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Working Paper

CLIMATE CHANGE AND GLOBAL AGRICULTURAL POTENTIAL PROJECT:

A CASE STUDY OF KENYA

Gunther Fischer and Harry T. van Velthuizen

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ACRONYMS AND ABBREVIATIONS

AEZ	Agro-Ecological 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 Meteorological 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-ecological 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 main reasons being:

- Exceeding optimal temperature ranges for photosynthesis and growth;
- Shortening of cereal growth cycles and periods of yield formation;
- Increased 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 impacts 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 central and western Kenya will dominate the agricultural production potential even more under projected climate change conditions. The main reasons of positive impacts appear to be:

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

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

Despite of overall positive effects for Kenya as a whole, impacts of climate change on land productivity may 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 protection 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-ecological 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-ecological 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-ecological 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 critical 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 natural resources management.

Agro-ecological 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 individual 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-ecological 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 individual 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-ecological 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 general 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 Meteorological 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.

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[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 biological processes, together with research into the problems of up-scaling of research results obtained at micro level (e.g., individual 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-ecological 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 natural 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 1, 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 Meteorological 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-ecological cells, which form the basic unit of analysis used in AEZ applications. The collection of agro-ecological 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 requirements:*** To assess the suitability of soils for individual 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 internal 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 marginal 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-ecological 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-ecological cell 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-ecological 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.

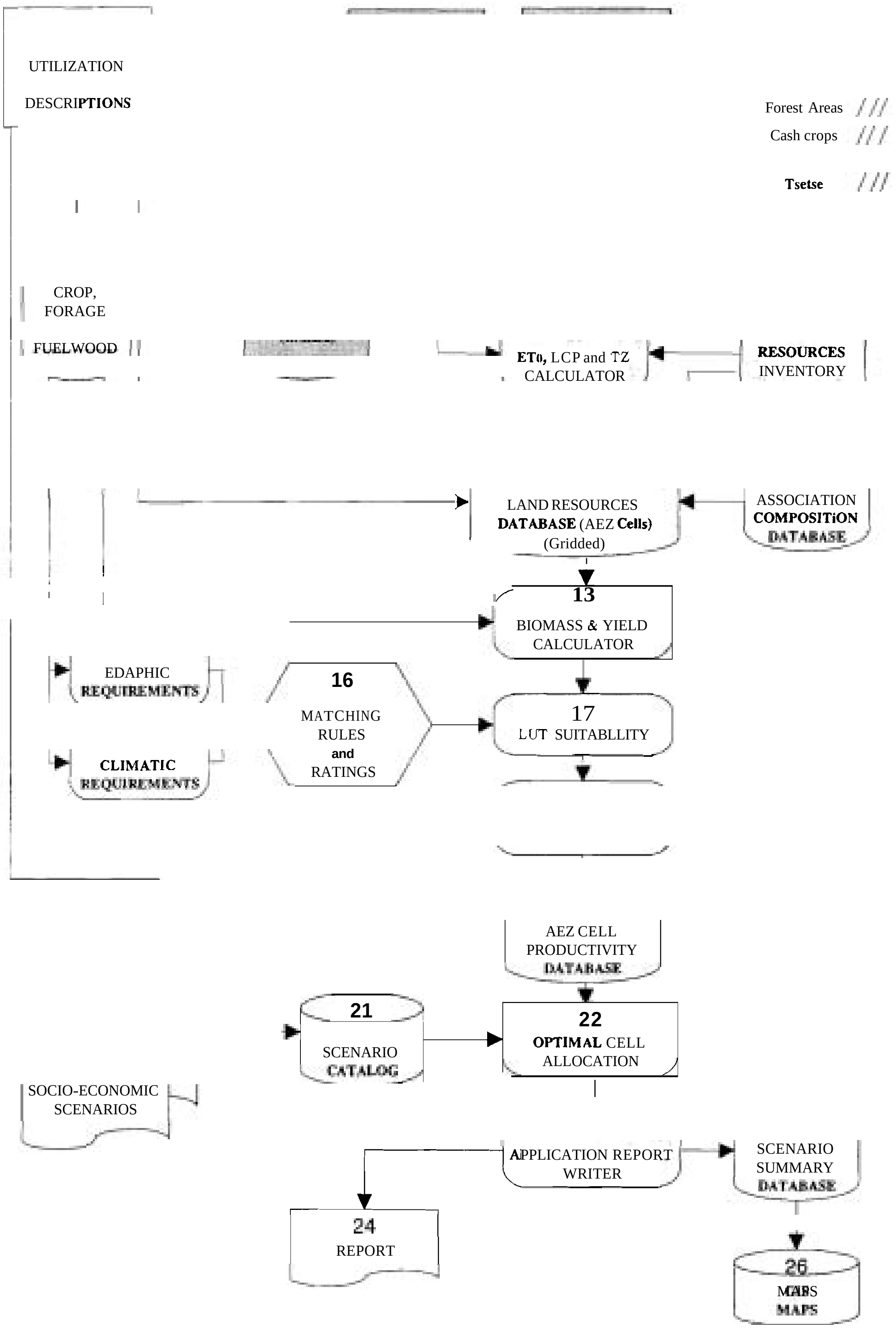
(19) ***AEZ cell productivity database:*** The productivity assessment records input level specific production of relevant and agro-ecologically feasible land utilization activities. The stored information includes a quantification of main produce and by-products, input requirements and estimates of 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-ecological cell 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 evapotranspiration*

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.

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 IV (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-ecological 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 individual 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 general 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 several complex and intertwined factors determining overall land productivity. These include changes of attainable yield levels and production potential of individual 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 individual 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 individual 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 several 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-ecological zones approach developed in this study appears most appropriate to capturing the diverse impacts that may affect the agricultural production potential in different ecological 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 provincial level occur in several 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.

- Impacts are usually positive for Central 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 central 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