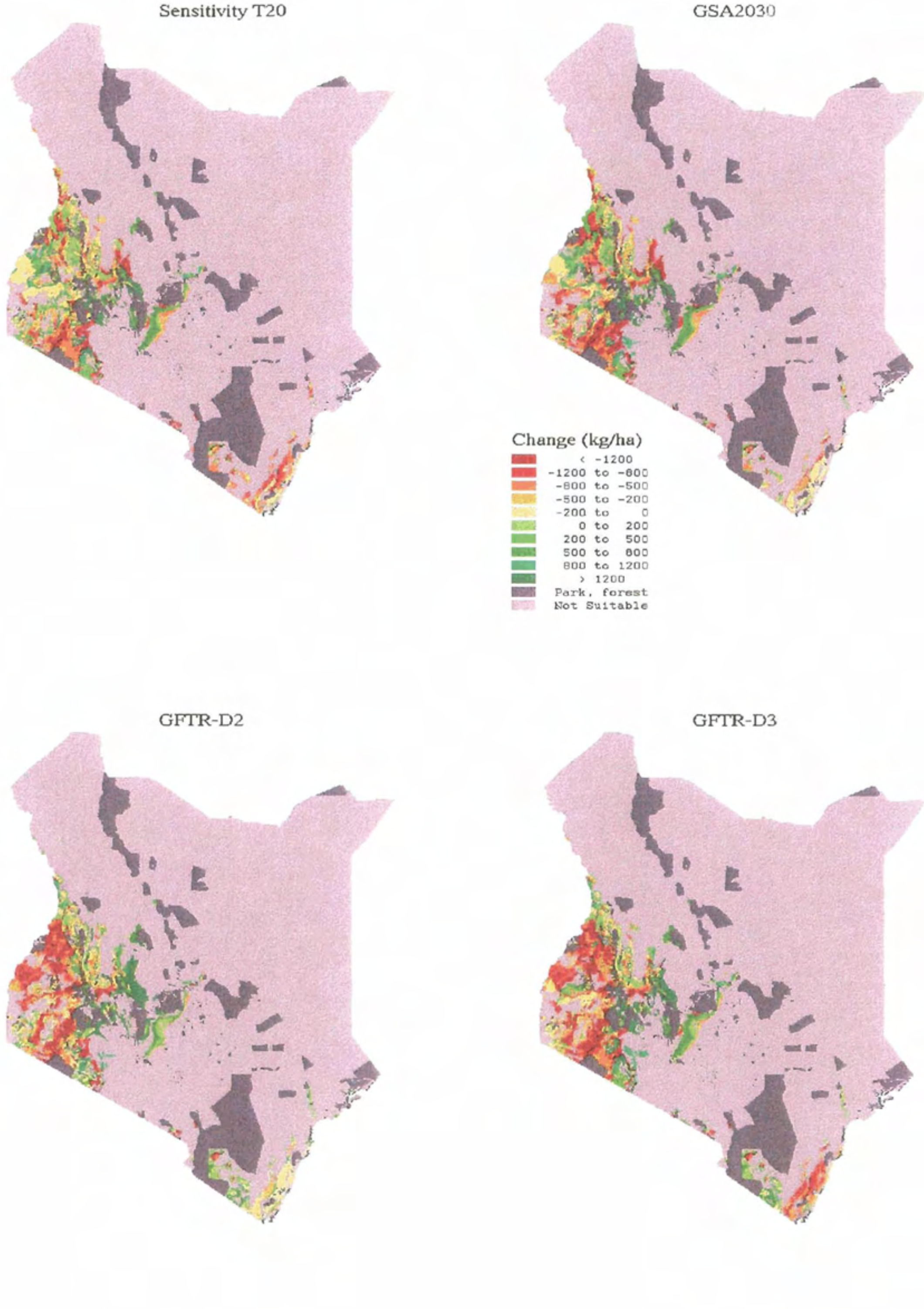


Figure 5.5 **Changes of wheat productivity for four climate change scenarios, relative to reference conditions**

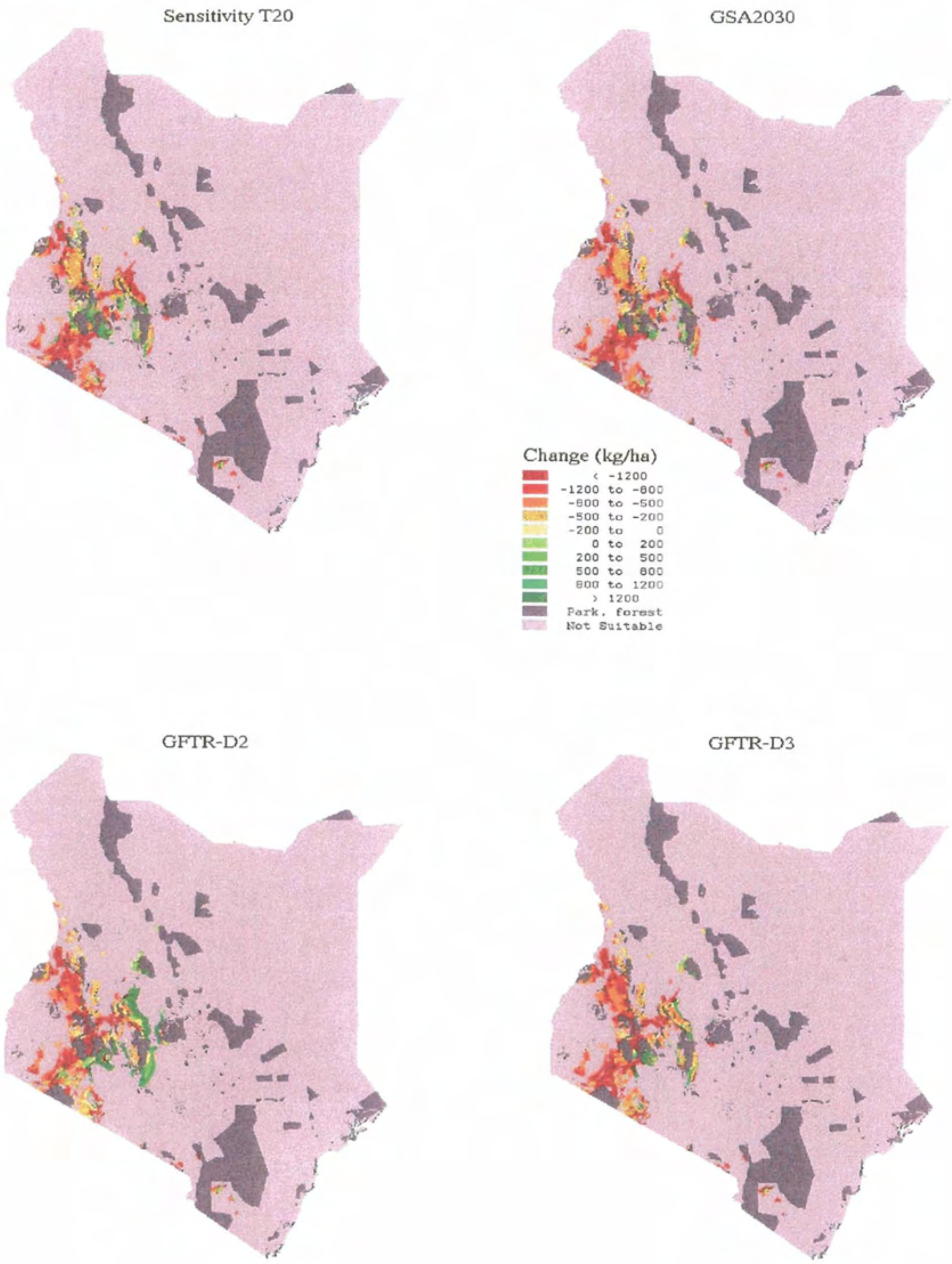


Figure 5.6 **Impacts on maize productivity by province for four climate change scenarios, relative to reference conditions (% change)**

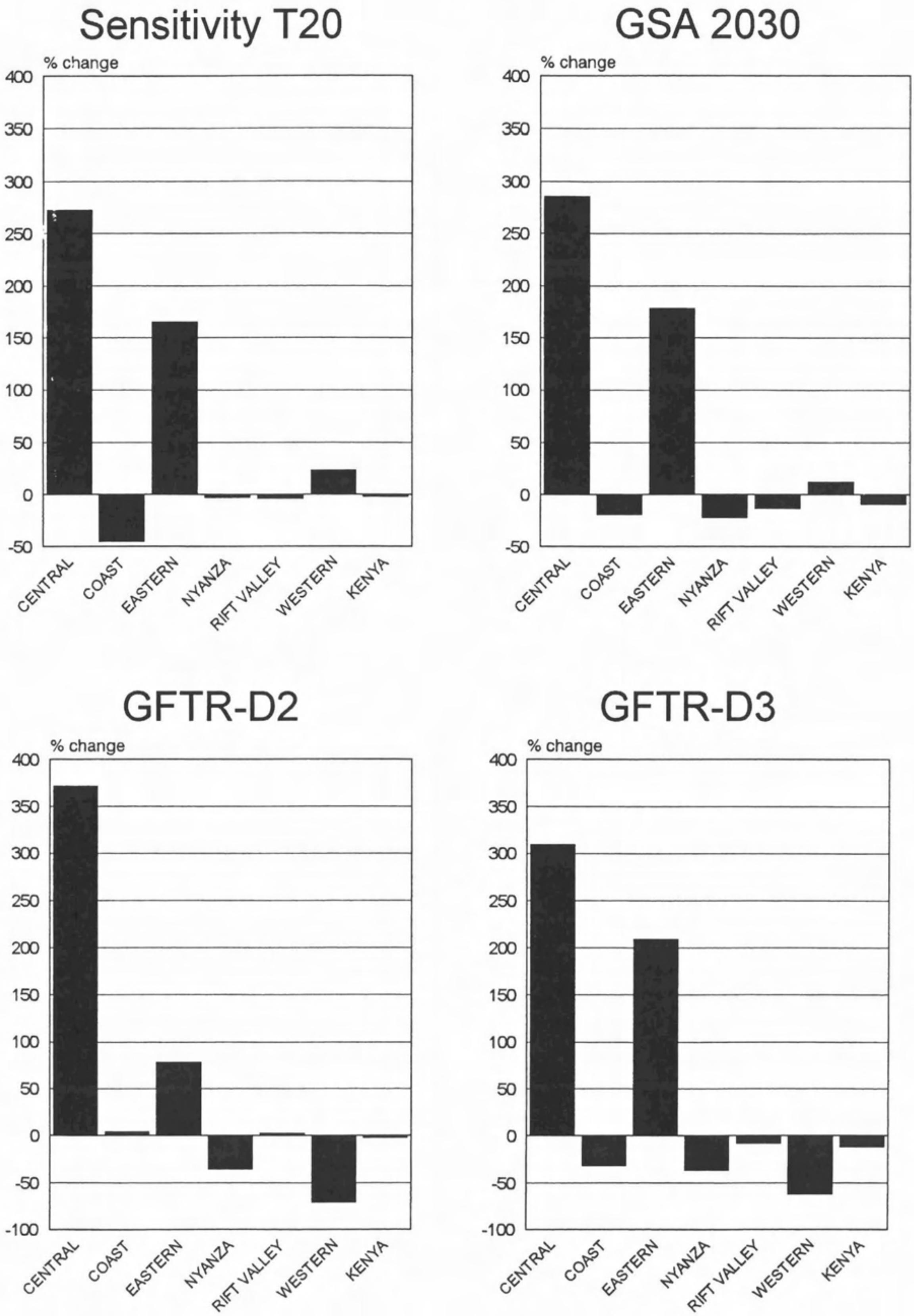


Figure 5.7 **Impacts on wheat productivity by province for four climate change scenarios, relative to reference conditions (% change)**

