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CLIMATE CHANGE AND GLOBAL AGRICULTURAL POTENTIAL

A case study of Nigeria

by

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Abstract

This study presents a spatially specific assessment of the potential impacts of the greenhouse effect on crop production potentials and land productivity in Nigeria. To this effect a large number of scenarios were used consisting of results from experiments with General Circulation Models (GCM's) as well as sensitivity scenarios in which single variables were changed. Each scenario is characterised by level of increase of atmospheric CO_2, change of stomatal resistance and climate change in terms of temperatures, rainfall and radiation. The effects of such changes have been assessed within the framework of the agro-ecological zones methodology, that was adapted and expanded for the purpose of the present study. Climate changes are applied to observed baseline conditions for the period 1960-1990 and simulated climate is used in combination with soil and landform conditions, plant physiological adaptations to elevated CO_2 and a number of sustainability criteria (e.g. fallow period requirements) to calculate crop production potentials and land productivity. Scenario outputs are compared with current conditions to asses potential impacts and sensitivity of agricultural production to global change phenomena.

A large number of maps and tables summarise the potential impacts on crop production potentials and land productivity. The low predictive value of GCM's and large differences between GCM's only allow to draw conclusions of policy relevance taking into account a cautionary bandwidth of possible events. The Nigerian middle belt will hardly be affected because changes are likely to be limited and farmers may adapt by choosing other crop varieties. The north of the country is very sensitive to changes of climate and the prevailing crops show little response to elevated CO_2 levels. GCM's are consistent in indicating climatic changes that lower land suitability for perennial crops in the south. The south-west, with a bimodal rainfall tendency, is particularly sensitive to climate change. Here small changes in scenario may cause either one long growing period or two short ones. However, lower productivity due to climate change, if any, is likely to be more than compensated by the effects of enhanced CO_2 levels. Prevalent crops in the south have a C_3 photosynthesis pathway, that is responsive to enhanced CO_2 levels, which is likely to result in increased of productivity of annual crops such as yams and cassava. Global change may thus exacerbate the current disparities of crop production potentials between the north and the south of the country.

Section 1
Introduction

1.1. Background

In the past, global climate has been changing continuously and has shown large fluctuations due to natural causes. Currently however, there is ample evidence of man-induced climate change resulting from increased atmospheric greenhouse gas levels, notably of CO_2, due to the burning of fossil fuels (IPCC, 1996). It is now clear that high emission rates of CO_2 and other greenhouse gasses will continue for some time to come and therefore a further forcing of climatic conditions may be expected. The change of climate, in combination with the effect of elevated CO_2 itself, is likely to cause important changes in agricultural potentials and their geographic distribution. Such changes are not only man-induced, but will also occur within the time scales of human planning and knowledge on the possible effects of global change is therefore of direct policy relevance.

Man-induced global change[1] occurs at a time when various other factors negatively affect the agricultural production systems of tropical developing countries. Most of the economies in this part of the world are largely based on agriculture. They are faced with rapidly increasing population numbers and consequently increased demand for food, fiber and industrial crops. Currently, agriculture is expanding into marginal areas and land already in use is cultivated more frequently. The latter often occurs without increasing input levels substantially, because of unfavourable socio-economic conditions and the tight cash constraint that most farmers concerned face. This situation results in low crop yields, low food supplies and more generally widespread poverty, but at the same time also puts the environment under great stress as is expressed for instance by massive forest destruction, soil nutrient mining and soil erosion (e.g. Stoorvogel et al., 1993). This in turn compromises attainable crop yields in the future. Whether or not global change will put yet an other constraining factor on development, through its effect on crop production potentials and land productivity, is therefore an important issue for policy planning in these countries.

A number of studies have now been conducted to assess the possible impact of global change (for a summary see Fischer and Van Velthuizen, 1996). Most of these use results from experiments with general circulation models (GCM). Apart from that, such studies differ markedly in terms of use of baseline data and methods of analysis. They vary from detailed point-wise analysis for individual crops or even varieties with crop models that are highly demanding in terms of data, to continental and global scale studies aimed at mapping for instance the likely shifts of broadly defined vegetation zones. However, land use and agricultural policies are mostly designed at the national level for sub-national entities (Keyzer and Voortman 1998) and policy planning therefore requires spatially explicit information within national boundaries.

The present study therefore takes an intermediate position and applies and tests a methodology for the country-wide and spatially explicit assessment of the effect of global change in Nigeria. Nigeria is a tropical developing country with the largest population of sub-Saharan

[1] The title of this paper is derived from the name of the project. Throughout the text *global change* is used to refer to combined effects of climate change and increased atmospheric CO_2 levels. *Climate change* is used when only the change of climatic variables is implied.

Africa. At present, it has a large variation in agro-ecological conditions, from tropical humid lowlands in the South to arid conditions in the North, and it includes some highland areas.

The study assesses the possible impacts of global change on potential crop production and land productivity on the basis of results from GCM experiments and single climatic variable sensitivity tests in combination with systematic nation-wide inventories of current climate as well as soil and landform conditions. It applies existing knowledge on the effects of global change on land productivity in an integrated manner and it is comprehensive in terms of coverage of factors affecting agricultural production. The methodology also distinguishes between levels of agricultural technology and for instance takes into account that under low input levels land needs to be set aside for fallows to restore the fertility of soils. A large variety of relevant crops is considered and this in combination with the above model features, allows the assessment of implications for development planning at the national level, including the options of farmers to switch crops, expansion of cultivated area, changing cropping intensity and the sensitivity to technological growth and crop variety development.

The main objectives of the present study are threefold. Firstly, it aims at further development and testing of a comprehensive and spatially explicit methodology for assessing the possible impacts of global change on potential crop production and land productivity at the national level. Secondly, it seeks to quantify current and possible future agricultural production conditions in Nigeria and to identify potential threats and opportunities for agricultural development that allow the design of policies for sub-national levels. Thirdly, it pursues improvements of Agro-Ecological Zones methodology proper.

1.2 Project organization

The present study is part of the FAO-initiated and FAO/IIASA/SOW-VU financed 'Climate change and Global Agricultural Potential Project' that aims at further development and testing of the FAO Agro-Ecological Zones (AEZ) methodology (see section 3) for the purpose of assessing global change impacts on agricultural production in developing countries. The project was implemented by SOW-VU and IIASA in collaboration with the Federal Department of Agricultural Land Resources (FDALR), Abuja, Nigeria. Other country-wide studies using AEZ-based methodology conducted within this project framework deal with Kenya and Bangladesh. The Kenya project (Fischer and Van Velthuizen, 1996) served as a pilot study where a large part of methodological development took place.

1.3 Structure of the report

Section 2 briefly summarizes research concerning the effects of global change on plant physiology, ecosystem functioning and consequently crop performance, which provides the guiding principles for adaption of the AEZ methodology for the present purpose. This is followed by a brief description of the global change scenario's of the study and the methods used to obtain a spatial representation of their impact on climatic conditions. Section 3 deals step-wise with the adaptation and implementation of the AEZ methodology for the purpose of this study. Results are presented in section 4. First the effect of global change on climatic resources is dealt with, followed by a discussion of the impact of climate change and elevated CO_2 on crop production potentials and land productivity. Section 5 concludes. We have opted for a concise main report and more detailed information is presented in various annexes.

Section 2

Global change effects and global change scenario's for Nigeria

2.1 Global change effects on the environment and agriculture

Global change due to increasing levels of greenhouse gasses in the atmosphere has a number of interrelated effects on plant growth, and consequently on land productivity. First, the increase of atmospheric CO_2 itself affects plant growth directly in terms of phenology and biomass production. Secondly, elevated CO_2-levels induce stomatal closure, leading to higher water use efficiencies. The effect of both phenomena varies with crop species and is related to their photosynthetic pathway. In addition, global change is expected to affect climatic variables such as temperature, precipitation, humidity and consequently evapotranspiration. Changes in terms of these variables impact on plant growth either directly, e.g. through effects of temperature on photosynthesis, or indirectly through changes in the water balance and consequently the duration of moisture availability that allows plant growth. The effect of changing basic climatic variables is again crop specific and related to both their photosynthesis pathway and their growth cycle length. Global change may also have important indirect impacts, because it will affect occurrence and vigor of weeds, pests and diseases. Crop growth and yield levels under conditions of global change will thus be determined by the simultaneous operation of a number of individual phenomena. Net effects will depend on their interactions, in combination with plant nutrient availability, and of course input use and agricultural management. Clearly, the complexity and nature of the issue at hand, suggest that assessments of possible effects of global change on crop yields and land productivity may benefit from an ecosystem functioning perspective.

However, from the onset it should be stressed that the importance of an ecosystem perspective was emphasized only recently (e.g. Körner, 1998). Much of the research on possible effects of atmospheric and climate change has been conducted under artificial conditions in controlled environments, where the effects of only one or a few variables have been studied in isolation (Soussana et al., 1998). Research findings therefore do not always lead to convergence of evidence regarding the possible total impacts of the combination of different phenomena. To some extent, it therefore remains uncertain what will happen under real-world conditions, where all variables are at play simultaneously, and where a 'myriad of unknown feedback's determines responses' (Körner, 1998). Another point that must invoke cautiousness, is that research has often been conducted with annual plants in their early stages of development, while there is considerable evidence that effects disappear with time, because acclimation takes place. Moreover, responses are often non-linear (Körner, 1998; Grünzweig and Körner, 1998), highly species specific (Ellsworth, 1998; Coffin, 1998; Körner, 1998; Jones, 1998) and the response of the same species may vary with the properties of the ecosystem in which it occurs (Körner, 1998; Norby et al., 1998). The effects of global change at the level of individual ecosystems may further be influenced significantly by land and crop management (Lüscher et al., 1998; Niinemets et al., 1998; Walker et al., 1998).

All this calls for a careful examination of global change research findings in order to ensure a proper design of a study aiming at assessing possible effects on crop yields and land productivity. This review is reported in full in Annex 1. The main conclusions and implications for the current study are presented in the following section.

2.2 Implications for the Nigeria case study

The main impact of global change derives from the positive response of photosynthesis to enhanced CO_2 levels, resulting in increased biomass production and crop yield. These responses have been widely observed and can be quantified with reasonable accuracy. In case of C_3-species the temperature dependency of growth rates, related to higher photorespiration rates at higher temperatures as well its inhibition at raised CO_2 levels, has to be accounted for.

With respect to crop phenology we observed a number of feedbacks (acclimation, decreased specific leaf areas, self-shading and leaf turn-over rates), that are likely to largely balance effects of CO_2-induced acceleration of early development. Leaf Area Indexes (LAI) may thus be higher, but less efficient in producing biomass. We therefore maintain currently used maximum Leaf Area Indexes (LAI) and their relation to crop growth.

Changes of assimilate partitioning patterns under elevated CO_2, expressed in root/shoot ratio's, have been extensively documented, but whether this is a direct effect of increased CO_2 itself seems uncertain. The impression exists that such changing patterns are contingent on other factors that become the most limiting resource such as nutrients and water. Although elevated CO_2 generally raises yields and changes assimilate allocation patterns, there is insufficient convergence of evidence that yield quantities in relation to total biomass would change. We therefore maintain currently applicable Harvest Indexes.

Higher water use efficiencies due to both, increased biomass production and reduced water use, have frequently been observed. Reduced water use is caused by increased stomatal resistance under higher atmospheric CO_2 concentrations. Clearly, this phenomenon needs to be accounted for and there is a considerable amount of quantitative information to allow this. However, stomatal resistance is measured at the leaf level and when scaling-up to crop canopy and season level, the reduction of water use observed for leaves may to some extent be balanced by simultaneous increases of biomass and LAI. Because of this, and since LAI's have been kept unchanged, we apply conservative changes to the canopy resistance term used to calculate potential evapotranspiration.

Global change, apart from increased CO_2 levels, entails a CO_2 level-specific change of climate. Possible changes of temperatures, rainfall and radiation are produced by experiments with General Circulation Models (GCM). The AEZ approach standardly deals with these variables and provides the framework to do so in an integrated manner. Thus, new waterbalances are calculated to determine the Length of the Growing Period (LGP) and temperature and radiation characteristics are calculated for its duration. This information is used in a crop growth model to calculate potential biomass production and crop yields under conditions of elevated CO_2. Specific constraints due to very high or too low temperatures are taken into account through thermal zone constraints.

The effect of pests, diseases and weeds is currently taken into account in AEZ through LGP specific agro-climatic constraints. As yet, there is insufficient evidence for a systematic change of the relationship between environmental characteristics (LGP) and incidence of pests, diseases and weeds.