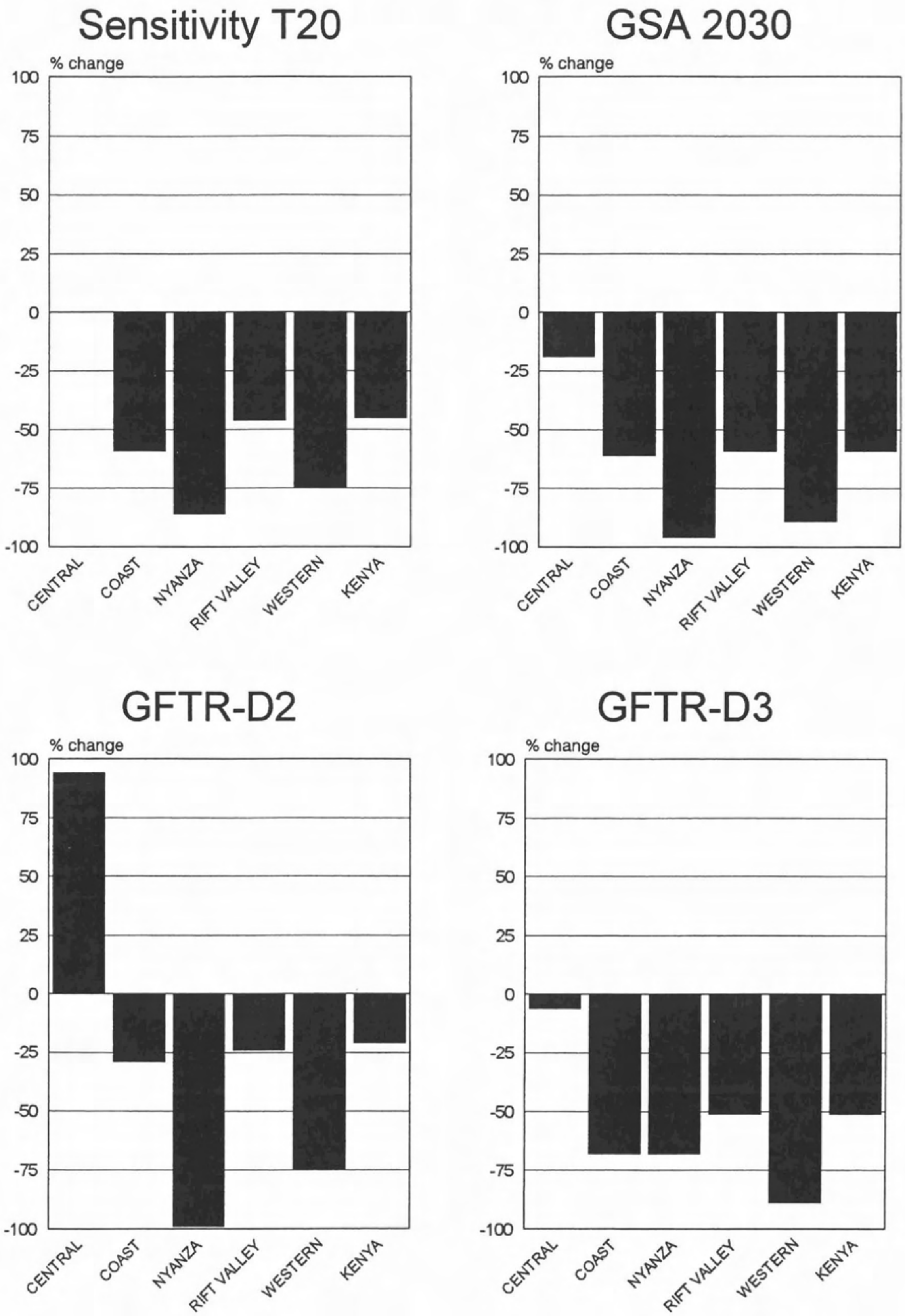


Figure 5.8 **Changes of land productivity for four climate change scenarios, relative to reference conditions**

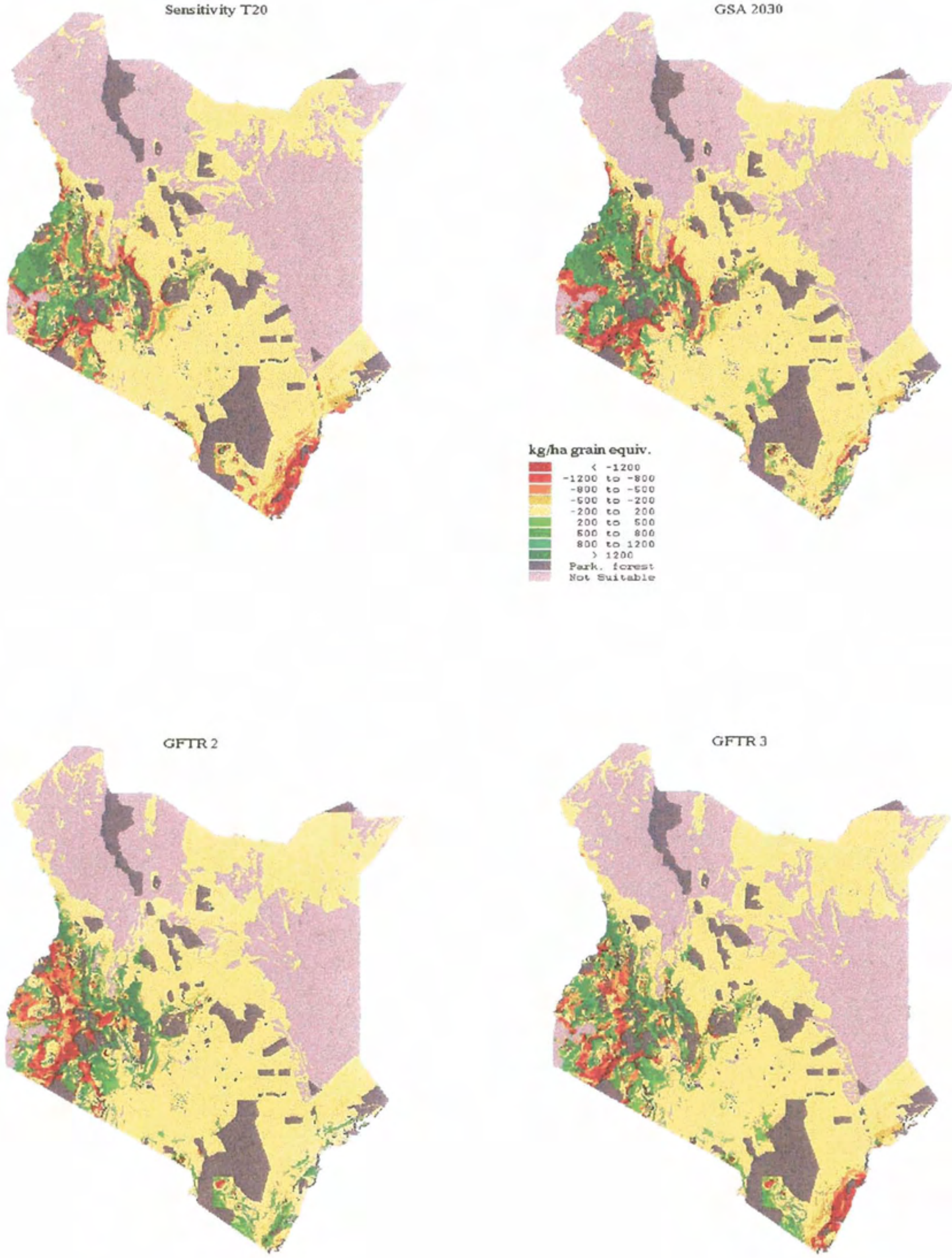


Figure 5.9 **Impacts on land productivity by province for four climate change scenarios, relative to reference conditions (% change)**

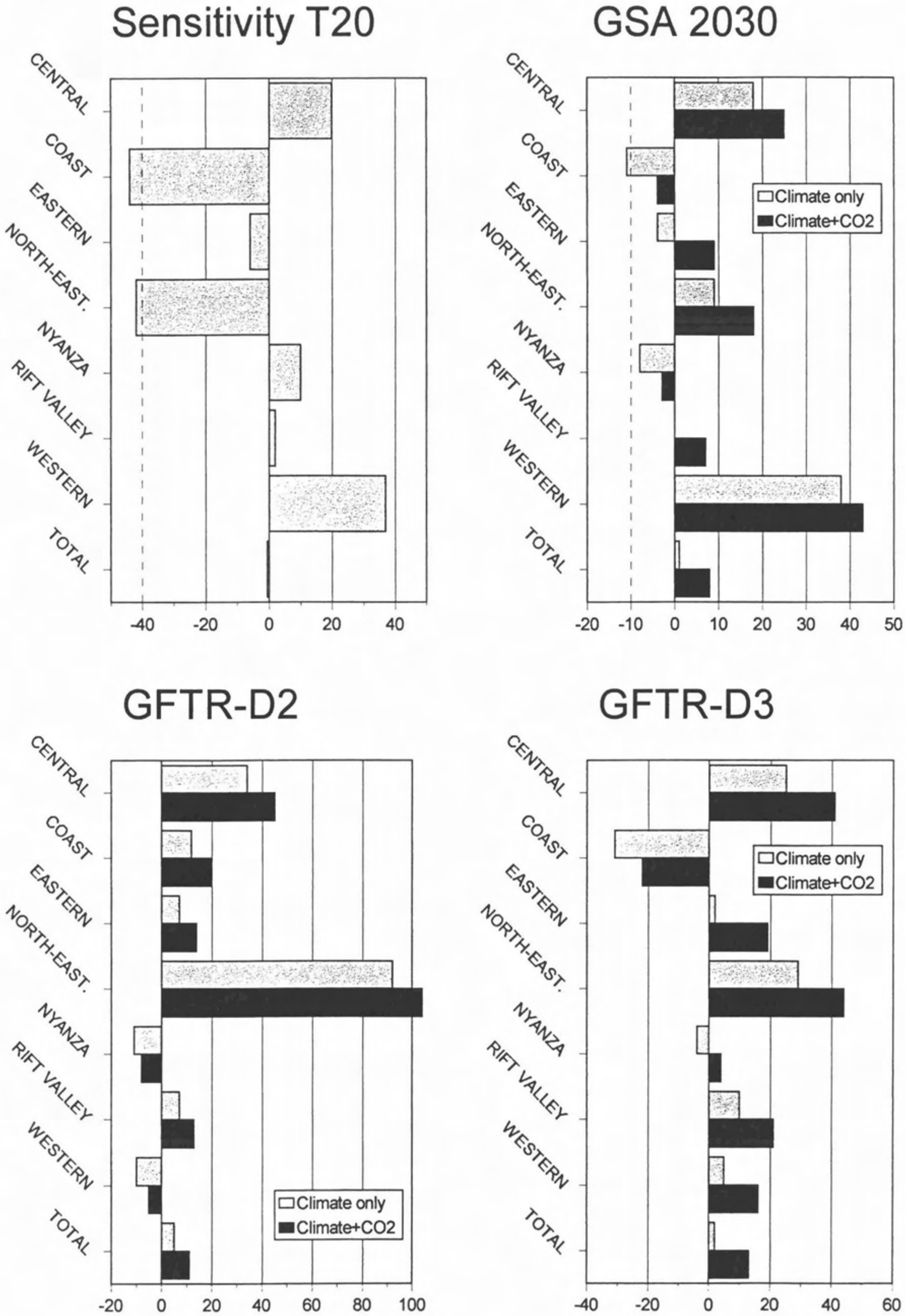


Figure 5.10 **Impacts on extents of arable land by province for four climate change scenarios, relative to reference conditions (% change)**

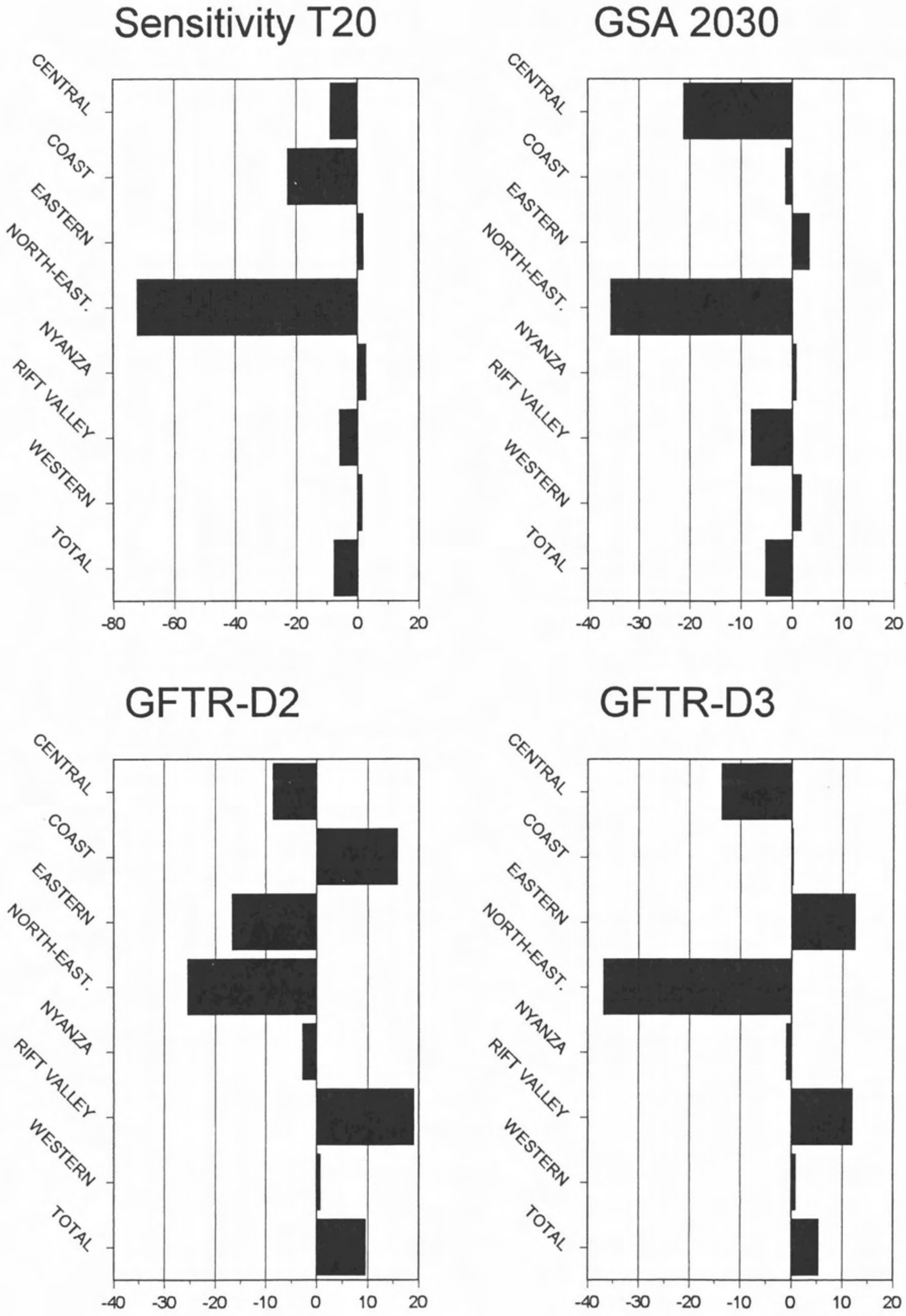
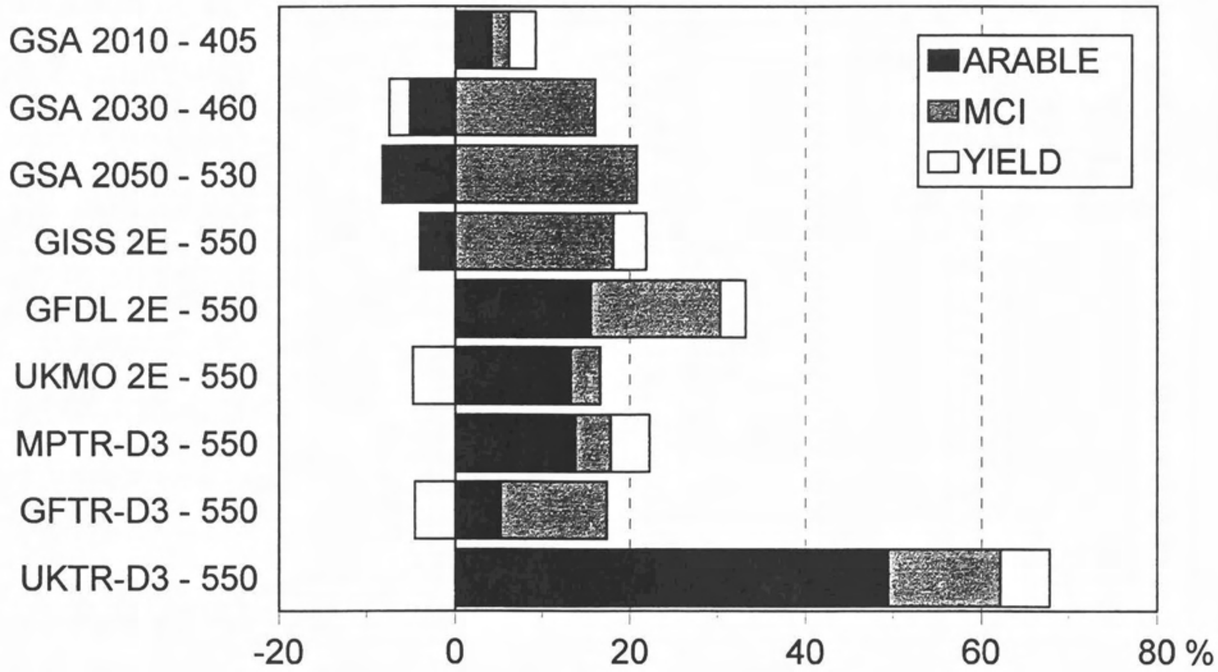
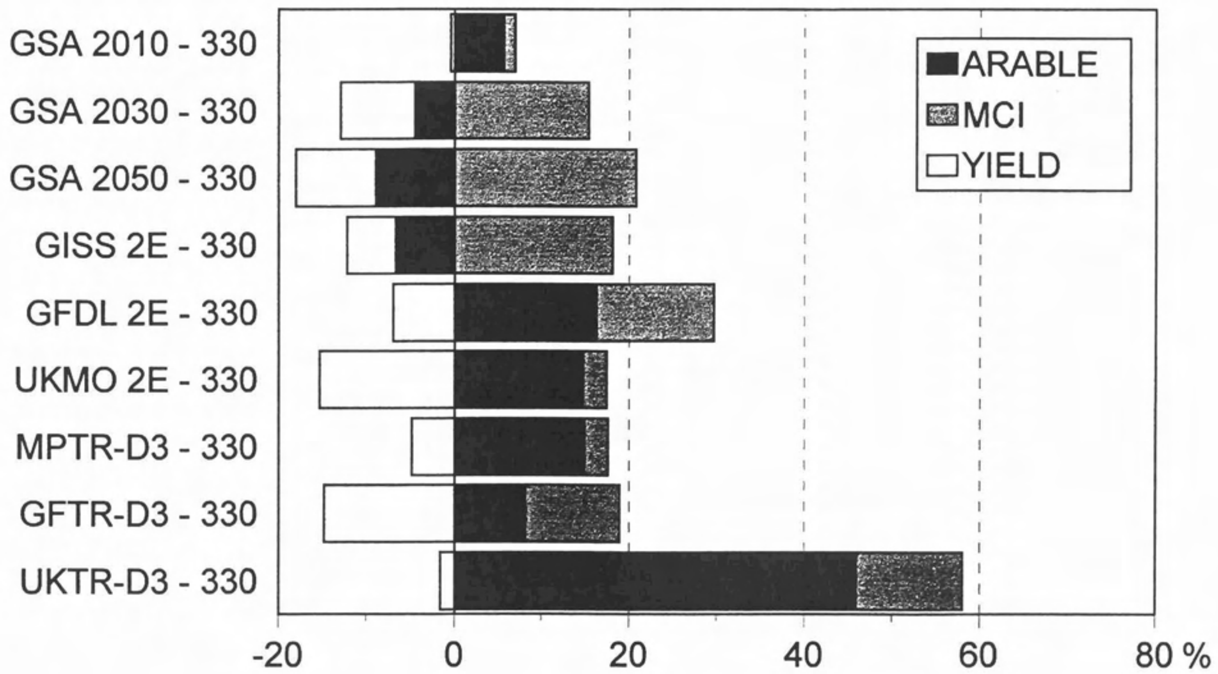


Figure 5.11 **Impacts of climate change on land productivity in terms of relative contributions from changes of arable land, yield change, and changes in cropping intensity, for scenarios with and without physiological effects from increases of atmospheric CO_2 (% change)**

a) With physiological effects of CO_2 on crop yields



b) Without physiological effects of CO_2 on crop yields



APPENDIX 1

CALCULATION OF POTENTIAL NET BIOMASS AND POTENTIAL YIELD

The AEZ methodology for the calculation of potential net biomass and yields is according to Kassam (1977). This model, based on eco-physiological principles, is outlined below:

To calculate the net biomass production (B_n) of a crop, an estimation of the gross biomass production (B_g) and respiration loss (R) is required:

$$B_n = B_g - R \quad (1)$$

The equation relating the rate of net biomass production (b_n) to the rate of gross biomass production (b_g) and the respiration rate (r) is:

$$b_n = b_g - r \quad (2)$$

The maximum rate of net biomass production (b_{nm}) is reached when the crop fully covers the ground surface. The inflection point of the cumulative growth curve (b_{nm}) is equal to the first derivative of the net growth occurring during the period of maximum growth. If the first derivative of growth is plotted against time the resulting curve shows a normal distribution. The model assumes that the seasonal average rate of net production (b_{na}) is half the maximum growth rate, i.e., 0.5 b_{nm}. The net biomass production for a crop of N days (B_n) is then:

$$B_n = 0.5\, b_{nm} \times N \quad (3)$$

The maximum rate of gross biomass production (b_{gm}) is dependent on the maximum rate of CO_2 exchange (P_m) which is dependent on temperature and the photosynthesis pathway of the crop.