In AEZ the impact of soils on crop yield is assessed by soil genetic group/class. It is unlikely that, within the time frame of concern in this study, soils would change in any significant extent from one group to another due to global change effects. Most changes may be expected in terms of topsoil properties as caused by organic matter dynamics. This might imply a change of soil class, but current knowledge on effects of global change on C and N cycles, organic matter dynamics and numerous feedbacks is limited to extent that even the direction of change of Carbon levels stored in soil organic matter is uncertain. Thus, the current state of knowledge does not allow to draw firm conclusions with respect to soil fertility changes that could be of relevance to crop yield assessments. Nevertheless common principles currently observed also seem to apply under elevated CO_2. In this study we therefore must assume that soil classes remain unaltered and that soil fertility will affect crop yields in a similar manner as it does at present. Maintaining the soil class and crop specific yield reductions of AEZ implies that the full effect of CO_2 fertilization can only be achieved when soil fertility is not limiting and that yield reductions are proportionate to the currently used soil constraints in AEZ methodology.

2.3 Global change scenario's for Nigeria

For the purpose of this study, scenarios of global change were developed to estimate possible effects on crop yields, extents of suitable land and agricultural production. Twelve scenario's are based on IPCC approved experiments with General Circulation Models (GCM) and fourteen refer to sensitivity tests (table 2.1).

The GCM based global change scenario's consist of physically consistent sets of changes in meteorological variables, based on generally accepted projections of CO_2 and other trace gas levels. Each GCM based scenario is characterized by its CO_2 concentration (ppm) and, as discussed in the previous section, can thus be related to crop specific responses of photosynthesis and improvements of water use efficiency due to decreased stomatal conductance (ΔRl). These CO_2-level specific parameters affect both the estimated reference evapotranspiration and the parameterization of the biomass calculation procedures (see Annex 3 and 5). The main output of GCM experiments are CO_2-level specific changes of temperature, radiation and rainfall amount for points on a widely spaced grid.

Transient GCM experiments have been used, that aim at capturing the time-dependent response of climate to time-dependent increases in greenhouse gasses, using coupled ocean-atmosphere models and recent projections of increases of concentrations of greenhouse gasses in the atmosphere (IPCC, 1992), The GCM's used are those of the Geophysical Fluid Dynamics Laboratory (GFTR; Manabe et. al., 1991), of the Hadley Centre (HCTR; Murphy, 1995; Murphy and Mitchell, 1995) and of the Max Planck Institute (MPTR; Cubasch et.al., 1992). These transient GCM's produce projections of future climate for the so-called decade 2 and decade 3 conditions (notation e.g. GFTR2), which refer to a 50 percent increase and a doubling of greenhouse gasses respectively. This in turn implies estimated atmospheric CO_2 concentrations of 460 and 550 ppm (notation e.g. GFTR2-460).

The crop specific impacts of these CO_2-levels is implemented in the biomass production module (see Annex 5). The CO_2-level dependant increase of stomatal resistance was, in accordance with the discussion in Annex 1 and following Fischer and van Velthuizen (1996), conservatively set at 15 and 25 percent for decade 2 and 3 conditions, respectively.

The sensitivity scenario's of the study are defined by changes in terms of single meteorological variables such as monthly temperatures or rainfall. Simulations were done exploring the potential consequences of temperature increases of between 2-4ºC. Precipitation changes were tested in the range of -30% to +30% of baseline conditions. The sensitivity scenario's have been run under two options, being with and without the effects of increased atmospheric CO_2. The characteristics of the scenarios are summarized in table 2.1.

2.4 GCM-derived data and their spatial representation

The GCM projections of future climate are produced on a monthly basis for a relative coarse grid consisting of the following climatic parameters:

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

The values from the coarse GCM grid-points within and around Nigeria have been interpolated to the 2 by 2 km grid of this study in order to allow a spatially explicit assessment of the effects of climate change.

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 observed baseline climate surfaces. Multipliers, i.e., the ratio between GCM climate change and control experiment, were used to impose changes on both precipitation and incident solar radiation. These adjustments were determined separately for each three-month period starting in December, i.e., December-January- February, March-April-May, etc., and for the year as a whole. The quarterly disturbance terms were scaled such, that the application to monthly climate attributes matches calculated annual changes. This method of generating climate scenarios captures the seasonal characteristics of GCM experiments, but largely avoids unrealistic multipliers, that could result from differences between GCM control experiments and actual baseline climate conditions for individual months. 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.

Relative humidity conditions[2] for scenario runs have been estimated by using a reliable regression between monthly values of relative humidity and selected climate parameters from the observed baseline data: rainfall, sunshine duration/global radiation and maximum temperature at sea level. The windrun data were kept unchanged from baseline values for all climate change scenarios.

[2] The regression for relative humidity is based on observations of all 12 months combined and reads as follows: RH=33.9562+100*(1-exp(-.571739E-03*rain))+100*(1-exp(-.075726*(100-sun)))-2.05963*Tmax0.Where rain' is the monthly rainfall, 'sun' is the mean sunshine duration and 'Tmax0' is the mean maximum temperature converted to sea level.

Table 2.1. Global change scenario's for the Nigeria case study

Global	Change	scenario	CO_2	ΔRl	ΔT	ΔP	ΔRg
			(ppm)	%	°C	%	%
GCM	1	GFTR 2-330	330	0	*	*	*
Decade 2	2	GFTR 2-460	460	15	*	*	*
	3	HCTR 2-330	330	0	*	*	*
	4	HCTR 2-460	460	15	*	*	*
	5	MPTR 2-330	330	0	*	*	*
	6	MPTR 2-460	460	15	*	*	*
GCM	7	GFTR 3-330	330	0	*	*	*
Decade 3	8	GFTR 3-550	550	25	*	*	*
	9	HCTR 3-330	330	0	*	*	*
	10	HCTR 3-550	550	25	*	*	*
	11	MPTR 3-330	330	0	*	*	*
	12	MPTR 3-550	550	25	*	*	*
P Sensitivity	13	PP10-330	330	0	0	10	0
	14	PP10-550	550	25	0	10	0
	15	PP30-330	330	0	0	30	0
	16	PP30-550	550	25	0	30	0
	17	PM10-330	330	0	0	-10	0
	18	PM10-550	550	25	0	-10	0
	19	PM30-330	330	0	0	-30	0
	20	PM30-50	550	25	0	-30	0
T Sensitivity	21	T20-330	330	0	2	0	0
	22	T20-460	460	15	2	0	0
	23	T20-550	550	25	2	0	0
	24	T40-330	330	0	4	0	0
	25	T40-460	460	15	4	0	0
	26	T40-550	550	25	4	0	0

* = GCM scenario output (variable in space)
ΔRl = change in stomatal resistance (%)
ΔT = change in temperature (absolute)
ΔP = change in precipitation (%)
ΔRg = change in global radiation (%)

Section 3

Agro-Ecological Zones methodology for global change impact assessment: the case of Nigeria

3.1 Basic principles and approach

The basic principles of the FAO Agro-Ecological Zones methodology (AEZ) have been adopted as the point of departure for further methodological developments, because AEZ provides a methodology for establishing a spatial inventory and database on land resources and crop production potential, which can be applied at a national level in a systematic manner. Data requirements are limited and readily available data are used to the maximum. Moreover, AEZ is comprehensive in terms of coverage of factors affecting agricultural production.

The FAO Agro-Ecological Zones (AEZ) methodology and the results for Africa were published in 1978 (FAO, 1978). Ever since, in more detailed country-wide and specific purpose studies the methodology has been further developed, albeit adhering to the overall approach (Kassam et al., 1982; Brammer et al., 1988; Kassam et al., 1992; Higgins et al., 1983; Shah et al., 1985; FAO, 1990; FAO/IIASA, 1993; Voortman and Buurke 1995). The present study builds upon the most recent grid-based version of the methodology developed over time at IIASA during the Kenya AEZ study (Kassam et al., 1992) the Kenya global change case study (Fischer and Van Velthuizen, 1996) and the Global AEZ study (Fischer et al., 1999).

Cornerstone of the AEZ methodology is the Length of the Growing Period (LGP). The LGP quantifies, on the basis of a water balance model, the duration of the period when sufficient moisture is available to sustain crop growth. The LGP is defined as the duration (in days) of the period when temperature permits plant growth and soil moisture supply exceeds half potential evapotranspiration (P > 0.5 PET). This definition of the LGP, in combination with common rainfall distribution patterns, takes into account that crop water requirements in the early growth stages and at maturation/ripening are less than full PET and that in between the requirements are near full PET. The used algorithm determines the number and type of growing periods per year (LGP pattern), start and end dates for each growing period and moisture excess and deficits during the entire LGP and parts of it. Growing periods that include a sub-period when precipitation exceeds full potential evapotranspiration are termed normal LGP's as compared to intermediate LGP's where rainfall exceeds 0.5 PET, but does not reach full PET. Such differences of LGP type are taken into account when assessing crop yield potentials (FAO, 1978-81).

Other environmental factors that directly affect crop growth, like temperature and radiation, are quantified for the duration of the LGP. If these factors meet with the crop physiological requirements then temperature, radiation and the duration of moisture availability are applied, in combination with crop physiological properties, in a crop growth model that calculates constraint-free biomass production and potential yields, under the assumption that other conditions are optimal (Kassam, 1977).

Constraint-free yields are combined with a number of other factors like climate-related constraints, soil and landform conditions to arrive at attainable crop yields. The method used is semi-quantitative, similar to parametric approaches of land evaluation (Riquier, 1974). The so-called agro-climatic constraints refer to factors that are known to considerably affect crop yields and management, but as yet they can not be fully quantified. The constraints deal with the likely effects of (i) variability of LGP length, (ii) quality of moisture supply during the LGP, (iii) occurrence of pests, diseases and weeds, and (iv) limitations of humid conditions for harvesting, handling and storage of produce. Presence and severity of agro-climatic constraints are crop and input level specific and linked to the location specific LGP. Thus, the application of agro-climatic constraints reduce constraint-free yields and result in climatic yield potentials that vary with crop, environmental conditions (LGP) and level of technology.

AEZ-type studies require soil information with full spatial coverage, as usually obtained from soil maps. Such maps show the geographic extent of soil types and associations, and relevant soil properties are derived from the classification and class limits used to characterize soil types. Soil class characteristics usually include aspects like texture, soil chemistry, drainage conditions, salinity and alkalinity, that, directly or indirectly, affect crop growth. The AEZ methodology often uses the inherent properties of the soil types defined for the FAO/UNESCO soil map of the world (FAO/UNESCO, 1974). A reduction factor is applied to the climatic potential when soil type properties are sub-optimal and/or when other known soil conditions, not implied by soil type itself, like topsoil texture, soil phase or landform, are limiting yield potentials. The semi-quantitative reduction factors are crop specific and vary again with level of inputs/management to reflect the extent to which technology levels can address soil limitations.

Overall effects of level of inputs/management on attainable crop yields are taken into account by scaling factors. In reality there are numerous combinations of input levels and management and these can be accommodated as long as they can be linked to maximum attainable yield levels. However, usually it is more practical to consider a limited number of sets of pre-defined, standardized and internally consistent production circumstances for which well established scaling factors have been developed. These production settings define, together with the crop(s), Land Utilization Types (LUT's), the basic unit of assessment in AEZ methodology.

The fact that Land Utilization Types are crop specific implies that crop requirements have to be defined in detail in terms of agro-climatology, agro-climatic constraints and soil/landform properties, and specifically for each level of inputs/management. These requirements define optimal and prohibitive conditions as well as the effect of suboptimal land resource conditions on crop yield.

The AEZ approach thus, in a systematic manner, considers crop requirements, climate, soil properties, landform and level of inputs/management to assess attainable crop yields. Because of its comprehensive coverage of factors affecting production and its spatially explicit nature, it is expected to be suitable as the coherent analytical framework, needed to assess the effect of global warming on land productivity at a country-wide level.

The procedures followed in this AEZ study are presented in fig. 3.1. It shows how first basic inventories are converted to a gridded databases which are combined into a land resource inventory that includes all aspects of soil and climatic resources. Such inventories are created for both baseline conditions and for scenario's of projected climate change. Production potentials and land productivity are assessed for land utilization types that combine crop types and production settings. These imply crop physiological characteristics for instance referring to photosynthesis pathway and the response to elevated CO_2 levels, but also define technology levels and consequently attainable yield levels. The land utilization types further define climatic and edaphic requirements and the response in terms of yield to sub-optimal conditions, as well as the extent to which farmers can deal with certain agro-climatic and soil constraints. Technology levels also have implications for fallow period requirements.

The land utilization type characteristics and requirements are, in a sequence of steps, matched with the inventory of natural resource characteristics. First potential biomass production and constraint-free yields are calculated, then the agro-climatic yield potentials are determined and this is followed by accounting for soil properties and constraints. Sustainable land productivity is then calculated on the basis of attainable crop yields, sustainability criteria referring to soil erosion hazard and the requirements to set land aside as fallow in order to restore soil fertility (in case of low external input conditions). This sequence of work is followed for baseline and scenario conditions and the last step is the comparison of the results in terms of crop production potential and land productivity. The following sections describe, within this framework, the issues that are specific to the Nigeria country study, the methodological adaptations made to allow an assessment of the impact of global change, as well as methodological improvements in AEZ proper.