For a crop in adaptability group I with P_m = 20 kg ha^{-1} hr^{-1} and a leaf area index of LAI = 5, rate of gross biomass production b_{gm} is calculated from the equation:

$$b_{gm} = F \times b_o + (1 - F)\, b_c \quad (4)$$

where:

F = the fraction of the daytime the sky is clouded, F = (A_c - 0.5 R_g) / (0.8 A_c), where A_c (or PAR) is the maximum active incoming short-wave radiation on clear days (de Wit 1965), and R_g is incoming short-wave radiation (both in cal $cm^{-2}.day^{-1}$)

b_o = gross dry mater production rate of a standard crop for a given location and time of the year on a completely overcast day, (kg ha^{-1} day^{-1}) (de Wit 1965)

b_c = gross dry mater production rate of a standard crop for a given location and time of the year on a clear overcast day, (kg ha^{-1} day^{-1}) (de Wit 1965)

When P_m is greater than 20 kg $ha^{-1}.hr^{-1}$, bgm is given by the equation:

$$b_{gm} = F\,(0.8 + 0.01 P_m)\, b_o + (1 - F)\,(0.5 + 0.025\, P_m) b_c \tag{5}$$

When P_m is less than 20 kg $ha^{-1}.hr^{-1}$, b_{gm} is given by the equation:

$$b_{gm} = F\,(0.5 + 0.025\, P_m)\, b_o + (1 - F)\,(0.05\, P_m)\, b_c \tag{6}$$

To calculate the maximum rate of net biomass production (b_{nm}) from the maximum rate of gross biomass production (b_{gm}) the rate of respiration is required. Here, growth respiration is considered a linear function of the rate of gross biomass production (McCree, 1974), and maintenance respiration a linear function of net biomass that has already been accumulated (B_m) When the rate of gross biomass production is b_{gm}, the respiration rate (r_m) is:

$$r_m = k\, b_{gm} + c\, B_m \; kg\; ha^{-1}\; day^{-1} \tag{7}$$

where k and c are the proportionality constants for growth respiration and maintenance respiration respectively, and B_m is the net biomass accumulated at the time of maximum rate of net biomass production. For both legume and non legume crops k equals 0.28. However c is temperature dependent and different for both groups of species. At 30 ^{o}C, factor c for a legume crop is 0.0283 and for a non-legume crop 0.0108. The temperature dependence of c for both species is included :

$$c_t = c_{30}\,(0.0044 + 0.0019\, T + 0.0010\, T^2). \tag{8}$$

It is assumed that the cumulative net biomass (B_m) of the crop equals half the net biomass that would be accumulated at the end of the crop's growth cycle Therefore, we set $B_m = 0.5\ B_n$, and, B_m for a crop of N days is determined according to:

$$B_m = 0.25\, b_{nm} \times N \tag{9}$$

By combining the respiration equation with the equation for the rate of gross photosynthesis, the maximum rate of net biomass production (b_{nm}) or the rate of dry matter production at full cover for a crop of N days becomes:

$$b_{nm} = 0.72\, b_{gm}/(1 + 0.25\, C_t N) \qquad (10)$$

Finally, the net biomass production (B_n) for a crop of N days, where 0.5 b_{nm} is the seasonal average rate of net biomass production, can be derived as:

$$B_n = (0.36\, b_{gm} \times L)/(1/N + 0.25\, C_t) \qquad (11)$$

where:

b_{gm} = maximum rate of gross biomass production at leaf area index (LAI) of 5

L = maximum growth ratio, equal to the ratio of b_{gm} at actual LAI to b_{gm} at LAI of 5

N = length of normal growth cycle

C_t = maintenance respiration, dependent on both crop and temperature according to equation (8)

Potential yield (Y_p) is calculated from net biomass (B_n) from the equation:

$$Y_p = H_i \times B_n \qquad (12)$$

where:

H_i = harvest index, i.e., proportion of the net biomass of the crop that is economically useful

Thus, climate and crop characteristics that apply in the computation of net biomass and yield are: (a) heat and radiation regime over crop cycle, (b) crop adaptability group to determine applicable rate of photosynthesis P_m, (c) length of growth cycle (from emergence to physiological maturity); (d) length of yield formation period;.(e) leaf area index at maximum growth rate, and (f) harvest index.

APPENDIX 2
CALCULATION OF REFERENCE EVAPOTRANSPIRATION

In the Kenya-AEZ system, the calculation of reference evapotranspiration (ET_0), i.e., the rate of evapotranspiration from a hypothetical crop with an assumed crop height of 12 cm, a fixed canopy resistance of 70ms^{-1} and an albedo of 0.23 (closely resembling the evapotranspiration from an extensive surface of green grass), is done according to the Penman-Monteith equation (Monteith 1965, 1981; FAO, 1992b). The calculation procedure uses a standardized set of input parameters, as follows:

T_{max} ... maximum daily temperature (°C)
T_{min} ... minimum daily temperature (°C)
RH ... mean daily relative humidity (%)
$U2$ ... wind speed measurement (ms^{-1})
SD ... bright sunshine hours per day (hours)
A ... elevation (m)
L ... latitude (deg)
J ... number of days in year

The *Penman-Monteith combination equation* can be written in terms of an aerodynamic and a radiation term:

$$ET_o = ET_{ar} + ET_{ra} \tag{1}$$

where the *aerodynamic term* can be approximated by

$$ET_{ar} = \frac{\gamma}{\vartheta + \gamma *} \cdot \frac{900}{T_a + 273} \cdot U2 \cdot (e_a - e_d) \tag{2}$$

and the *radiation term* by

$$ET_{ra} = \frac{\vartheta}{\vartheta + \gamma *} \cdot (R_n - G) \cdot \frac{1}{\lambda} \tag{3}$$

where variables in (2) and (3) are as follows:

γ ... psychrometric constant (kPa °C^{-1})
$\gamma*$ .. modified psychrometric constant (kPa °C^{-1})
ϑ ... slope vapor pressure curve (kPa °C^{-1})
T_a ... average daily temperature (°C)
e_a ... saturation vapor pressure (kPa)
e_d ... vapor pressure at dew point (kPa)
$(e_a - e_d)$ vapor pressure deficit (kPa)

$U2$ ... wind speed measurement (ms^{-1})
R_n ... net radiation flux at surface ($MJ\ m^{-2}\ d^{-1}$)
G ... soil heat flux ($MJ\ m^{-2}\ d^{-1}$)
λ ... latent heat of vaporization ($MJ\ kg^{-1}$)

In the calculation procedure for the reference crop we use the following relationships to define terms in (2):

Average daily temperature:

$$T_a = 0.5(T_{\max} + T_{\min}) \tag{4}$$

Latent heat of vaporization:

$$\lambda = 2.501 - 0.002361\, T_a \tag{5}$$

Atmospheric pressure (kPa) at elevation A:

$$P = 101.3\left(\frac{293 - 0.0065\,A}{293}\right)^{5.256} \tag{6}$$

Psychrometric constant:

$$\gamma = 0.0016286 \cdot \frac{P}{\lambda} \tag{7}$$

Aerodynamic resistance:

$$r_a = \frac{208}{U2} \tag{8}$$

Crop canopy resistance:

$$r_c = \frac{R_l}{0.5\,LAI} \tag{9}$$

where under ambient CO_2 concentrations the average daily stomata resistance of a single leaf, R_l (sm^{-1}), is set to $R_l = 100$, and leaf area index of the reference crop is assumed as $LAI = 24 \cdot 0.12 = 2.88$.

Modified psychrometric constant:

$$\gamma^* = \gamma\left(1 + \frac{r_c}{r_a}\right) \tag{10}$$

Saturation vapor pressure ea for given temperatures $T_{\min}$ and $T_{\max}$

$$e_{ax} = 0.6108 \exp\left(\frac{17.27\, T_{\max}}{237.3 + T_{\max}}\right) \tag{11}$$

$$e_{an} = 0.6108 \exp\left(\frac{17.27\, T_{\min}}{237.3 + T_{\min}}\right) \tag{12}$$

$$e_a = 0.5\,(e_{ax} + e_{an}) \tag{13}$$

Vapor pressure at dew point, e_d:

$$e_d = \frac{RH}{100} \cdot \frac{0.5}{\left(\frac{1}{e_{ax}} + \frac{1}{e_{an}}\right)} \tag{14}$$

Slope vapor pressure curve, ϑ, for given temperatures $T_{\max}$ and $T_{\min}$:

$$\vartheta_x = \frac{4096\, e_{ax}}{(237.3 + T_{\max})^2} \tag{15}$$

$$\vartheta_n = \frac{4096\, e_{an}}{(237.3 + T_{\min})^2} \tag{16}$$

$$\vartheta = 0.5\left(\vartheta_x + \vartheta_n\right) \tag{17}$$

Using (4)-(9) all variables in (2) can be calculated from the input parameters of the ET_o computer subroutine. To determine the remaining variables R_n and G used in the radiation term ET_{ra} of equation (3), we proceed with the following calculation steps:

Latitude expressed in rad:

$$\varphi = \frac{L\pi}{180} \tag{18}$$

Solar declination (rad):

$$\delta = 0.4093 \cdot \sin\left(\frac{2\pi}{365} J - 1.405\right) \tag{19}$$

Relative distance Earth to Sun:

$$d = 1 + 0.033 \cos\left(\frac{2\pi}{365} J\right) \tag{20}$$

Sunset hour angle (rad):

$$\psi = arc\cos\,(-\tan\varphi \tan\delta) \tag{21}$$

Extraterrestrial radiation (MJ m^{-2} d^{-1}):

$$R_a = 37.586\, d\, (\psi \sin\varphi \sin\delta + \cos\varphi \cos\delta \sin\psi) \tag{22}$$

Maximum daylight hours:

$$DL = \frac{24}{\pi}\,\psi \tag{23}$$

Short-wave radiation R_s (MJ m^{-2} d^{-1})

$$R_s = \left(0.25 + 0.5\frac{SD}{DL}\right) R_a \tag{24}$$

For a reference crop with an assumed albedo coefficient $\alpha = 0.23$ *net incoming short-wave radiation* R_{ns} (MJ m^{-2} d^{-1}) is:

$$R_{ns} = 0.77\, R_s \tag{25}$$

Net outgoing long-wave radiation R_{nl} (MJ m^{-2} d^{-1}) is estimated using:

$$T_{kx} = 273.16 + T_{\max} \tag{26}$$

$$T_{kn} = 273.16 + T_{\min} \tag{27}$$

$$R_{ne} = 4.903 \cdot 10^{-9} \left(0.1 + 0.9\frac{SD}{DL}\right)\left(0.34 - 0.139\sqrt{e_d}\right) \frac{(T_{kx})^4 + (T_{kn})^4}{2} \tag{28}$$

Using (25) and (28), *net radiation flux* at surface, R_n, becomes

$$R_n = R_{ns} - R_{nl} \tag{29}$$

Finally, *soil heat flux* is approximated using

$$G = 0.14\, (T_{a,n} - T_{a,n-1}) \tag{30}$$

where $T_{a,n}$ and $T_{a,n-1}$ are average monthly temperatures of current and previous month, respectively. With equations (5), (10), (17), (29) and (30) all variables in (3) are defined and can be calculated from the input parameters described at the beginning of this Appendix.

APPENDIX 3
DETERMINATION OF GROWING PERIOD

The methodology for the calculation of reference length of growing period used in the AEZ-Kenya system is based on a water balance model comparing moisture supply from rainfall and storage with potential evapotranspiration. The implementation is based on methods described in FAO, 1991, 1992a, 1992b, as follows:

First the climatic (or weather) input parameters are prepared from the database of monthly climate averages:

Average day-time temperature, T_d (°C):

$$T_d = T_a + \frac{T_{max} - T_{min}}{4\pi} \cdot \frac{11+h}{12-h} \cdot \sin\left(\pi \frac{11-h}{11+h}\right) \quad (1)$$

Average night-time temperature, T_n (°C)

$$T_n = T_a + \frac{T_{max} - T_{min}}{4\pi} \cdot \frac{11+h}{h} \cdot \sin\left(\pi \frac{11-h}{11+h}\right) \quad (2)$$

where

$$h = 12 - 0.5 \cdot DL \quad (3)$$

T_{max} ... maximum daily temperature (°C)
T_{min} ... minimum daily temperature (°C)

Relative humidity, RH(%), is either given (when using station data) or calculated according to a regression equation (when working with the gridded climate dataset):

$$RH = 179.9 - 2.1357\, T_{max} - 1.5684\, T_{min} + 0.0491 \cdot R - 0.0156\, A - 0.0317 \cdot CD2 \quad (4)$$

with

R ... monthly rainfall (mm)
A ... elevation (m)
CD2 ... the smaller of distance to coast and 200 (km)

Sunshine duration, SD (hours), is either given (station data) or calculated according to a regression equation (gridded climate dataset)

$$\begin{aligned} SD_{rel} = {} & 0.8548 \cdot T_{max} - 0.8739 \cdot T_{min} - 0.0926857 \cdot R \\ & - 0.0016132 \cdot A + 0.0139573 \cdot U2 - 0.2952 \cdot RH + 79.9745 \end{aligned} \quad (5)$$

$$SD = SD_{rel} \cdot DL / 100 \tag{6}$$

Reference evapotranspiration, ET_0 (mm), is calculated according to the combination method of Penman-Monteith, as described in Appendix 2:

$$ET_o = f\left(T_{\max}, T_{\min}, R, U2, RH, SD, A, L, J\right) \tag{7}$$

For convenience, the monthly (or 10-day) average climate parameters are then converted to daily data by means of piece-wise linear functions ensuring consistency of daily levels with monthly means, resulting in daily values for *Tmax, Tmin, Ta, Td, ET0, U2, RH,* and *SD*. From these series a daily *water balance*, W, and *actual evapotranspiration*, *ETa* is calculated:

$$W_{j+1} = \min\left(W_j + R - ET_a, Sa\right) \tag{8}$$

$$ET_a = \begin{cases} ET_o & \text{if } (W_j + R) \cdot d \geq Sa \cdot d \cdot (1 - p) \\ \rho\, ET_o & \text{else} \end{cases} \tag{9}$$

where

$$\rho = \frac{ET_a}{ET_o} = \frac{W_j + R}{Sa \cdot (1 - p)} \tag{10}$$

Sa ... field capacity (mm/m)
d ... rooting depth (m)
p ... soil water depletion fraction when $ETa < ET0$
ρ ... actual evapotranspiration proportionality factor.

The beginning of a growing period is reached when actual evapotranspiration, *ETa*, reaches half potential evapotranspiration (and temperature is above 5 °C),

$$ET_a \geq 0.5\, ET_o \tag{11}$$

for at least *LGPmin* days[1] A growing period ends on the day when first

$$ET_a < 0.5\, ET_o \tag{12}$$

In this way all the growing periods are fully determined with starting and ending dates, length and *ETa* values. The procedure also records the dates and length of any humid

[1] The algorithm first keeps track of all periods with $ET_a > 0.5\, ET_o$, then discards such multiple periods if length is less than $LGP_{\min} = 10$ days.

phase, of each growing period defined as days where moisture supply exceeds potential evapotranspiration, i.e., with

$$W_j + R > ET_o \tag{13}$$

Keeping exact records of moisture and temperature profiles then allows a more accurate calculation of potential biomass production as detailed in Appendix 1.

APPENDIX 4

SUB-NATIONAL RESULTS OF IMPACTS OF CLIMATE CHANGE ON CROP PRODUCTION POTENTIAL AND LAND PRODUCTIVITY

Table A4.1a **Impacts on land potential productivity, by province and district for sensitivity climate change scenarios (% change)**

		REF	T10	T20	T30	T40	T50	P05	P10	PM05	PM10
		ppm 330	330	330	330	330	330	330	330	330	330
101	Kiambu	4332	-3	-6	-9	-10	-4	12	25	-14	-29
102	Kirinyaga	1314	-18	-23	-19	-12	-13	5	20	-15	-29
103	Muranga	4249	-10	-4	7	6	0	9	24	-8	-20
104	Nyandarua	7171	33	86	119	115	92	-1	-2	3	5
105	Nyeri	5054	-9	-19	-20	-12	-4	24	44	-16	-31
	CENTRAL	22121	5	20	32	33	27	10	20	-8	-17
201	Kilifi	28777	-26	-53	-67	-74	-81	17	35	-17	-36
202	Kwale	25243	-29	-46	-56	-64	-71	23	45	-23	-38
203	Lamu	6388	-21	-35	-42	-52	-61	12	28	-12	-22
204	Mombasa	1602	-3	-48	-67	-69	-72	9	19	-2	-26
205	Taita	13140	-15	-30	-41	-52	-59	23	43	-21	-39
206	Tana River	6178	-12	-29	-40	-51	-62	12	40	-13	-26
	COAST	81330	-23	-44	-55	-64	-71	19	39	-19	-35
301	Embu	1332	-2	-6	-9	-12	-13	4	9	-4	-7
302	Isiolo	2063	-14	-25	-37	-45	-54	22	39	-19	-38
303	Kitui	9038	-4	-10	-16	-20	-25	3	7	-3	-6
304	Machakos	6695	-3	-7	-13	-18	-23	4	8	-4	-7
305	Marsabit	3571	-15	-28	-38	-50	-60	21	38	-20	-42
306	Meru	6420	7	20	31	36	37	8	15	-6	-12
	EASTERN	29119	-3	-6	-9	-12	-17	8	15	-7	-14
	Nairobi Area	249	9	6	-4	2	-11	8	14	-14	-31
501	Garissa	1283	-25	-49	-60	-68	-76	16	33	-14	-31
502	Mandera	620	-15	-29	-45	-60	-71	35	89	-28	-60
503	Wajir	634	-21	-37	-51	-62	-70	45	100	-33	-56
	NORTH-EAST.	2537	-21	-42	-54	-65	-73	28	63	-22	-45
601	South Nyanza	36316	-3	-7	-8	-17	-23	5	9	-6	-15
602	Kisii	14968	22	48	78	103	138	-25	-42	30	56
603	Kisumu	15305	20	20	11	6	0	-3	-6	0	-6
604	Siaya	25609	23	5	-14	-25	-37	-1	-6	-3	-18
	NYANZA	92199	12	10	7	4	3	-3	-6	2	-3
701	Baringo	27364	-9	-16	-22	-25	-29	8	20	-10	-18
702	Elgeyo Mar.	10493	5	9	5	-1	-7	7	15	-6	-18
703	Kajiado	8029	-11	-21	-31	-38	-47	28	59	-22	-40
704	Kericho	42170	9	8	1	2	11	-6	-13	6	4
705	Laikipia	20166	-1	-12	-37	-53	-63	33	64	-23	-44
706	Nakuru	22331	16	34	37	27	18	3	7	-5	-8
707	Nandi	20139	14	18	17	26	28	-4	-11	-1	-5
708	Narok	88300	-5	-10	-21	-35	-51	7	13	-9	-18
709	Samburu	2465	-13	-21	-33	-46	-55	31	72	-23	-44
710	Trans-Nzoia	25340	2	18	34	40	41	5	3	-4	-5
711	Turkana	909	-25	-43	-57	-66	-75	58	134	-38	-55
712	Uasin Gishu	23947	5	5	-5	-9	-1	1	2	-3	-6
713	West Pokot	34553	1	13	14	10	6	8	17	-10	-17
	RIFT VALLEY	326207	1	2	-4	-9	-14	6	12	-7	-14
801	Bungoma	16141	17	42	56	66	68	-6	-12	7	11
802	Busia	11114	34	30	23	16	12	-1	-21	-1	-6
803	Kakamega	24066	19	36	54	66	76	-7	-15	8	14
	WESTERN	51321	22	37	48	55	59	-5	-15	6	9
	KENYA TOTAL	605081	1	0	-4	-8	-12	6	11	-6	-14

Table A4.1b **Impacts on land potential productivity, by province and district for GCM equilibrium climate change scenarios (% change)**

		GSA 2010 330	GSA 2030 330	GSA 2050 330	GSA 2010 405	GSA 2030 460	GSA 2050 530	GISS 2E 330	GFDL 2E 330	UKMO 2E 330	GISS 2E 550	GFDL 2E 550	UKMO 2E 550
101	Kiambu	16	-13	-7	20	-6	6	2	34	-4	15	60	9
102	Kirinyaga	1	-26	-18	5	-23	-9	-5	36	23	8	56	40
103	Muranga	10	-14	12	14	-7	25	17	72	8	31	86	19
104	Nyandarua	46	103	117	48	112	136	118	107	90	143	124	112
105	Nyeri	13	-38	-19	20	-31	-17	-18	71	-31	-14	104	-22
	CENTRAL	23	18	33	27	25	46	37	74	24	53	95	39
201	Kilifi	-12	-15	-38	-9	-9	-31	-37	-21	-63	-29	-10	-59
202	Kwale	-5	-7	-38	-1	1	-29	-35	-30	-41	-23	-16	-33
203	Lamu	2	-24	-36	5	-20	-32	-37	-23	-51	-32	-17	-46
204	Mombasa	-3	11	-24	-1	17	-4	-11	9	-70	10	21	-64
205	Taita	7	-9	-24	12	-1	-14	-24	-16	1	-11	-1	18
206	Tana River	-2	-6	-28	0	-2	-22	-28	4	-24	-22	11	-20
	COAST	-5	-11	-35	-1	-4	-26	-33	-21	-42	-23	-9	-35
301	Embu	2	-8	-11	3	-4	-5	-5	18	22	5	35	49
302	Isiolo	-5	-14	-27	-2	-8	-18	-31	40	-13	-21	55	0
303	Kitui	-3	-12	-17	3	3	4	-15	-4	-10	17	29	10
304	Machakos	0	-8	-13	4	11	12	-12	2	20	18	32	39
305	Marsabit	-4	5	-9	-2	10	-2	-31	-25	-4	-24	-16	8
306	Meru	7	10	23	12	21	40	40	73	52	67	113	83
	EASTERN	0	-4	-7	4	9	11	-5	16	13	20	45	34
	Nairobi Area	25	10	17	27	16	26	20	41	43	29	52	61
501	Garissa	-7	-19	-46	-1	-13	-40	-55	2	-46	-49	10	-42
502	Mandera	17	39	24	21	53	43	-25	53	90	-12	72	113
503	Wajir	10	37	18	13	46	31	-31	30	85	-23	47	117
	NORTH-EAST.	3	9	-13	8	18	-2	-42	21	20	-33	34	36
601	South Nyanza	0	-16	-9	1	-11	-3	-9	22	-24	0	33	-16
602	Kisii	19	43	73	21	50	92	122	6	104	147	13	116
603	Kisumu	14	-5	7	16	-2	14	-2	15	-25	5	25	-17
604	Siaya	27	-30	-30	31	-24	-23	-37	29	-49	-30	43	-41
	NYANZA	13	-8	1	15	-3	10	5	20	-11	17	31	-2
701	Baringo	-7	-4	-6	-6	2	6	-26	31	-18	-18	41	-10
702	Elgeyo Mar.	8	16	23	11	26	37	-3	47	6	12	66	20
703	Kajiado	-1	-1	-4	0	5	9	-5	37	15	11	56	36
704	Kericho	2	1	6	5	5	13	19	16	-8	31	23	6
705	Laikipia	23	-31	-42	28	-23	-34	-54	82	-20	-46	111	-5
706	Nakuru	24	41	41	26	49	54	29	72	19	47	89	30
707	Nandi	12	12	20	13	18	30	28	8	-1	41	16	9
708	Narok	-1	-31	-38	3	-24	-24	-7	20	-4	13	32	10
709	Samburu	3	-11	-13	5	-6	-7	-34	96	21	-26	123	31
710	Trans-Nzoia	3	29	45	6	36	61	43	23	27	60	38	41
711	Turkana	-16	-42	-37	-15	-38	-32	-52	187	176	-46	211	218
712	Uasin Gishu	4	22	12	5	26	22	-9	9	-13	-3	19	-9
713	West Pokot	5	29	30	8	38	42	16	41	28	30	56	43
	RIFT VALLEY	4	0	0	7	7	11	2	31	2	17	44	14
801	Bungoma	22	48	58	25	53	68	73	32	57	86	44	69
802	Busia	35	19	17	35	24	25	17	26	8	26	33	15
803	Kakamega	22	39	52	23	45	63	82	22	75	93	33	86
	WESTERN	25	38	46	26	43	56	65	26	55	76	36	65
	KENYA TOTAL	7	1	0	10	8	11	4	23	0	18	36	12