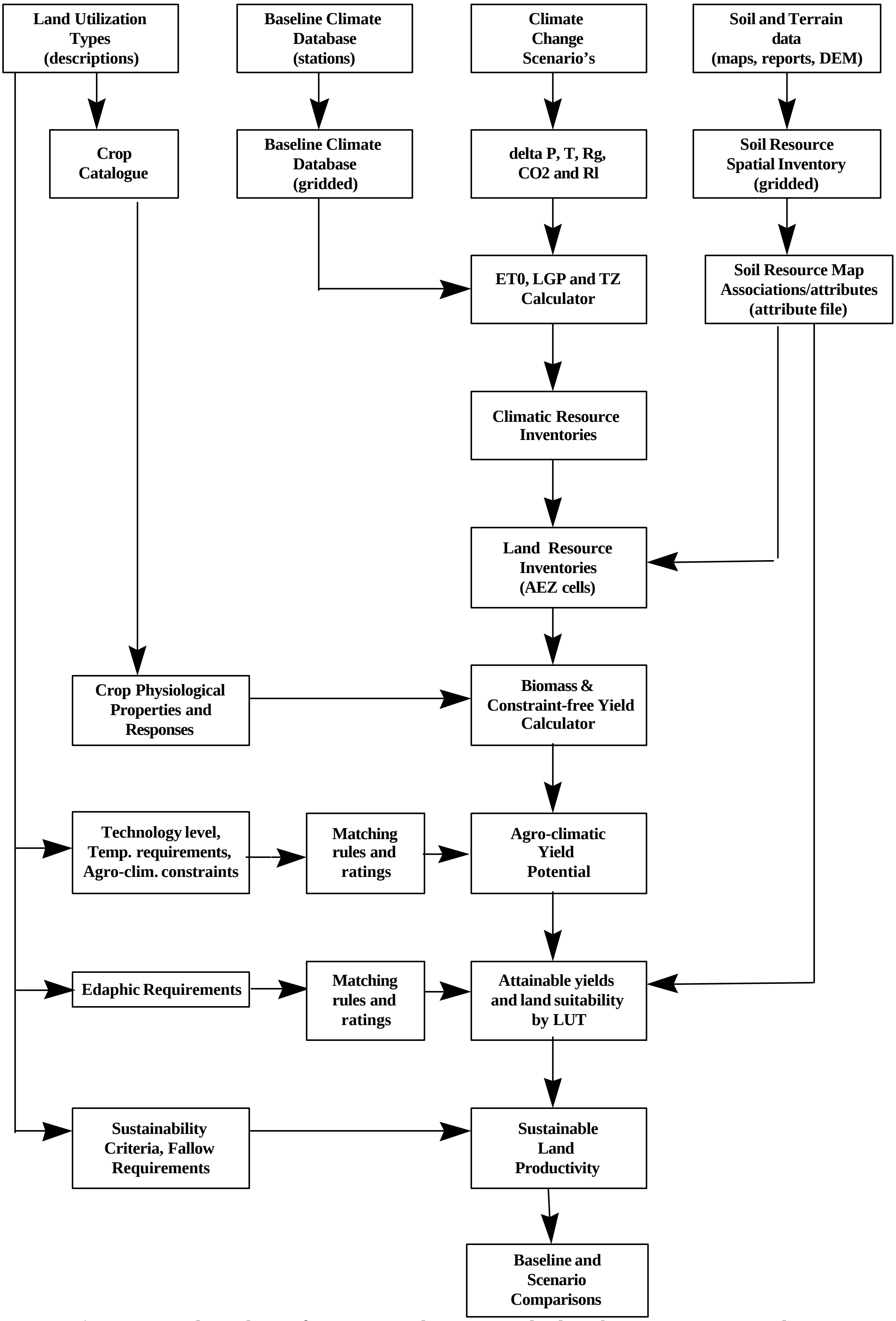


Figure 3.1: Flow chart of AEZ procedures as applied in the Nigeria case study

3.2 Land utilization types and crops

Land Utilization Types

The first step in an AEZ application is the selection and description of land utilization types (LUT's), followed by the definition of their soil and climatic requirements. LUT descriptions comprise sets of alternative activities available to achieve specified objectives, i.e. usually the production of crops in combination with a set of technical specifications within a socio-economic setting. (FAO, 1984).

Of necessity, the setting of agricultural production needs to be standardized in the present study to allow comparisons of land productivity under different scenario's. It also needs to be relatively simple because neither current nor future production conditions can be specified with any precision for an entire country. It is common practice in AEZ, to define generalized levels of input use and management like high, intermediate and low. Such levels link attainable yield levels with a coherent set of production circumstances referring to market orientation (subsistence/commercial), capital intensity, labour intensity, power sources (manual labour/mechanization), technology employed (local/high yielding varieties, fertilizer use, use of agro-chemicals, fallow period requirements), market accessibility, level of advisory services and size and fragmentation of land holdings. The databases and assessment criteria that have been developed in this study consider these three levels of input/management circumstances and their settings are presented in table 3.1.

With respect to produce, a selection of 18 crops has been made in collaboration with the Nigerian Federal Department of Agricultural Land Resources, based on current importance, the need for a balanced diet and possible future potentials (table 3.2). At three input levels this results in 54 land utilization types. Two crop species, maize and sorghum, are subdivided in tropical and temperate/highland varieties, because these differ in temperature and LGP requirements. For Phaseolus beans lowland tropical species have not been considered. Each crop species is represented by a number of varieties of different growth cycle duration, which are separately matched to environmental conditions. In total 50 crop varieties have been used.

Three Yam species (Dioscorea rotundata, D. alata and D. cayenensis) commonly grown in Nigeria are new to AEZ type studies. Pertinent to the definition of low and intermediate input/management circumstances of these crops are staked production conditions. Under high inputs un-staked conditions are assumed because staking hampers mechanized harvesting. The greater Leaf Area Index due to staking is separately stored in the crop catalogue and the assessment of yams also accounts for the large volumes of economic produce that have to be reserved for planting material.

Crop characteristics

Crop characteristics of relevance to the present study are maintained in a crop catalog, a computer representation of the quantitative aspects of the LUT descriptions in a database format. The crop catalog database includes parameters describing temperature requirements of crops, 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 etc.. Maximum constraint-free yield

Table 3.1: Setting and attributes of land utilization types

Attribute	Low inputs	Intermediate inputs	High inputs
Produce and production	Rainfed cultivation of crops of this study. Sole and multiple cropping only in appropriate cropping patterns and rotations		
Market orientation	Subsistence production	Subsistence production plus commercial sale of surplus	Commercial production
Capital intensity	Low	Intermediate with credit on accessible terms	High
Labour intensity	High, including uncosted family labour	Medium, including uncosted family labour	Low, family labour costed if used
Power sources	Manual labour with hand tools	Manual labour with hand tools and/or animal traction with improved implements; some mechanization	Complete mechanization including harvesting
Technology	Traditional cultivars No fertilizer or chemical pest, disease and weed control. Fallow periods. Minimum conservation measures	Improved cultivars as available. Appropriate extension packages including some fertilizer application and some chemical pest, disease and weed control. Some fallow periods and some conservation measures	High yielding cultivars including hybrids. Optimum fertilizer application. Chemical pest, disease and weed control. Full conservation measures
Infrastructure	Market accessibility not necessary. Inadequate advisory services	Some market accessibility necessary with access to demonstration plots and services	Market accessibility essential. High level of advisory services and application of research findings
Land holding	Small, fragmented	Small, sometimes fragmented	Large, consolidated
Income level	Low	Moderate	High

Note: No production involving irrigation or other techniques using additional water. No flood control measures

Table 3.2 : Crops of the Nigeria global change study

Crop name	Scientific name	Minimum Cycle Length	Maximum Cycle Length	Number of Varieties	Crop Adaptability Group	Photo-synthesis pathway	Optimum Temperature (deg. C)	Maximum Photosynth. rate (mg CO2 dm-2 h-1)
Maize (lowland)	Zea mays	70	140	4	III	C4	30-35	70-100
Maize (highland)	Zea mays	120	220	4	IV	C4	20-30	70-100
Sorghum (lowland)	Sorghum bicolor	70	130	3	III	C4	30-35	70-100
Sorghum (highland)	Sorghum bicolor	120	220	4	IV	C4	20-30	70-100
Millet	Pennisetum typhoides	60	100	2	III	C4	30-35	70-100
Rice	Oryza sativa	80	140	3	II	C3	25-30	40-50
Cowpea	Vigna unguiculata	80	140	2	II	C3	25-30	40-50
Groundnut	Arachis hypogaea	80	140	2	II	C3	25-30	40-50
Soybean	Glycine max	80	140	2	II	C3	25-30	40-50
Phaseolus bean	Phaseolus spp.	90	120	1	II	C3	25-30	40-50
Phaseolus bean (highland)	Phaseolus spp.	120	180	2	I	C3	15-20	20-30
Sweet Potato	Ipomoea batatas	115	155	3	II	C3	25-30	40-50
White Yam	Dioscorea rotundata	180	240	2	II	C3	25-30	40-50
Greater Yam	Dioscorea alata	210	285	2	II	C3	25-30	40-50
Yellow Yam	Dioscorea cayenensis	300	360	1	II	C3	25-30	40-50
Cassava	Manihot esculenta	150	330	1	II	C3	25-30	40-50
White Potato	Solanum tuberosum	90	170	3	I	C3	15-20	20-30
Sugarcane	Saccharum officinarum	210	365	1	III	C4	30-35	70-100
Banana/plantain	Musa spp.	240	365	1	II	C3	25-30	40-50
Oilpalm	Elaeis guineensis	210	365	1	II	C3	25-30	40-50
Cotton	Gossypium hirsutum	150	160	1	II	C3	25-30	40-50

levels were calculated for each crop and variety using FAO/SOW-VU software (Voortman and Buurke, 1995).

Crop requirements

A catalogue of crop requirements has been developed, that defines optimal growth conditions and yield responses to sub-optimal conditions for each crop with respect to a number of factors. The factors concerned cannot be directly applied in the biomass and potential yield calculations, because scientific knowledge is insufficiently developed to include them in crop growth models. However, not considering them at all leads to serious over-estimations of attainable crop yields. This refers a.o. to agro-climatic constraints and the effect of soil properties (soil type, soil phase, soil texture, soil drainage class) and landform on land suitability. In accordance with AEZ methodology, these are dealt with in a semi-quantitative way, by matching rules and ratings. Crop requirements have been subjected to thorough review for the purpose of the Nigeria study which will be further discussed in the sections on agro-climatic yield potentials and land suitability.

3.3 Observed baseline climate data

Observed climatic data are derived from 324 stations within and close to Nigeria. These include 52 synoptical stations, 46 agro-meteorological stations and 226 rainfall stations. The database, data handling and methods used to construct gridded climate surfaces are more elaborately described in Annex 2.

All data were first thoroughly checked and all doubtful cases have been rejected for further use. This was followed by data-screening of time series of annual rainfall using software developed by Dahmen and Hall (1990). This software tests the stability of time series, variously expressed as stationarity, consistence and homogeneity, to detect data irregularities that may be caused by extraneous influences. It was found that, in parts of the study area, the time series are not stationary. However, extent and magnitude of change of statistical properties of time series occurs in a coherent geographical pattern, that cross-cuts national boundaries which cannot be explained by extraneous influences. It was concluded that climate change occurred in recent history (Voortman, 1998). The implications of these findings for the present study will be further discussed in section 5.

The present study uses the mean values of climatic variables for the period 1961-1990 as baseline conditions. Mean climatic parameters for observation points were, on a monthly basis, interpolated in a GIS to constitute a grid of 2 by 2 km size. The interpolation was directly applied to observed values for sunshine duration, windspeed, relative humidity and global radiation. For maximum and minimum temperatures the observed temperatures were first converted to sea level, using the relation between temperature and altitude, and then interpolated. The interpolated values were, for each gridcell, again used to recalculate altitude specific temperatures on the basis of a Digital Elevation Model. Monthly values of average daily reference evapotranspiration (ET_0) were, on a gridcell basis, calculated with the modified Penman-Monteith equation, as recommended by FAO (FAO, 1992b). Details of the calculation procedure are described in Annex 3.

3.4 Agro-climatic resources inventory

The agro-climatic resources inventory referring to baseline conditions is derived from the datasets described in the previous section. In the case of scenario's, first the scenario implied changes were applied and then reference evapotranspiration and the three data layers of the AEZ agro-climatic resource inventories were calculated: the Length of the Growing Period (LGP), the LGP-pattern and temperature or thermal zones. These three layers are used in combination to assess crop climatic suitability.

Length of the growing period

Basic climatic data are used to calculate derived climatic parameters, a daily water balance and actual evapotranspiration and subsequently temperature zones, LGP pattern and LGP length. The LGP analysis generates pseudo-daily values from the monthly climate variables through spline-interpolation which also allows assessment of growth conditions during different crop stages. The LGP calculations are soil specific and account for the maximum soil moisture storage capacities as established by the soil resource inventory (see section 3.5). Calculation procedures are further specified in Annex 4. The LGP analysis for scenario's that imply increased CO_2 concentrations accounts for the slow down of transpiration due to partial closure of leaf stomata, by modifying the canopy resistance term of the potential evapotranspiration formula.

Current AEZ procedures not only account for shortfall of available length of growing period but also for the quality of moisture supply conditions during the LGP. The latter may require adaptation under conditions of global change beyond changes of canopy resistance, because of possible changes in crop specific yield response to water stress (k_y factor, see FAO, 1992a), as related to changes in water-use efficiencies. However, at present, there is insufficient evidence to consider such adaptations of crop and crop phenological stage specific k_y values.

LGP's for Nigeria based on mean data referring to observed climate of the period 1961-1990 are shown in fig. 3.2. Gridcell values have been classified into twelve LGP zones with a thirty-day interval. Generally speaking, the growing period zones show a parallel pattern in East-West direction with high values near the tropical Atlantic and lower values towards the North. This general pattern is modified by relief, that causes higher rainfall on windward slopes and less precipitation in rainshadow areas. More locally, the effect of differences in waterholding capacities of soils is evident.

LGP pattern

The LGP pattern of observed climate calculated with mean monthly data shows that the entire country has one single LGP per year (fig. 4.3). The bimodal tendency of rainfall in south-west Nigeria (Keyzer et al., 1997) is insufficiently strong and regular to affect LGP pattern if calculated with mean data. The growing period type is normal for almost the entire country. The exceptions are intermediate types in the very north associated with short LGP's and in the very south where a small area has a year-round growing period.

Thermal zones

Thermal zones quantify the temperature attributes of the LGP and their value for baseline climate are depicted in fig. 3.3. Original gridcell values have been classified into zones with 2.5°C intervals, i.e., >30°C, 27.5-30°C, 25-27.5°C, etc. The classification is based on mean annual temperature as seasonality effects due to latitude are minor in Nigeria. Maximum and minimum values associated with the means and their effect on crop performance are taken into account in the crop suitability assessment. The map shows most of Nigeria to be warmer than 25° C and cooler conditions are restricted to relatively small areas at higher elevations.

Fig. 3.2 : Spatial distribution of reference length of growing periods

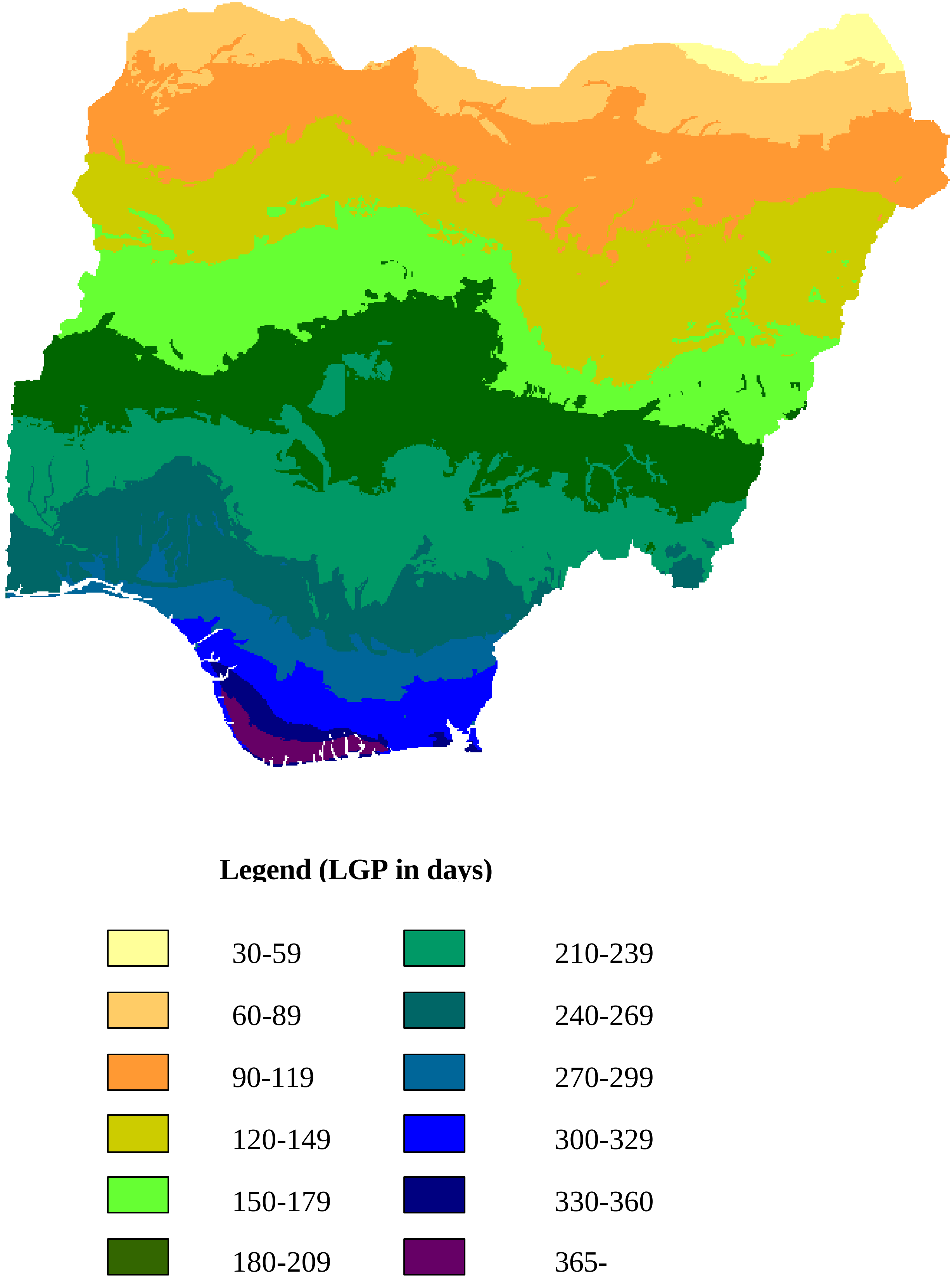
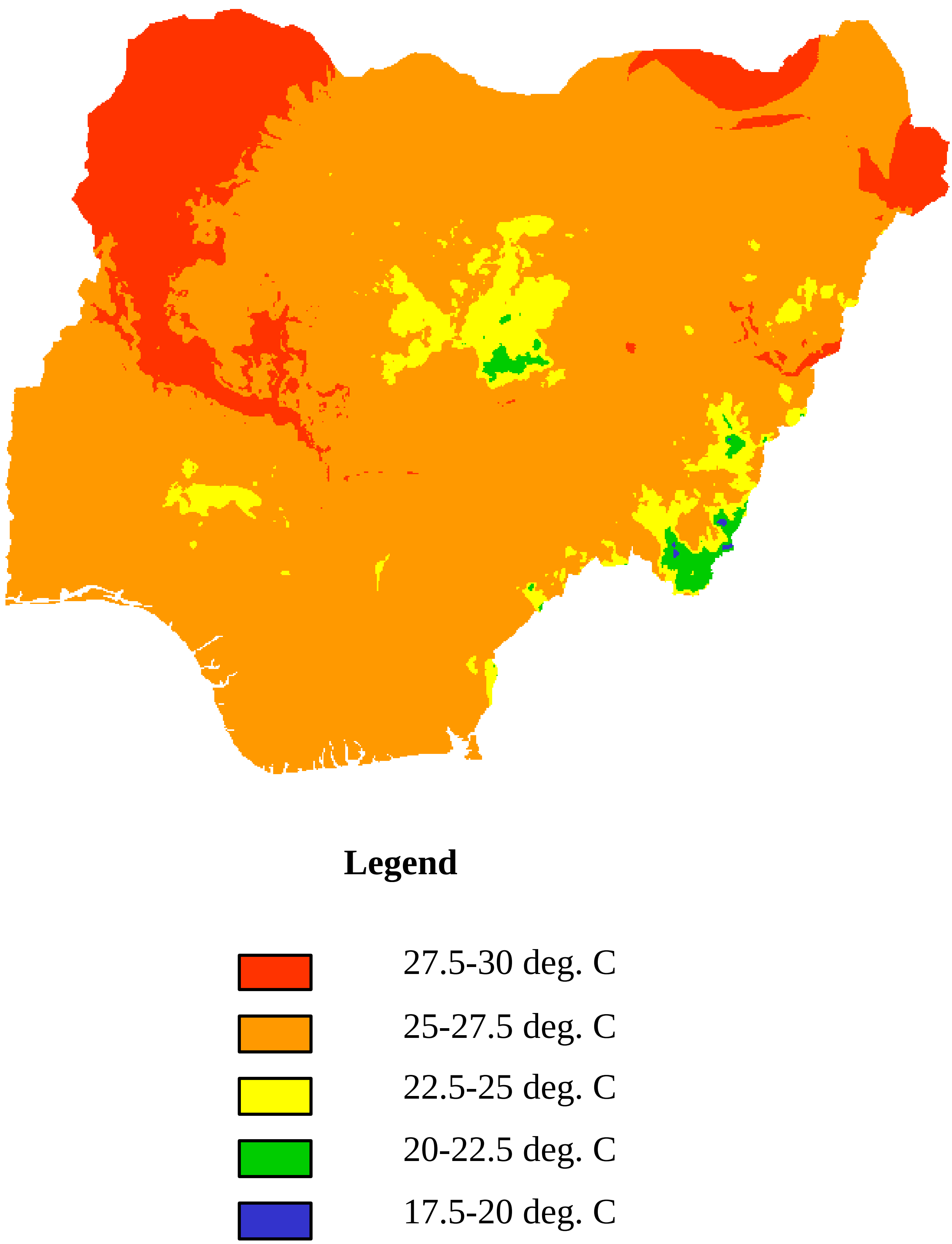


Fig. 3.3 : Spatial distribution of reference thermal zones



3.5 Soil and land resource inventory

Soil resource inventory

A nation-wide soil and terrain inventory was made that complies with the selected methodologies for assessment of agricultural production and water erosion hazard. Soil and land form data are stored in a Geographical Information System (GIS) to facilitate data logistics and processing. The spatial data consist of three thematic layers: soil associations, slope and altitude. Information on the individual soil units within mapped associations are stored in an attribute file that is linked to the spatial information. The soil inventory is fully documented in Sonneveld (1998).

The data used for compiling the soil resource inventory include regional soil resource inventories that in total cover about 70 percent of Nigeria. These studies, their location and extent, are more extensively described in Annex 6. The regional studies are typically at a scale of 1:250 000-1:500 000 and most of them use land systems or similarly defined entities as mapping unit. Land systems are characterized by their composition in terms of extent of individual soil types. For each type a description of soil and land characteristics is provided, including typical profile descriptions and results of chemical an physical analysis of individual soil horizons (Bawden et al., 1966; Bawden et al., 1972; Hill and Wall, 1978a-f; UNDP/FAO, 1969; Sombroek and Zonneveld, 1971; Smyth and Montgomery, 1962; Murdoch, 1978; Fölster et al., 1983).

For the remaining 30 percent of the Nigeria n territory use has been made of the FAO/UNESCO Soil Map of the World at a scale of 1:5 000 000 and the FDALR national map at scale 1: 1 000 000 (FDALR, 1991). The location map pertaining to some 200 fully documented soil profiles of the latter study was provided by FDALR and this allowed to update the FAO/UNESCO map in terms of spatial extent of mapping units, their composition and soil classification.

Altitude and slope angle have been derived from a Digital Elevation Model (DEM, EROS, 1998). A grid with altitude observations at 30-arc-second intervals was generated using ANUDEM (Hutchinson, 1989).

Mapping unit composition and the extent of individual soil types within mapping units is derived from information presented in the above mentioned studies. FAO/UNESCO soil type (FAO/UNESCO/ISRIC, 1996) and soil phase, if present, were determined for each of the individual units, based on soil profile descriptions and results of chemical and physical analysis. For each soil type within a mapping unit the following properties were tabulated: texture, soil drainage class, soil depth, total available water capacity and slope. In addition, each soil type was assessed with respect to soil erodibility and the topographic factor for erosion hazard. This tabular information on soil characteristics is linked to the mapping unit components by means of an attribute table (for details see Annex 6).