Table A4.1c Impacts on land potential productivity, by province and district for GCM transient climate change scenarios (% change)

		MPTR D2 330	GFTR D2 330	UKTR D2 330	MPTR D2 460	GFTR D2 460	UKTR D2 460	MPTR D3 330	GFTR D3 330	UKTR D3 330	MPTR D3 550	GFTR D3 550	UKTR D3 550
101	Kiambu	17	30	152	28	41	192	20	-3	445	40	14	491
102	Kirinyaga	-4	8	2	6	25	11	20	-8	261	30	7	316
103	Muranga	16	27	36	21	37	53	37	0	397	53	11	445
104	Nyandarua	34	26	10	40	31	17	96	87	52	111	104	64
105	Nyeri	26	63	35	39	82	52	7	-7	334	34	11	376
	CENTRAL	23	34	48	32	45	66	45	25	272	63	41	307
201	Kilifi	20	7	-59	28	15	-54	-49	-56	-48	-40	-51	-37
202	Kwale	22	19	-28	31	27	-21	-32	-31	-8	-22	-19	11
203	Lamu	6	5	-41	18	14	-39	-26	-29	-40	-20	-22	-36
204	Mombasa	15	6	-53	21	18	-5	-39	-52	-11	-30	-53	11
205	Taita	28	9	38	39	19	52	-7	8	235	9	23	299
206	Tana River	14	17	-16	27	23	-13	-12	-1	6	-6	7	12
	COAST	20	12	-29	30	20	-21	-32	-31	16	-22	-22	37
301	Embu	-2	4	33	5	10	44	8	-5	382	23	6	422
302	Isiolo	31	37	29	39	45	38	5	20	172	17	33	216
303	Kitui	-5	-5	9	8	4	24	-5	-11	53	17	8	84
304	Machakos	1	1	126	12	7	155	2	-1	736	24	17	834
305	Marsabit	41	45	-29	46	51	-26	3	-2	-13	14	9	-4
306	Meru	9	-1	61	23	8	89	31	19	386	54	39	450
	EASTERN	8	7	45	19	14	64	7	2	299	27	19	351
	Nairobi Area	20	21	16	25	27	23	23	29	375	36	24	493
501	Garissa	23	24	-48	35	31	-42	-26	-10	-16	-17	-3	-3
502	Mandera	145	166	-51	165	187	-47	82	98	81	104	121	103
503	Wajir	132	155	-36	146	173	-32	61	41	63	85	62	85
	NORTH-EAST.	80	92	-46	94	104	-41	22	29	27	38	44	45
601	South Nyanza	22	-4	7	27	0	13	5	-5	26	15	3	36
602	Kisii	-19	-31	-42	-14	-27	-40	52	-1	-52	64	8	-49
603	Kisumu	9	-13	0	12	-12	2	6	-2	-5	13	6	0
604	Siaya	28	-10	-2	35	-5	2	9	-5	-6	21	3	6
	NYANZA	15	-11	-5	20	-8	0	14	-4	-1	25	4	8
701	Baringo	17	27	43	22	31	46	7	22	36	14	29	42
702	Elgeyo Mar.	24	36	42	32	43	50	26	33	42	41	47	56
703	Kajiado	47	8	272	57	14	296	-1	16	1124	10	26	1294
704	Kericho	-24	-35	-19	-20	-34	-17	-4	-14	-42	6	-7	-41
705	Laikipia	52	112	137	65	131	157	70	49	230	95	69	270
706	Nakuru	36	23	23	40	27	29	47	44	44	59	55	56
707	Nandi	-7	-31	-26	-3	-29	-24	6	-10	-28	15	-4	-21
708	Narok	11	-2	30	19	7	39	7	-4	47	15	9	60
709	Samburu	69	114	190	79	125	220	102	69	349	131	86	395
710	Trans-Nzoia	4	-15	-10	10	-10	-6	15	1	-15	29	13	-9
711	Turkana	101	150	1273	113	167	1335	400	96	1882	436	117	2032
712	Uasin Gishu	10	-11	1	13	-12	2	-4	-8	-20	0	-7	-23
713	West Pokot	22	22	33	30	29	37	31	37	41	44	49	53
	RIFT VALLEY	13	7	34	19	13	40	17	10	64	28	21	79
801	Bungoma	8	-8	-21	13	-5	-18	45	8	-10	55	17	1
802	Busia	22	-6	-6	24	-1	-2	27	-5	11	35	4	22
803	Kakamega	1	-12	-19	8	-7	-15	43	9	-4	52	22	3
	WESTERN	8	-10	-17	13	-5	-13	41	5	-3	49	16	6
	KENYA TOTAL	14	5	16	21	11	23	12	2	61	24	13	78

Table A4.2a **Impacts on extents with rainfed cultivation potential, by province and district for sensitivity climate change scenarios (% change)**

		REF	T10	T20	T30	T40	T50	P05	P10	PM05	PM10
		330	330	330	330	330	330	330	330	330	330
101	Kiambu	614	-10	-25	-27	-7	22	11	25	-10	-21
102	Kirinyaga	166	-37	-58	-48	-27	-24	5	6	-14	-32
103	Muranga	604	-24	-21	8	19	20	7	15	-7	-16
104	Nyandarua	728	11	19	26	18	11	-10	-21	6	9
105	Nyeri	731	-5	-21	-35	-24	-10	14	26	-14	-29
	CENTRAL	2846	-8	-14	-9	-1	8	5	10	-7	-15
201	Kilifi	2313	-20	-34	-42	-53	-66	3	8	-16	-25
202	Kwale	2242	-7	-19	-32	-40	-52	14	30	-3	-15
203	Lamu	1024	-24	-38	-37	-48	-57	14	29	-14	-22
204	Mombasa	87	-1	-8	-15	-15	-14	0	0	-1	-3
205	Taita	1447	-8	-26	-33	-43	-46	28	46	-34	-51
206	Tana River	499	-20	-43	-45	-50	-59	22	48	-17	-24
	COAST	7611	-14	-29	-37	-46	-56	14	27	-15	-26
301	Embu	83	4	-1	-23	-29	-2	25	27	1	-12
302	Isiolo	53	-26	-58	-25	2	-4	13	72	-45	-58
303	Kitui	964	18	20	-3	-21	-34	-17	-2	-22	-44
304	Machakos	327	26	23	-7	-28	-35	-4	1	0	-38
305	Marsabit	148	-39	-74	-82	-86	-87	60	91	-54	-85
306	Meru	698	5	22	51	70	72	17	36	-16	-26
	EASTERN	2274	10	12	7	2	-3	3	19	-19	-39
	Nairobi Area	22	14	0	-18	27	9	5	14	-14	-41
501	Garissa	125	-40	-77	-84	-90	-97	13	16	-13	-38
502	Mandera	0	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
503	Wajir	3	-67	-100	-100	-100	-100	-100	33	-67	-100
	NORTH-EAST.	128	-41	-77	-84	-91	-97	10	16	-14	-40
601	South Nyanza	2075	13	20	20	11	1	-1	-3	2	0
602	Kisii	629	11	38	59	71	84	-18	-25	30	45
603	Kisumu	795	11	13	15	14	11	-7	-11	5	6
604	Siaya	1158	8	9	2	0	-4	-2	-6	0	-2
	NYANZA	4657	11	19	20	17	13	-5	-8	6	6
701	Baringo	2220	-8	-13	-20	-26	-31	7	15	-10	-19
702	Elgeyo Mar.	848	0	-1	-5	-10	-13	3	7	-5	-13
703	Kajiado	636	10	14	11	6	-3	40	66	-27	-44
704	Kericho	1820	8	18	21	22	25	-7	-12	9	15
705	Laikipia	1781	-11	-25	-46	-65	-76	28	59	-22	-44
706	Nakuru	1945	4	6	8	6	3	1	5	-3	-5
707	Nandi	957	5	13	22	26	26	-7	-14	6	13
708	Narok	5138	-7	-13	-19	-32	-43	8	18	-7	-16
709	Samburu	184	-15	-27	-35	-52	-60	30	64	-20	-42
710	Trans-Nzoia	1602	6	11	13	14	13	-2	-7	3	5
711	Turkana	142	-29	-37	-49	-58	-85	63	132	-35	-48
712	Uasin Gishu	1614	10	13	13	13	16	1	0	0	1
713	West Pokot	2506	1	3	-1	-4	-9	0	3	-3	-7
	RIFT VALLEY	21396	-1	-2	-6	-12	-17	6	13	-5	-11
801	Bungoma	954	15	29	32	28	24	-2	-3	4	7
802	Busia	594	22	17	14	11	8	2	-2	2	2
803	Kakamega	1346	8	38	49	45	32	-1	-8	6	12
	WESTERN	2894	13	31	36	33	24	-1	-5	4	8
	KENYA TOTAL	41827	-1	-2	-5	-11	-16	6	12	-6	-12

Table A4.2b Impacts on extents with rainfed cultivation potential, by province and district for equilibrium climate change scenarios (% change)