Land resource inventory

The land resource inventory consist of an overlay of the climatic surfaces with the soil surfaces while maintaining its linkages to the soil attribute file. The basic unit of assessment is the agro-ecological cell that consists of an individual and homogenous component of the soil association as defined by the soil mapping unit, which is further characterized by its (near) homogeneous climatic conditions. In the Nigeria case study there are about 13000 of such agro-ecological cells.

3.6 Biomass production and yield calculation

The basic model to calculate potential net biomass and constraint-free yields (Kassam, 1977) uses the length of the growing period, data of radiation and temperature regimes, together with crop eco-physiological characteristics to calculate constraint-free yields. For GCM-based and sensitivity scenario's the effect of the different levels of atmospheric CO_2 concentrations are taken into account. A summary description of the basic procedures is given in the Annex 5. The AEZ biomass model, in addition to the basic climatic data, requires values for parameters that can be calculated with the above data sets. Photosynthetic active radiation (PAR) is required and adjusted to actual global radiation (R_g) or sunshine duration relative to day-length. Average daily as well as day-time temperatures are calculated using the values for minimum and maximum temperature.

Plants respond differently to increases of atmospheric CO_2 concentrations depending on their photosynthesis pathway (Annex 1). In addition, there are important differences in the response of photosynthesis to temperature. In the case of C_3 species, one group is adapted to operate under conditions of moderately cool and cool temperatures (10-20°C), e.g., wheat, barley and white potato and a second group is adapted to moderately warm to warm conditions (25-30°C), e.g. rice, cotton and groundnut. These two crop groups constitute adaptability groups I and II of the AEZ system, respectively.

Likewise, the C_4 species can be divided in two groups of cultivars or ecotypes. One is adapted to operate under warm to very warm conditions (25-35°C), e.g. lowland maize, lowland sorghum and sugarcane an the second group is adapted to lower temperatures (15-25°C), and includes highland maize and highland sorghum varieties. These C_4 groups of crop ecotypes are adaptability groups III and IV of the AEZ system respectively. A fifth adaptability group has the so-called CAM photosynthetic pathway, but such crops were not selected for the present study.

The AEZ biomass and potential yield model uses this division of crops into four adaptability groups (see table 3.2) and applies temperature specific maximum photosynthesis rates that need to be adapted when atmospheric CO_2 concentrations increase. The maximum photosynthesis rates used in the AEZ system for current CO_2 levels are presented in table 3.3

Table 3.3. Maximum photosynthesis rates (P_m in kg CH_2O ha^{-1} hr^{-1}) by mean day-time temperatures at current 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

The effects of increases of atmospheric CO_2 concentrations on photosynthesis rates, the different responses of C_3 and C_4 crops and the temperature dependence were described in Annex 1. Based on the experiments and evidence quoted, temperature dependent changes of maximum rates of photosynthesis (P_m) for each crop adaptability group have been proposed for doubled atmospheric CO_2 conditions (table 3.4; Fischer and Van Velthuizen, 1996). Maximum photosynthesis rates used in the AEZ biomass model of the present study depend on the projections of scenario implied increases of atmospheric CO_2. Intermediate values of Pm are calculated through interpolation for circumstances when CO_2 levels are in between those to which table 3.3 and 3.4 refer.

Table 3.4: Maximum photosynthesis rates (in kg CH_2O ha^{-1} hr^{-1}) by mean day-time temperatures at doubled 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	10	22.5	30	22.5	10	0	0	0
II (C_3)	0	0	12.5	37.5	55	65	60	10	0
III (C_4)	0	0	5	45	65	68	68	50	10
IV (C_4)	0	5	45	65	68	68	50	10	0

3.7 Agro climatic yield potentials

Thermal zone assessment

Effects of temperature on crop growth are, to a large extent, taken into account in the biomass and constraint-free crop yield model. Additional temperature related constraints are applied on the basis of thermal zone characteristics. Thermal zones are defined in terms of mean temperatures, but are obviously related to minimum and maximum values. Mean temperatures in combination with the extremes may put additional constraints on crop growth and phenology. There is no evidence that such relationships would alter with global change and the thermal zone assessment has therefore not been modified. However, the temperature rise of some scenario's is such that yield reductions are applied to sensitive crops while under baseline conditions these are not affected.

Agro-climatic constraints

The agro-climatic constraints as applied to constraint-free potential yields and their linkage to LGP length and thermal zones, under conditions of global change, is assumed to be identical to baseline conditions (Annex 1). They have, however, been extensively reviewed. In case of crops with a broad growth cycle range these constraints were made variety specific and agro-climatic constraints that are applicable to the intermediate input level were developed for the purpose of this study. These take into account that, under such conditions, pests, diseases and weeds may to some extent be taken care of by the farmer and that workability/mechanization constraints due to humid conditions are less restrictive if compared to high input/mechanized conditions.
As yet, there is insufficient evidence to suggest that the currently applied relationship between environmental characteristics and incidence of pests, diseases and weeds would change in a systematic manner.

Agro-climatic suitability

The agro-climatic suitability assessment is based on the matching of crop characteristics with climatic conditions through the application of the biomass production and yield model and by further imposing the effect of thermal zones and agro-climatic constraints. It is assumed that functional relationships for comparing crop requirements with climatic attributes developed for current conditions remain valid under increased atmospheric CO_2 concentrations. Examples of climatic suitability maps referring to intermediate levels of inputs and baseline conditions are presented in fig. 3.4.

3.8 Land suitability

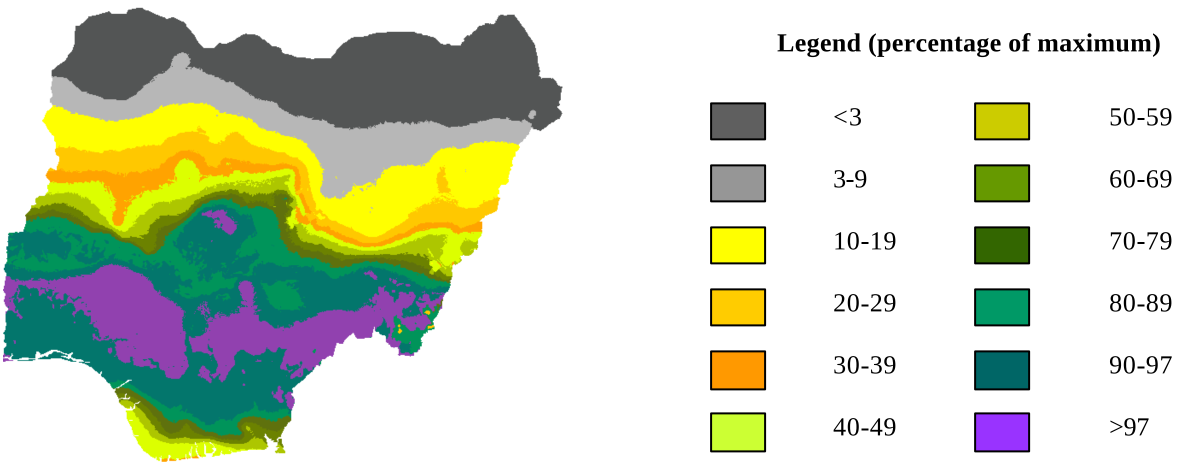
Edaphic requirements

Edaphic requirements of LUT's have been inventoried to allow the assessment of the suitability of soils for each individual LUT's specifically. Distinction is made between internal soil requirements of LUTs, such as soil moisture regime, soil fertility, effective soil depth for root development and other physical and chemical soil properties, and external requirements related to slope angle, occurrence of flooding and soil accessibility.

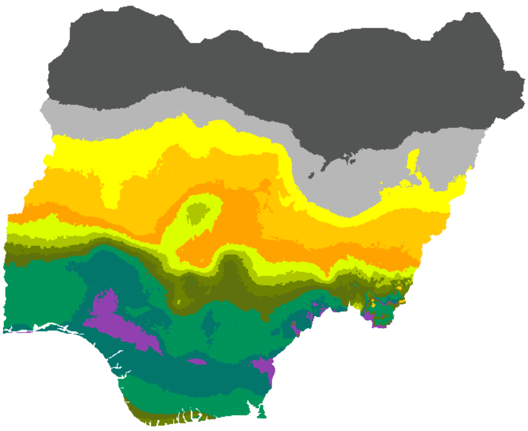
Annex 1 concludes that at present there is insufficient convergence of research evidence that would allow to apply systematic changes to current soil characteristics, that would result from climate change and increases of atmospheric CO_2. The same applies to the current state of knowledge on possible different ways and magnitudes of interaction of soil properties with other environmental variables, in the process of biomass production. The basic principles of the edaphic crop suitability classifications have therefore been maintained. Hence, 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 crop growth only when soils are not suffering from severe nutrient deficiencies, toxic substances or other limitations that make them unsuitable for agriculture. The full effect of CO_2 fertilization is realized only when soils do not impose limitations to the productivity of LUTs. Under suboptimal soil conditions yield increases due to the CO_2 effect are proportionate to the degree of limitations that soils would impose under current conditions.

The existing soil suitability ratings, as applicable to soil class, however, have been subjected to a thorough review in particular with respect to aspects of soil fertility. The detailed soil information as stored in the attribute file also had to be accounted for. The previously used assessment rules essentially derive from Sys and Riquier (1984) and consist of ratings applicable to FAO/UNESCO soil class that were largely determined through expert knowledge, based on inherent properties of these classes. However, increasingly quantitative information on the properties of FAO/UNESCO soil classes becomes available and knowledge and insights on crop requirements is also improving (e.g Sys et al.1993, Voortman, 1985). Matching such knowledge and insights with quantitative information on FAO soil class properties, as presented in the WISE 2.1 data base (Batjes, 1995), suggests that the existing rating systems need revision. A new system of soil ratings was therefore developed, which also allowed to reduce the discontinuities of the previously used rating systems (see Annex 7).

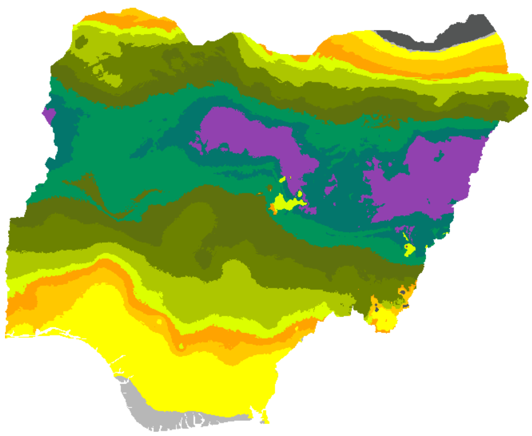
Fig. 3.4 :Current climatic yield potential for selected crops (as a % of the maximum)



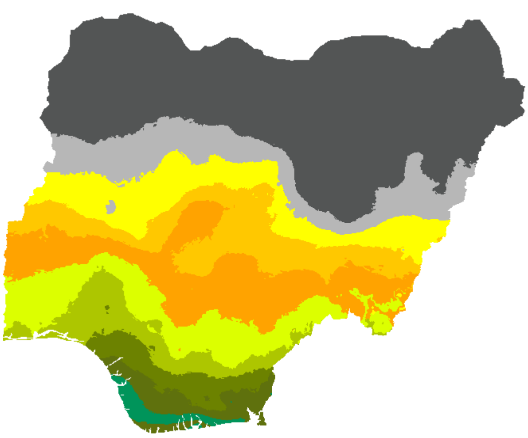
White Yam



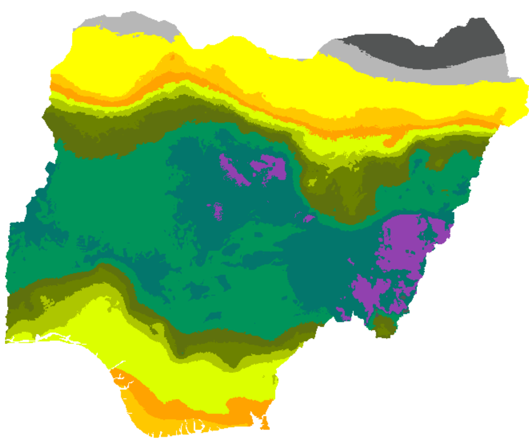
Greater Yam



Millet



Cassava



Maize

xxxxx

Land suitability

The land suitability assessment combines the effects of soil properties with climatic yield potentials and calculates attainable yield levels. The matching of crop edaphic requirements with actual soil properties defines reductions to be applied to climatic yield potentials resulting in attainable crop yields. These are converted to percentages of the maximum attainable yield for the crop and input level under consideration. Thus, specific estimates of attainable yields for all LUT's at different levels of management and input use are available for each agro-ecological cell.

3.9 Sustainable land productivity

The attainable yields for all crops are used to calculate land productivity given a certain level of input use and management and global change scenario. The land productivity assessment may, in addition to crop yields, consider the effects of multiple cropping, sustainability criteria with respect to erosion and the need for fallow periods to restore soil fertility.

Multiple cropping increments

Production increases due to multiple cropping resulting from intensification of cultivation in space and time can be taken into account in the AEZ analysis. Under conditions of climate change the total effect of changed crop component suitability and changed growth cycle duration can be accounted for in the AEZ model. There is no conclusive data or indications of some evidence available of changed crop-crop interactions in sequential, relay or intercropping systems that would result from climate change or increased atmospheric CO_2 concentrations. Therefore, the interaction effects as established in previous AEZ studies have been kept unchanged.

Sustainability criteria

The Nigeria climate change case study uses a modified version of the Universal Soil Loss Equation (USLE) to quantify erosion impacts. Excessive erosion hazard will imply that the land is considered not suitable for agriculture. The USLE factors referring to soil erodibility, slope angle and slope length are available in the soil attribute file. The 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. There is insufficient evidence to suggest that soil erosion/productivity loss relationships would significantly alter under global change conditions.

Fallow period requirements

The land productivity estimates should refer to sustainable production and therefore fallow requirements, to maintain soil fertility and structure and to counteract soil degradation caused by cultivation, are included in the land productivity assessment. It implies, that a proportion of the land can not be cultivated in any one year. This proportion varies with climatic conditions, soil type and the level of inputs and management applied. Climate change is expected to affect fallow period requirements, through its effect on nutrient cycling. However, as described in Annex 1, as yet it is unclear which direction this will take and what the magnitude will be, in different kinds of environment. Possible changes of fallow period requirements have therefore not yet been taken into account in the present analysis, but could be implemented in the system as soon as systematic and quantitative estimates become available.

3.10 AEZ land productivity database

The productivity assessment records input level specific production of relevant and agro-ecologically feasible land utilization activities and stores quantified information on crop yields, agricultural production, cultivable areas and multiple cropping increments. 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. The resulting database allows for tabulating and mapping at 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 global change scenarios.

Section 4

Global change impacts for Nigeria

4.1 Climate change

4.1.1 Temperature

Current mean annual temperatures have been presented as thermal zones with a 2.5 °C interval in section 3. The extents of identically defined zones under conditions of global change are presented in table 4.1. and a spatial representation of reference and selected scenario conditions is shown in figs. 4.1 and 4.2. The GCM scenarios consistently predict a continuous increase of temperatures, but differ in terms of magnitude, and thus speed, of change. The MPTR and GFTR scenario's predict faster increases of temperature than HCTR. Second decade results of MPTR and GFTR are quite similar and both are close to the T20 sensitivity run. The increases for HCTR are less and this difference with the other two GCM's is maintained in the third decade. In fact, the HCTR3-550 result is quite similar to GFTR2-460. The rise of temperature for MPTR3-550 slightly higher than GFTR3-550, as reflected by the higher thermal zone class in the main alluvial valleys at lower elevations and a further reduction of size of cooler areas in mountainous terrain. The temperature increases of all decade 3 results are less than the sensitivity run of 4 degree temperature increase (T40).

In terms of agricultural potential, the most obvious implication of warming will be the reduction of areas suitable for growing temperate crops, like white potato and temperate phaseolus beans. In decade 3 situations, climatically suitable conditions for these crops are restricted to isolated mountain tops, where leached soils of low fertility and high erosion hazard due to steep slopes, may be prohibitive for cultivation anyway. The extent of currently very suitable areas for crops that prefer moderately warm conditions, like soybeans, will likewise reduce in size. Thus, production opportunities for special crops, often with a local value or export potential, are lost. To some extent, this may be compensated by increased productivity of tropical crops in the affected areas. Particularly in the North-West and North-East of the country temperatures become high enough to affect physiological processes of some crops. The negative effect of high mean temperatures and associated high maxima on sensitive crops has been accounted for, through the assessment of thermal zones.

4.1.2 Growing period pattern

Growing period pattern describes the number of growing periods per year and the type of growing period. Fig. 4.3 presents location and extent of these zones for selected scenario's. The number of LGP pattern types is limited in Nigeria, when mean monthly climate data are used, in contrast to for instance Kenya (Fischer and van Velthuizen, 1996). All GCM-based scenario's and sensitivity tests show that more than 95 percent of Nigeria has one single normal growing period. The limited variation of growing period pattern and type is demonstrated by the two extremes from the rainfall sensitivity runs with increases and decreases of 30 % of rainfall, respectively (PP30 -330 and PM 30-330) . All other scenario's take an intermediate position

Table 4.1: Impact of climate change on the distribution of thermal zones (km2)

Climate Scenario's	Thermal Zones	TZ6 (17.5-20.0 deg.C)	TZ5 (20.0-22.5 deg.C)	TZ4 (22.5-25.0 deg. C)	TZ3 (25.0-27.5 deg. C)	TZ2 (27.5-30.0 deg.C)	TZ1 (>30.0 deg. C)
Reference		300	7,804	48,680	723,324	128,164	0
GCM-T D2	GFTR 2	4	1,656	13,184	186,432	657,556	49,440
	HCTR 2	48	4,564	24,060	596,400	278,116	5,084
	MPTR 2	4	912	10,564	110,748	727,880	58,164
GCM-T D3	GFTR 3	4	740	10,616	88,400	728,504	80,008
	HCTR 3	4	1,768	15,716	290,904	565,132	34,748
	MPTR 3	4	368	5,244	26,004	588,256	288,396
P Sensitivity	PP10 (+10% P)	300	7,804	48,680	723,324	128,164	0
	PP30 (+30% P)	300	7,804	48,680	723,324	128,164	0
	PM10 (-10% P)	300	7,804	48,680	723,324	128,164	0
	PM30 (-30% P)	300	7,804	48,680	723,324	128,164	0
T Sensitivity	T20 (+ 2 deg.C)	0	1,460	11,684	105,136	725,740	64,252
	T40 (+4 deg. C)	0	0	1,464	14,624	200,376	691,808

Fig. 4.1 : Spatial distribution of thermal zones

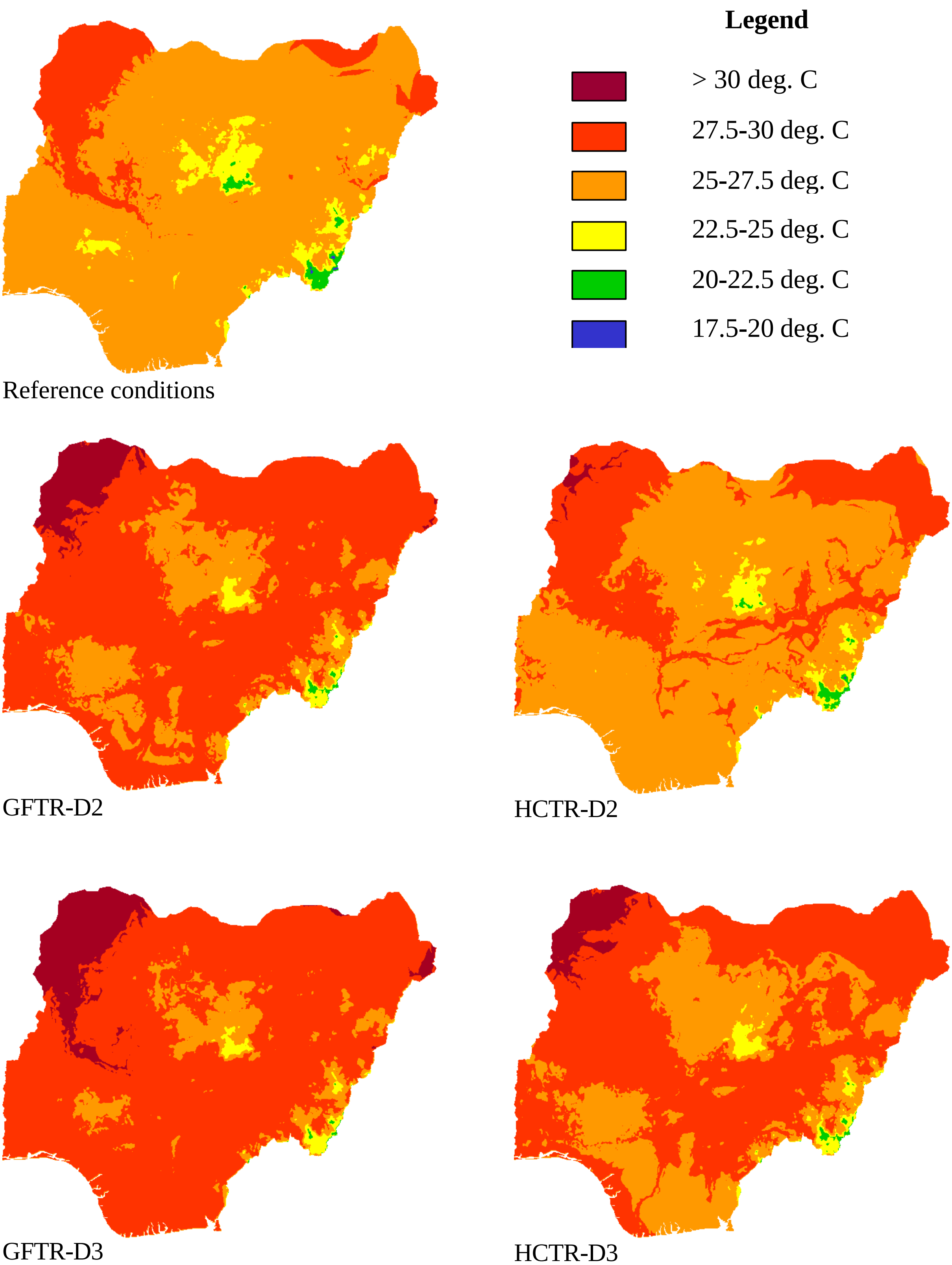


Fig. 4.2 :Spatial distribution of thermal zones (ctnd.)