		GSA 2010 330	GSA 2030 330	GSA 2050 330	GSA 2010 405	GSA 2030 460	GSA 2050 530	GISS 2E 330	GFDL 2E 330	UKMO 2E 330	GISS 2E 550	GFDL 2E 550	UKMO 2E 550
101	Kiambu	5	-30	-15	7	-26	-9	-7	7	-10	-2	18	-5
102	Kirinyaga	-1	-67	-44	-1	-64	-27	-7	57	66	17	80	90
103	Muranga	-13	-28	22	-13	-24	28	30	38	34	37	47	51
104	Nyandarua	14	15	11	12	14	12	16	16	26	18	15	28
105	Nyeri	2	-36	-33	4	-40	-39	-32	12	-40	-35	24	-42
	CENTRAL	2	-22	-7	3	-21	-5	0	20	5	4	28	11
201	Kilifi	2	-12	-29	3	-11	-26	-29	-17	-36	-23	-13	-27
202	Kwale	7	-8	-11	7	-5	-13	-12	-14	-4	-15	-18	10
203	Lamu	3	-27	-36	6	-25	-36	-38	-26	-48	-35	-24	-42
204	Mombasa	-1	0	-7	-1	0	-5	-5	0	-23	-1	0	-26
205	Taita	41	15	-3	41	17	-3	-2	-10	54	-2	-8	88
206	Tana River	-2	8	-30	4	14	-21	-37	19	-31	-28	21	-30
	COAST	11	-6	-20	12	-4	-19	-20	-14	-11	-18	-13	3
301	Embu	18	-5	-36	2	-22	-40	4	99	148	8	82	207
302	Isiolo	-40	-28	19	-47	-26	11	4	164	251	-11	147	281
303	Kitui	45	45	-9	6	7	-23	33	102	127	29	40	4
304	Machakos	10	41	57	-28	20	52	65	120	345	65	85	196
305	Marsabit	14	-59	-76	17	-55	-72	-82	71	122	-70	86	166
306	Meru	-2	10	38	-5	4	41	69	98	42	76	103	43
	EASTERN	20	24	10	-3	2	4	39	102	136	40	73	68
	Nairobi Area	64	0	36	64	14	59	59	68	145	68	68	155
501	Garissa	-17	-41	-82	-3	-34	-76	-82	-28	-92	-74	-24	-89
502	Mandera	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
503	Wajir	-67	0	-33	-100	-100	-67	-100	-33	67	-67	33	467
	NORTH-EAST.	-18	-39	-80	-5	-36	-76	-83	-28	-88	-74	-23	-76
601	South Nyanza	19	8	10	19	10	14	17	17	12	20	17	16
602	Kisii	11	38	54	12	38	55	76	17	74	74	17	74
603	Kisumu	10	11	11	11	11	12	11	10	1	13	10	8
604	Siaya	8	4	-1	8	7	3	0	11	-8	1	12	-2
	NYANZA	14	11	14	14	13	16	20	14	13	21	14	18
701	Baringo	-2	-25	-23	-2	-23	-20	-27	17	-14	-24	20	-9
702	Elgeyo Mar.	2	-10	-9	3	-10	-7	-12	19	-10	-10	20	-4
703	Kajiado	40	53	70	36	42	66	71	91	140	72	85	165
704	Kericho	9	16	20	9	15	20	28	15	21	29	16	25
705	Laikipia	4	-42	-59	6	-43	-58	-66	57	-34	-64	69	-25
706	Nakuru	15	1	5	17	4	11	3	25	10	9	29	12
707	Nandi	8	2	18	8	3	19	26	-3	-6	27	0	3
708	Narok	1	-22	-29	3	-16	-18	-19	18	15	-7	25	26
709	Samburu	-3	-35	-33	-3	-33	-30	-42	96	-3	-38	112	8
710	Trans-Nzoia	7	3	8	7	3	8	14	6	8	13	8	10
711	Turkana	-15	-36	-34	-15	-35	-32	-44	166	177	-38	192	222
712	Uasin Gishu	10	14	14	11	14	15	14	7	-5	14	11	0
713	West Pokot	3	-10	-4	4	-9	-3	-4	14	5	-2	16	11
	RIFT VALLEY	6	-9	-9	7	-8	-5	-6	22	7	-2	27	15
801	Bungoma	15	29	34	16	32	39	30	40	18	38	49	27
802	Busia	22	15	18	22	18	22	8	13	2	23	31	-1
803	Kakamega	13	47	56	14	52	70	40	42	19	47	42	24
	WESTERN	16	34	41	16	39	50	30	35	15	39	42	20
	KENYA TOTAL	9	-2	-4	8	-2	-1	-1	20	12	3	22	16

Table A4.2c Impacts on extents with rainfed cultivation potential, by province and district for transient climate change scenarios (% change)

		MPTR D2 330	GFTR D2 330	UKTR D2 330	MPTR D2 460	GFTR D2 460	UKTR D2 460	MPTR D3 330	GFTR D3 330	UKTR D3 330	MPTR D3 550	GFTR D3 550	UKTR D3 550
101	Kiambu	9	25	43	16	30	49	6	-23	91	15	-10	101
102	Kirinyaga	-23	4	-22	-17	9	-20	43	-21	99	75	-2	110
103	Muranga	-19	-2	5	-16	3	11	34	-15	93	48	-15	113
104	Nyandarua	-23	-28	-30	-26	-29	-36	26	-1	-30	25	-1	-32
105	Nyeri	8	24	8	13	31	15	-12	-16	70	1	-6	74
	CENTRAL	-7	4	3	-4	8	6	14	-14	55	25	-8	63
201	Kilifi	-2	-5	-31	-1	-3	-33	-22	-32	-31	-14	-29	-24
202	Kwale	11	16	-28	15	18	-25	-8	-3	-11	3	9	-3
203	Lamu	9	13	-28	19	20	-28	-27	-34	-30	-24	-31	-32
204	Mombasa	0	0	-24	0	0	-8	-7	-28	-6	-8	-20	-1
205	Taita	52	65	12	53	66	14	37	70	89	46	71	94
206	Tana River	36	41	-31	41	42	-32	-12	-3	-5	-9	13	-1
	COAST	16	20	-21	19	22	-21	-7	-2	0	2	4	5
301	Embu	46	47	58	24	18	29	58	20	530	39	2	546
302	Isiolo	81	42	109	53	25	66	57	64	958	55	38	1004
303	Kitui	75	53	52	6	-39	0	65	116	28	-30	-1	71
304	Machakos	28	-13	317	-7	-48	312	94	29	1065	44	-4	1156
305	Marsabit	114	122	66	101	118	65	93	79	120	118	98	145
306	Meru	27	-8	97	21	-21	102	23	19	230	32	20	229
	EASTERN	55	29	106	17	-21	83	58	66	285	14	13	319
	Nairobi Area	18	41	18	18	36	18	82	45	177	95	23	227
501	Garissa	-6	-18	-85	15	-14	-76	-50	-38	-64	-41	-35	-46
502	Mandera	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
503	Wajir	67	100	-100	-67	0	-100	33	-100	67	167	133	133
	NORTH-EAST.	-4	-14	-85	13	-15	-77	-48	-40	-62	-36	-32	-41
601	South Nyanza	16	-3	-2	16	-2	0	23	-2	0	25	0	2
602	Kisii	-15	-26	-19	-4	-19	-13	48	7	-14	48	9	-9
603	Kisumu	-3	-16	-14	-4	-14	-13	11	-6	-4	14	-5	-4
604	Siaya	9	-5	-7	10	2	-3	3	5	-2	9	8	-2
	NYANZA	7	-9	-8	8	-5	-5	19	0	-3	22	2	-2
701	Baringo	3	7	16	4	8	17	11	-7	6	14	-3	7
702	Elgeyo Mar.	4	6	12	5	6	11	16	-4	1	18	-2	3
703	Kajiado	61	52	221	69	53	235	89	69	862	90	78	910
704	Kericho	-23	-29	-18	-24	-30	-20	14	-7	-34	17	-4	-33
705	Laikipia	28	78	93	31	88	101	55	17	127	66	19	133
706	Nakuru	8	4	7	10	4	8	23	-3	0	28	-1	4
707	Nandi	-15	-29	-28	-15	-28	-30	9	-13	-28	11	-12	-34
708	Narok	7	8	34	11	13	37	15	7	42	20	15	46
709	Samburu	25	79	201	31	82	220	123	26	326	142	37	323
710	Trans-Nzoia	-4	-27	-28	-3	-25	-25	9	-15	-28	11	-14	-27
711	Turkana	132	181	947	141	192	985	352	125	1518	392	139	1606
712	Uasin Gishu	8	-23	-15	8	-25	-16	5	-23	-41	8	-27	-43
713	West Pokot	0	-7	2	0	-6	3	13	-6	4	15	-6	7
	RIFT VALLEY	6	5	28	8	7	30	22	0	51	27	4	55
801	Bungoma	29	21	-6	31	22	-5	21	48	16	28	53	20
802	Busia	32	60	49	37	62	52	21	40	48	31	53	49
803	Kakamega	20	4	-10	23	9	-9	31	33	4	40	38	4
	WESTERN	26	21	4	29	24	5	26	39	17	34	46	19
	KENYA TOTAL	11	8	15	11	8	16	18	5	46	21	6	52

Table A4.3 Estimates of land with rainfed crop production potential in Kenya and individual provinces for the various climate change scenarios

KENYA

CLIMATE SCENARIOS		C1 (km^2)	C2 (km^2)	C3 (km^2)	C4 (km^2)	Total (km^2)	Weighted Total	% change
Reference		12812	9121	18253	35340	75526	41826	-
GSA	GSA 2010-330	15626	9956	18028	36201	79811	45452	9
	GSA 2030-330	14245	8347	15913	33727	72232	40820	-2
	GSA 2050-330	15553	8150	14838	30271	68813	40225	-4
	GSA 2010-405	15937	10316	17241	35216	78710	45277	8
	GSA 2030-460	14710	9344	14329	33294	71677	41036	-2
	GSA 2050-530	16442	9231	13990	29905	69568	41362	-1
GCM-E	GISS 2E 330	16781	7768	15217	30792	70557	41540	-1
	GISS 2E 550	17533	8995	14180	31863	72570	43027	3
	GFDL 2E 330	17904	10398	19235	40299	87837	50110	20
	GFDL 2E 550	19268	11780	16715	39522	87284	50890	22
	UKMO 2E 330	13820	8248	22726	41941	86736	46841	12
	UKMO-2E 550	17045	10439	17735	40320	85538	48457	16
GCM-T D2	MPTR 2 330	14450	9970	19170	40606	84196	46389	11
	MPTR 2 460	14989	10568	18437	38932	82926	46428	11
	GFTR 2 330	12631	10843	16993	44562	85028	45359	8
	GFTR 2 460	13472	11704	15913	41598	82687	45281	8
	UKTR 2 330	14503	8669	21948	44458	89577	48258	15
	UKTR 2 460	15442	9385	20329	43347	88504	48484	16
GCM-T D3	MPTR 3 330	17673	10742	17720	40652	86787	49423	18
	MPTR 3 550	19539	12086	16407	37903	85934	50688	21
	GFTR 3 330	12525	9826	17806	41591	81748	43923	5
	GFTR 3 550	13688	11398	16449	37995	79529	44356	6
	UKTR 3 330	20045	11635	26077	52519	110276	61088	46
	UKTR 3 550	22120	12195	25827	52718	112859	63526	52
T Sensitivity	T10 (+1°C)	14458	7816	17160	34068	73502	41426	-1
	T20 (+2°C)	15881	7831	15348	30910	69969	40801	-2
	T30 (+3°C)	16362	7479	14011	28884	66736	39590	-5
	T40 (+4°C)	16129	6990	13084	25788	61992	37430	-11
	T50 (+5°C)	15420	6883	11981	23554	57839	35280	-16

Note: Results are presented in terms of four productivity classes, C1 to C4 referring to land where attainable yields reach 80-100 percent of maximum attainable yield (MAY), 60-80 percent, 40-60 percent and 20-40 percent respectively. Crops producing yields of less than 20 percent of MAY are considered economically not viable and are not included in the estimates