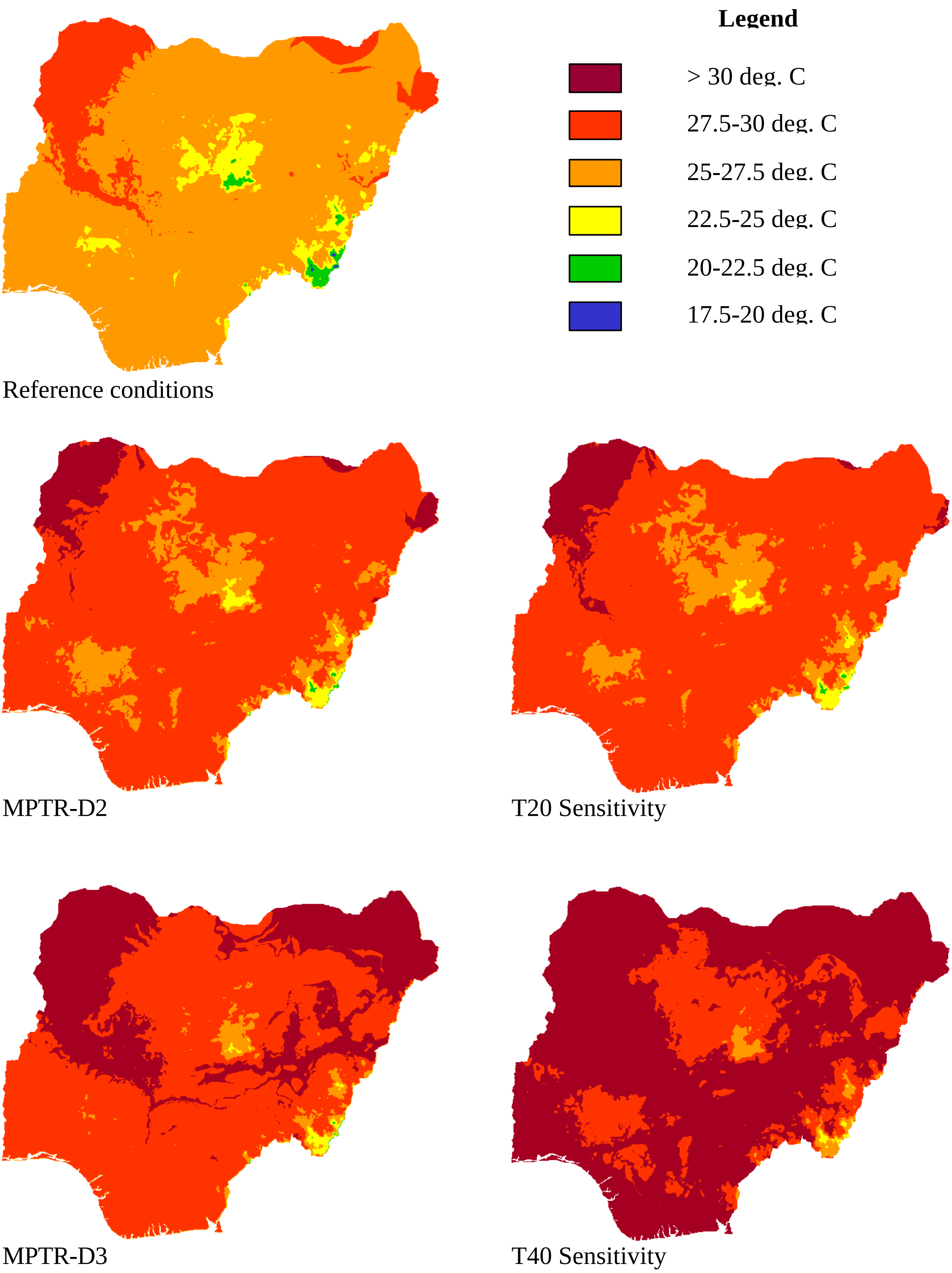
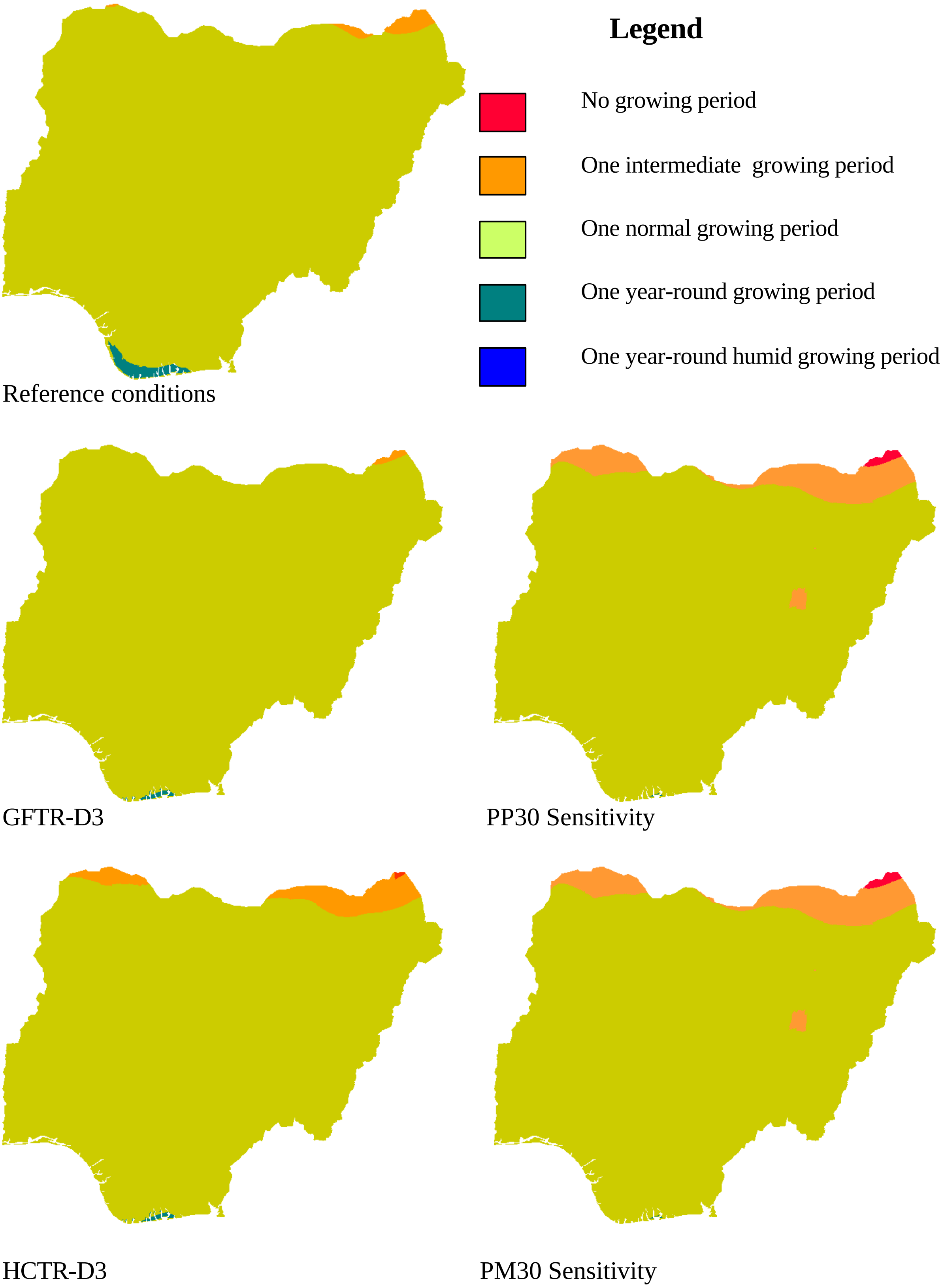


Fig. 4.3 : Spatial distribution of the pattern of the length of growing period (examples)



between these two extremes. The percentage change of areas with different LGP pattern and type is presented in table 4.2.

All GCM scenarios (both decades) produce a small area in the North-East with one intermediate growing period per year. Such conditions imply that crops can be grown, but yields will be reduced because of moisture stress. Most scenario's also show similar conditions of very local extent in the extreme North-West. Some scenario's show a tiny area with no growing period at all near Lake Chad. Reference conditions show very humid conditions with year-long LGP's as a coastal strip in southern Nigeria. This area reduces in size to about 30% in decade 2, irrespective of the GCM scenario, and in decade 3 only a very small area remains. Sensitivity runs with increasing rainfall, of course, show an expansion of humid conditions and part of it changes pattern from year-round normal growing period to year-round humid growing period.

The changes of LGP patterns are limited in extent, but where they occur there is a large impact on crop production. The change of pattern from a year-round growing period to one normal growing period implies dry conditions during some part of the year and may seriously affect perennial crop production. Changing from a normal growing period (without moisture stress) to an intermediate type (where moisture stress is implied), will reduce annual crop yields considerably, particularly because such changes mostly occur when current LGP's are short already. Effects of changing from one growing period to no growing period at all is self-evident. All changes in growing period pattern and type are accounted for in the assessment of changes in land productivity.

4.1.3 Growing period length

The Length of the Growing Period as calculated with observed climate data has been presented in section 3. Reference conditions, examples of GCM-based LGP's and the extremes of rainfall sensitivity tests are depicted in fig. 4.4. The maps show that the overall pattern of east-west parallel zones is maintained irrespective of the scenario used. The rainfall sensitivity results show considerable and systematic shifts over the entire territory, in northward direction in the case of increasing rainfall and southward when rainfall decreases. The GCM scenario's (including the effect of ΔRl) show more localized effects because GCM-based changes in rainfall vary in geographic space. Relative changes of LGP zone extents are given in table 4.3.

All GCM scenario's imply a reduction of currently humid areas and, with the exception of the GFTR3-550 scenario, they indicate an increase of areas with dry conditions. Systematic effects of increased water use efficiency on LGP length may be observed in table 4.3. For instance, increases of dry conditions are less when water use efficiency is taken into account and similarly the expansion of extents of humid conditions may be greater.

Spatial patterns and magnitude of change of LGP length for GCM scenario's (including the effect of ΔRl) are given in fig. 4.5. Generally speaking, increases of LGP length are of limited magnitude. Decreases may be much more pronounced, and large decreases are often concentrated either in the currently very humid parts of southern Nigeria or in currently dry parts of the extreme north-east. MPTR2-460 is an exception since it indicates a rather systematic decrease of more than 20 days for an extensive east-west belt. GFTR2-460 shows slight decreases in the south, slight increases in the middle belt and again a slight decrease in the north. The latter decrease, although slight in absolute terms will substantially affect crop yields because current LGP's are already of short duration. The same scenario shows for decade 3 a further reduction of LGP's in the south, but more northwards the reverse trend is found with considerable increases of LGP length. HCTR 2-460 produces rather localized decreases and increases and decade 3

Table 4.2: Impacts of climate change on number and types of growing period (% change)

Climate Scenarios	Growing Period Pattern	No Growing Period **/	One Intermediate Growing Period	One Normal Growing period	One Normal Year-round Growing Period	One Perhumid Year-round Growing Period **/
Reference (km2)		0	7,916	894,156	6,200	0
GCM-T D2	GFTR 2 330	0.22	424.8	-3.6	-53.8	
	GFTR 2 460	0.19	410.7	-3.5	-46.8	
	HCTR 2 330		154.0	-0.9	-69.5	
	HCTR 2 460		137.4	-0.8	-64.8	
	MPTR 2 330	0.15	335.8	-2.5	-84.4	
	MPTR 2 460	0.12	323.6	-2.4	-83.5	
GCM-T D3	GFTR 3 330		-72.5	1.2	-84.5	
	GFTR 3 550		-77.4	1.3	-82.6	
	HCTR 3 330	0.08	368.8	-2.7	-87.0	
	HCTR 3 550	0.05	344.1	-2.5	-85.0	
	MPTR 3 330	0.16	242.3	-1.6	-97.0	
	MPTR 3 550	0.11	224.4	-1.4	-96.9	
P Sensitivity	PP10 (+10% P)		-58.1	0.2	39.9	0.00
	PP30 (+30% P)		-99.6	0.1	79.2	0.20
	PM10 (-10% P)		133.6	-0.8	-58.5	
	PM30 (-30% P)	0.28	633.3	-5.2	-98.6	
T Sensitivity	T20 (+ 2 deg.C)	0.01	91.8	-0.3	-69.4	
	T40 (+4 deg. C)	0.14	193.1	-1.2	-91.0	

*** */** the percentage of the total territory is given in case the value of the reference conditions is zero

Fig. 4.4: Spatial distribution of Length of Growing Period Zones (examples)