Table A4.3 **Continued**

CENTRAL PROVINCE

CLIMATE SCENARIOS		C1 (km^2)	C2 (km^2)	C3 (km^2)	C4 (km^2)	Total (km^2)	Weighted Total	% change
Reference		789	593	773	3500	5654	2846	-
GSA	GSA 2010-405	1007	794	429	3189	5419	2925	3
	GSA 2030-460	603	495	637	2721	4455	2248	-21
	GSA 2050-530	704	1127	748	2141	4719	2709	-5
GCM-E	GISS 2E 550	815	1422	614	2090	4941	2958	4
	GFDL 2E 550	1072	1308	933	3140	6453	3654	28
	UKMO-2E 550	847	691	1402	3017	5957	3169	11
GCM-T D2	MPTR 2 460	1003	843	629	2149	4624	2724	-4
	GFTR 2 460	1122	1123	437	2490	5172	3068	8
	UKTR 2 460	1067	466	1306	2599	5438	3021	6
GCM-T D3	MPTR 3 550	1123	1278	604	3284	6289	3547	25
	GFTR 3 550	787	608	914	2577	4885	2626	-8
	UKTR 3 550	2211	1873	515	2050	6649	4637	63
T Sensitivity	T10 (+1°C)	851	400	493	3530	5274	2612	-8
	T20 (+2°C)	673	449	368	3676	5167	2452	-14
	T30 (+3°C)	690	798	291	3335	5114	2584	-9
	T40 (+4°C)	766	1340	292	2540	4939	2817	-1
	T50 (+5°C)	896	1692	366	1948	4902	3064	8

COAST PROVINCE

CLIMATE SCENARIOS		C1 (km^2)	C2 (km^2)	C3 (km^2)	C4 (km^2)	Total (km^2)	Weighted Total	% change
Reference		1299	2711	2745	8034	14788	7610	-
GSA	GSA 2010-405	1347	3447	3302	7985	16080	8524	12
	GSA 2030-460	1042	2664	2486	8400	14592	7295	-4
	GSA 2050-530	914	1891	2121	7860	12785	6183	-19
GCM-E	GISS 2E 550	883	1892	2146	7993	12914	6211	-18
	GFDL 2E 550	1137	2032	2100	8300	13569	6650	-13
	UKMO-2E 550	1121	3664	2815	6958	14558	7854	3
GCM-T D2	MPTR 2 460	1489	3869	3305	8226	16889	9076	19
	GFTR 2 460	1422	4288	3357	8064	17131	9310	22
	UKTR 2 460	864	2250	2099	6749	11961	6029	-21
GCM-T D3	MPTR 3 550	1312	3128	2232	8225	14897	7726	2
	GFTR 3 550	1226	3773	2154	7654	14808	7908	4
	UKTR 3 550	2249	1951	2619	8344	15163	8002	5
T Sensitivity	T10 (+1°C)	910	2199	2482	7662	13252	6553	-14
	T20 (+2°C)	592	1672	2133	7055	11453	5429	-29
	T30 (+3°C)	402	1370	1981	6763	10515	4822	-37
	T40 (+4°C)	270	959	2011	5920	9160	4106	-46
	T50 (+5°C)	192	765	1584	5070	7611	3357	-56

Note: Results are presented in terms of four productivity classes, C1 to C4 referring to land where attainable yields reach 80-100 percent of maximum attainable yield (MAY), 60-80 percent, 40-60 percent and 20-40 percent respectively. Crops producing yields of less than 20 percent of MAY are considered economically not viable and are not included in the estimates

Table A4.3 Continued

EASTERN PROVINCE

CLIMATE SCENARIOS		C1 (km²)	C2 (km²)	C3 (km²)	C4 (km²)	Total (km²)	Weighted Total	% change
Reference		16	22	821	5355	6214	2274	-
GSA	GSA 2010-405	25	44	412	5749	6231	2204	-3
	GSA 2030-460	147	84	217	5973	6420	2323	2
	GSA 2050-530	425	125	242	5154	5946	2374	4
GCM-E	GISS 2E 550	557	151	566	6608	7881	3191	40
	GFDL 2E 550	381	267	717	8835	10201	3932	73
	UKMO-2E 550	275	344	1155	7896	9671	3816	68
GCM-T D2	MPTR 2 460	89	105	288	6978	7459	2656	17
	GFTR 2 460	22	48	156	4956	5182	1798	-21
	UKTR 2 460	512	388	869	8592	10361	4160	83
GCM-T D3	MPTR 3 550	194	194	816	5359	6562	2584	14
	GFTR 3 550	165	126	290	6408	6990	2560	13
	UKTR 3 550	1997	1694	3393	13004	20088	9534	319
T Sensitivity	T10 (+1°C)	26	53	999	5643	6721	2503	10
	T20 (+2°C)	155	82	1385	4704	6326	2556	12
	T30 (+3°C)	335	163	1336	3663	5498	2425	7
	T40 (+4°C)	570	175	982	3199	4926	2318	2
	T50 (+5°C)	638	129	900	2875	4543	2196	-3

NORTH-EAST PROVINCE

CLIMATE SCENARIOS		C1 (km²)	C2 (km²)	C3 (km²)	C4 (km²)	Total (km²)	Weighted Total	% change
Reference		0	63	29	188	280	127	-
GSA	GSA 2010-405	0	62	24	177	263	120	-6
	GSA 2030-460	0	37	23	121	181	81	-36
	GSA 2050-530	0	2	2	84	89	30	-76
GCM-E	GISS 2E 550	0	4	4	82	90	32	-75
	GFDL 2E 550	0	52	24	135	211	98	-23
	UKMO-2E 550	0	0	0	92	92	30	-76
GCM-T D2	MPTR 2 460	0	73	28	219	321	145	14
	GFTR 2 460	0	74	30	105	209	109	-14
	UKTR 2 460	0	2	2	81	85	29	-77
GCM-T D3	MPTR 3 550	0	41	22	113	176	81	-36
	GFTR 3 550	0	51	24	102	177	87	-31
	UKTR 3 550	0	24	19	137	180	74	-42
T Sensitivity	T10 (+1°C)	0	42	24	90	156	76	-40
	T20 (+2°C)	0	4	4	70	79	28	-78
	T30 (+3°C)	0	0	0	60	60	20	-84
	T40 (+4°C)	0	0	0	37	37	12	-91
	T50 (+5°C)	0	0	0	11	11	3	-98

Note: Results are presented in terms of four productivity classes, C1 to C4 referring to land where attainable yields reach 80-100 percent of maximum attainable yield (MAY), 60-80 percent, 40-60 percent and 20-40 percent respectively. Crops producing yields of less than 20 percent of MAY are considered economically not viable and are not included in the estimates

Table A4.3 **Continued**

NYANZA PROVINCE

CLIMATE SCENARIOS		C1 (km²)	C2 (km²)	C3 (km²)	C4 (km²)	Total (km²)	Weighted Total	% change
Reference		1613	556	2554	3579	8302	4657	-
GSA	GSA 2010-405	2340	736	2497	3029	8603	5309	14
	GSA 2030-460	2240	1164	2100	2858	8362	5264	13
	GSA 2050-530	2544	1002	1789	3295	8629	5415	16
GCM-E	GISS 2E 550	2897	858	1881	3129	8765	5652	21
	GFDL 2E 550	2182	1255	2119	2961	8517	5322	14
	UKMO-2E 550	2969	656	1690	3253	8569	5502	18
GCM-T D2	MPTR 2 460	1864	789	2926	2798	8377	5035	8
	GFTR 2 460	1410	1109	1325	4232	8076	4419	-5
	UKTR 2 460	1277	912	2032	3970	8191	4438	-5
GCM-T D3	MPTR 3 550	2835	1071	1863	2953	8722	5687	22
	GFTR 3 550	1674	1205	1674	3671	8225	4764	2
	UKTR 3 550	1375	923	2294	3653	8245	4585	-2
T Sensitivity	T10 (+1°C)	2084	822	2685	2887	8478	5177	11
	T20 (+2°C)	2665	834	2397	2630	8525	5522	19
	T30 (+3°C)	2877	766	2117	2855	8615	5600	20
	T40 (+4°C)	2810	638	1862	3318	8628	5446	17
	T50 (+5°C)	2592	701	1605	3660	8558	5248	13

RIFT VALLEY PROVINCE

CLIMATE SCENARIOS		C1 (km²)	C2 (km²)	C3 (km²)	C4 (km²)	Total (km²)	Weighted Total	% change
Reference		8882	4435	9251	11776	34343	21396	-
GSA	GSA 2010-405	10404	4324	8615	12708	36051	22789	7
	GSA 2030-460	8638	4263	7173	11549	31623	19788	-8
	GSA 2050-530	9205	4569	7532	10013	31320	20280	-5
GCM-E	GISS 2E 550	10370	3956	7245	10328	31899	20914	-2
	GFDL 2E 550	12219	5967	9954	14081	42221	27083	27
	UKMO-2E 550	10917	4140	8653	16845	40555	24559	15
GCM-T D2	MPTR 2 460	8995	3875	10078	16301	39250	23041	8
	GFTR 2 460	8063	4023	9687	19141	40914	22954	7
	UKTR 2 460	10920	4602	13138	17824	46484	27739	30
GCM-T D3	MPTR 3 550	12248	5410	9837	15651	43147	27137	27
	GFTR 3 550	7529	4576	10308	16036	38449	22160	4
	UKTR 3 550	12880	4914	16092	22626	56512	33184	55
T Sensitivity	T10 (+1°C)	9822	3497	8529	11764	33612	21201	-1
	T20 (+2°C)	10183	3943	7456	10808	32391	20994	-2
	T30 (+3°C)	10184	3610	6726	10357	30878	20180	-6
	T40 (+4°C)	9984	3113	6369	8769	28235	18866	-12
	T50 (+5°C)	9671	3064	5652	7765	26152	17782	-17

Note: Results are presented in terms of four productivity classes, C1 to C4 referring to land where attainable yields reach 80-100 percent of maximum attainable yield (MAY), 60-80 percent, 40-60 percent and 20-40 percent respectively. Crops producing yields of less than 20 percent of MAY are considered economically not viable and are not included in the estimates

Table A4.3 Continued

WESTERN PROVINCE

CLIMATE SCENARIOS		C1 (km^2)	C2 (km^2)	C3 (km^2)	C4 (km^2)	Total (km^2)	Weighted Total	% change
Reference		213	742	2081	2842	5878	2893	-
GSA	GSA 2010-405	813	908	1962	2273	5956	3366	16
	GSA 2030-460	2040	636	1683	1618	5977	4009	39
	GSA 2050-530	2645	499	1546	1324	6013	4333	50
GCM-E	GISS 2E 550	2004	689	1715	1608	6017	4028	39
	GFDL 2E 550	2276	899	850	1987	6013	4109	42
	UKMO-2E 550	911	930	1996	2171	6008	3466	20
GCM-T D2	MPTR 2 460	1548	1014	1178	2188	5929	3720	29
	GFTR 2 460	1433	1038	913	2535	5919	3592	24
	UKTR 2 460	803	765	880	3461	5909	3040	5
GCM-T D3	MPTR 3 550	1827	965	1017	2213	6022	3880	34
	GFTR 3 550	2306	1058	1068	1493	5925	4219	46
	UKTR 3 550	1366	810	875	2856	5907	3434	19
T Sensitivity	T10 (+1°C)	764	803	1949	2416	5931	3276	13
	T20 (+2°C)	1613	845	1604	1899	5962	3794	31
	T30 (+3°C)	1873	773	1560	1798	6004	3940	36
	T40 (+4°C)	1724	747	1562	1986	6020	3834	33
	T50 (+5°C)	1428	516	1869	2207	6021	3603	25

Note: Results are presented in terms of four productivity classes, C1 to C4 referring to land where attainable yields reach 80-100 percent of maximum attainable yield (MAY), 60-80 percent, 40-60 percent and 20-40 percent respectively. Crops producing yields of less than 20 percent of MAY are considered economically not viable and are not included in the estimates