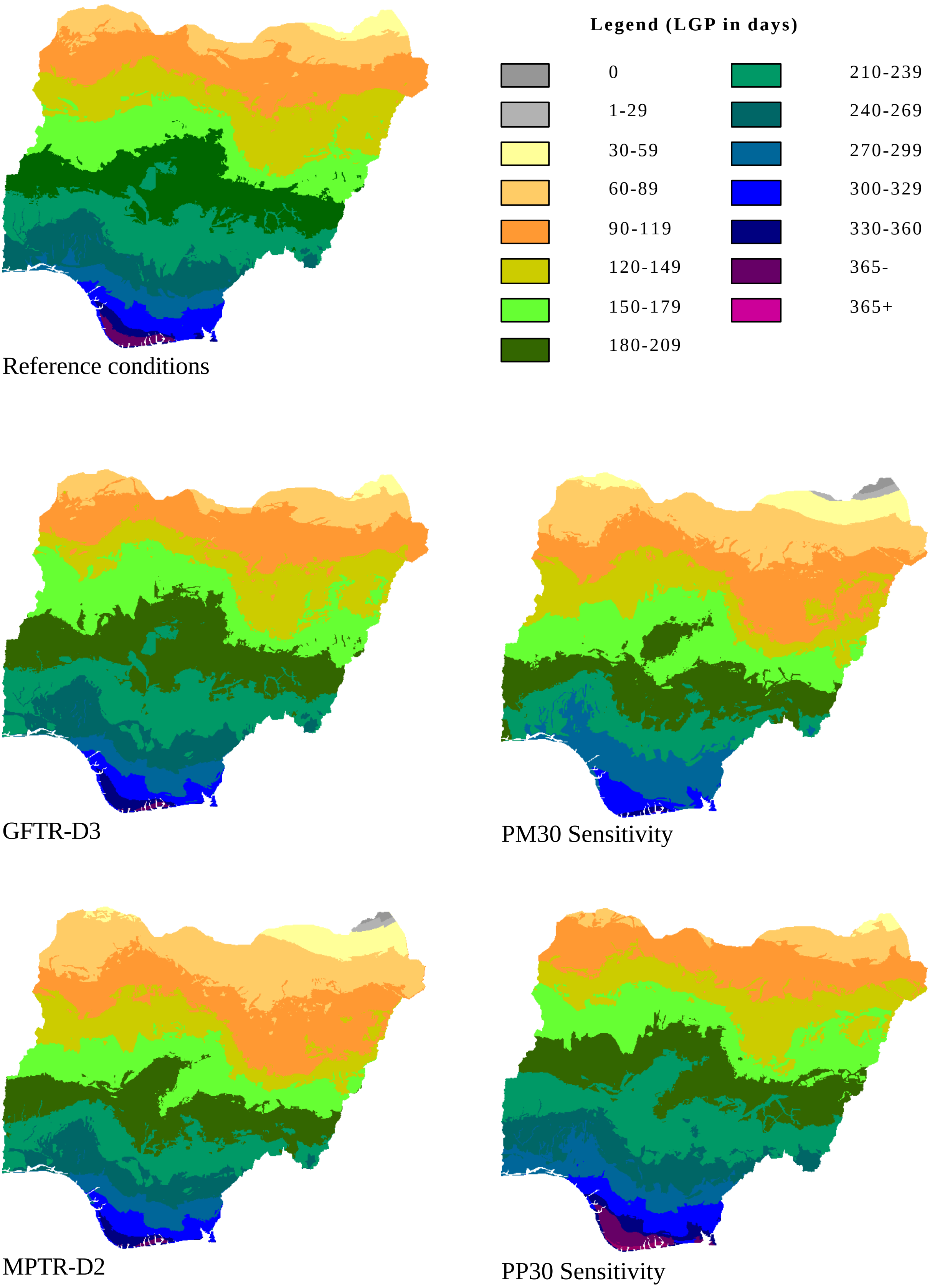
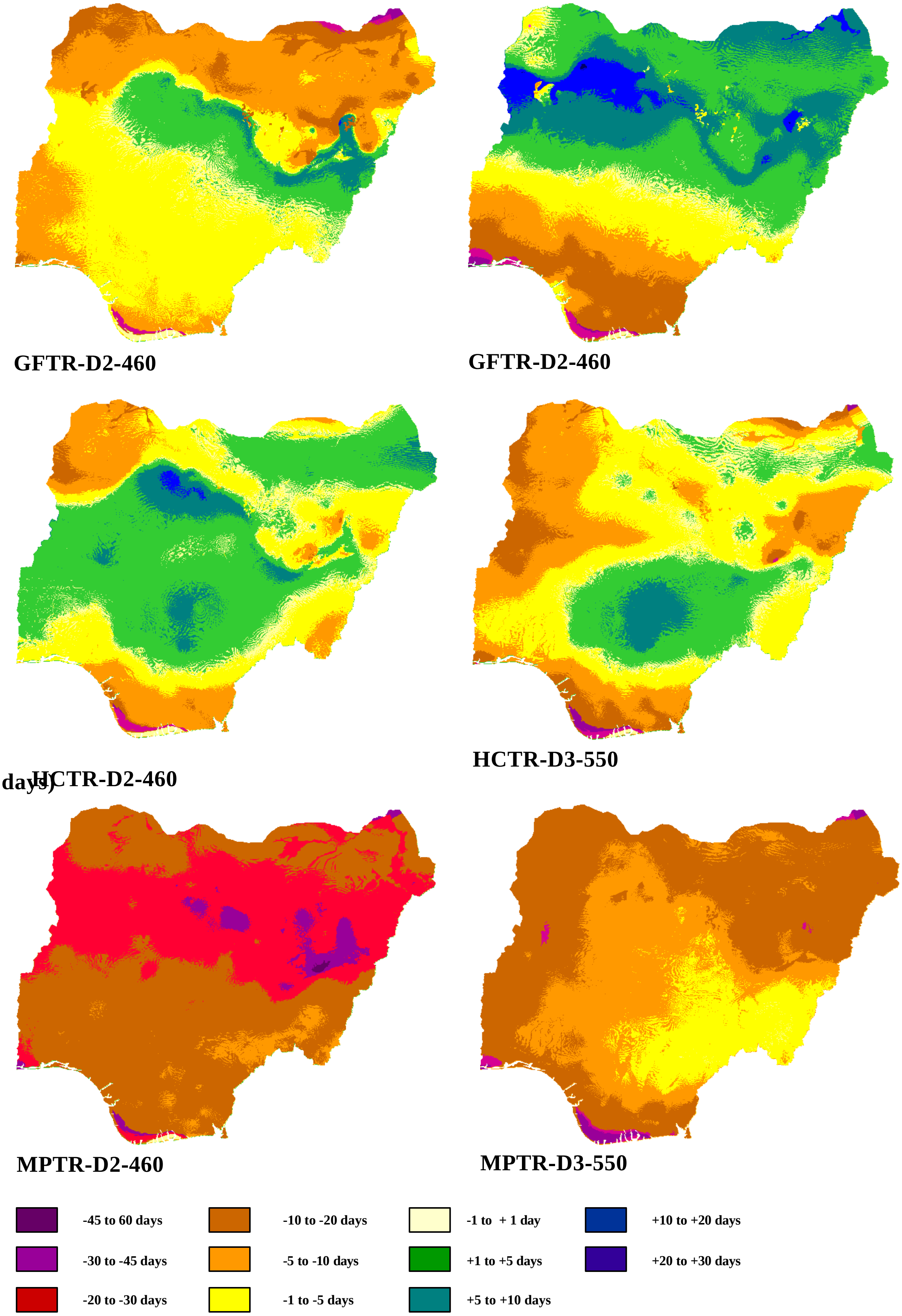


Table 4.3: Impacts of climate change on the distribution of growing period lengths (% change)

Climate Scenario's	LGP classes	Hyperarid 0 days **/	Arid 1-59 days	Dry Semi-arid 60-119 days	Moist Semi-arid 120-179 days	Sub-humid 180-270 days	Humid 270-360 days	Near and fully Perhumid 365- and 365+ days
Reference (km2)		0	12,836	212,616	267,236	341,788	67,596	6,200
GCM-T D2	GFTR 2 330	0.22	89.2	8.9	-12.7	2.2	-3.7	-53.8
	GFTR 2 460	0.19	87.2	7.6	-12.1	2.5	-3.7	-46.8
	HCTR 2 330		5.1	4.1	-7.3	4.4	-0.9	-69.5
	HCTR 2 460		0.4	3.3	-7.2	4.9	-0.6	-64.8
	MPTR 2 330	0.15	182.4	50.3	-20.2	-17.9	-16.3	-84.4
	MPTR 2 460	0.12	177.5	49.2	-19.7	-17.5	-15.7	-83.5
GCM-T D3	GFTR 3 330		-47.0	-3.3	-0.1	8.7	-16.5	-84.5
	GFTR 3 550		-51.7	-4.8	0.1	9.4	-15.6	-82.6
	HCTR 3 330	0.08	32.8	7.5	-3.5	-1.2	-3.1	-87.0
	HCTR 3 550	0.05	26.6	6.1	-2.8	-0.8	-1.9	-85.0
	MPTR 3 330	0.16	112.8	20.6	-12.5	-4.2	-8.9	-97.0
	MPTR 3 550	0.11	107.2	18.3	-11.0	-3.8	-7.8	-96.9
P Sensitivity	PP10 (+10% P)		-30.9	-6.2	-2.3	4.4	8.7	40.5
	PP30 (+30% P)		-66.7	-18.0	-4.1	7.7	36.7	108.9
	PM10 (-10% P)		40.9	8.2	-0.8	-3.5	-7.3	-58.5
	PM30 (-30% P)	0.28	203.9	38.9	-4.8	-21.0	-30.5	-98.6
T Sensitivity	T20 (+ 2 deg.C)	0.01	31.7	6.3	-1.6	-2.0	-3.4	-69.4
	T40 (+4 deg. C)	0.14	58.1	15.6	-5.8	-3.9	-10.7	-91.0

****/** the percentage of the total territory is given in case the value of the reference conditions is zero

Fig. 4.5: Pattern and magnitude of changes of LGP compared with reference conditions (in days)



shows a further expansion of areas with reduced LGP's, that follows the patterns of decade 2. Both MPTR scenario's result in shorter LGP's for almost the entire territory, generally being more severe for decade 2.

In summary, the results of GCM experiments, with respect to temperatures, consistently indicate a gradual rise of temperatures along quite similar geographic patterns, obviously related to altitude. They only differ rather slightly in the magnitude of change. With respect to rainfall, all GCM-based scenario's are consistent for the south of the country in terms of both, direction and magnitude of change. However, otherwise we note large differences between GCM's and for the same GCM decade 3 may show a reversal of the trend indicated by decade 2 conditions. This is unfortunate because at present the length of the growing period and consequently crop yields are moisture limited in most of Nigeria and this limitation is likely to be further enhanced by rising temperatures. It therefore seems possible to derive conclusions on the effect of global change for land productivity only, provided that this is done in a context of a cautionary band-width of the likely events following from the greenhouse effect.

4.2 Potential crop production and land productivity

The assessment of global change impacts on potential crop production and land productivity is described on the basis of a selection of scenario's. The GCM-based scenario's, that always imply increased atmospheric CO_2 levels, are used in combination with an extensive set of sensitivity scenario's. The latter serve to assess cause and effect of changing single factors and their combinations. Results are discussed for *intermediate input level* conditions. This level was chosen because current input levels are somewhat above the low level and intermediate, if not high, input level conditions need to be reached within the time horizon of this study, if the food demand of a growing population is to be met.

4.2.1 Potential crop production

Scenario and crop specific changes of production potential for rainfed crops under sole cropping circumstances at the national level are presented in table 4.4. First and foremost, it can be concluded that impacts of climate change are not extreme, irrespective of the scenario used, except for Phaseolus beans and White Potato, i.e. the temperate crops of the study.

Productivity of Phaseolus beans and White Potato is currently low and reduces drastically for all GCM scenario's, due to rising temperatures. Sensitivity scenarios show large variations for these crops, from very positive to very negative, depending on assumptions and the implied effects on length of growing period and temperature. Keeping precipitation constant and varying CO_2 levels, clearly demonstrates the positive impacts of increased CO_2 levels on these C_3 crops. Increasing CO_2 levels has little effect on the temperature scenario's because the negative impact of increased temperatures overrules any positive effect of CO_2 fertilization.

Except for the temperate crops, GCM scenario based changes of potential crop production at the national level fall within a range of roughly 30 %. Important differences in magnitude are observable between C_3 and C_4 crops, due to the differential impact of elevated CO_2 on these crop groups. If the general tendency of a scenario is towards increased productivity, then such increases are much higher for C_3 crops. In case of an overall decreasing trend, the decreases for C_3 crops are often much less compared to C_4 crops, unless important changes in LGP also play a

Table 4.4: Impacts of global change on potential production of rainfed crops (% change for sole cropping systems)

Scenario	Reference	GFTR-D2	GFTR-D3	HCTR-D2	HCTR-D3	MPTR-D2	MPTR-D3	PP10	PP10	PP30	PP30
Temp. change	0	*	*	*	*	*	*	0	0	0	0
Rainfall change (%)	0	*	*	*	*	*	*	10	10	30	30
CO2 level (ppm.)	330	460	550	460	550	460	550	330	550	330	550
Crop	1000 MT	%	%	%	%	%	%	%	%	%	%
Maize	145451	0.0	9.4	4.0	3.5	-14.0	-5.8	2.1	11.1	5.1	14.5
Sorghum	94901	0.3	11.2	3.3	3.2	-11.8	-4.4	1.0	9.9	2.5	11.8
Millet	74905	-1.9	9.4	2.8	5.3	-8.0	-4.3	-0.5	8.3	-1.6	6.8
Rice	99518	12.0	27.8	18.6	26.5	-5.0	12.6	4.2	32.8	11.1	40.9
Cowpea	57252	12.9	31.5	18.4	27.7	-2.5	14.1	1.9	34.5	4.8	39.1
Groundnut	83515	12.8	31.5	18.7	27.4	-2.2	14.3	1.7	34.4	4.4	38.7
Soybean	49741	8.8	28.4	14.9	23.1	-5.4	10.4	1.5	33.8	3.3	36.9
Beans (Phaseolus)	383	-70.8	-82.5	-14.1	-59.5	-82.5	-94.0	-3.1	66.1	-8.6	64.8
Sweet Potato	477212	14.5	32.1	19.2	28.5	-3.0	17.0	2.7	34.6	7.4	41.2
White Yam	391766	20.5	34.9	23.5	36.3	-1.0	25.7	6.4	37.7	15.4	49.3
Greater Yam	335936	14.2	23.4	24.2	35.5	-6.6	16.5	7.9	44.9	22.2	62.4
Yellow Yam	93181	12.5	11.5	24.7	41.7	-13.8	12.3	17.4	69.0	50.0	110.8
Cassava	155179	17.0	27.6	24.2	37.9	-5.6	20.2	9.4	52.6	24.7	75.2
White Potato	75	-97.3	-97.3	-82.7	-94.7	-97.3	-100.0	-12.0	65.3	-20.0	73.3
Sugarcane	77433	-1.4	-5.9	11.5	15.1	-22.1	-9.3	12.8	30.3	35.6	53.8
Banana	1200	6.8	-1.4	-33.6	-21.6	-39.7	-36.6	51.0	142.9	164.3	311.5
Oilpalm	2101	12.9	15.0	-11.9	9.9	-27.2	-10.9	36.7	112.6	113.8	205.6
Cotton	28617	25.3	47.2	26.4	33.1	4.9	26.6	1.8	32.6	4.7	36.6

Scenario	Reference	PM10	PM10	PM30	PM30	T20	T20	T20	T40	T40	T40
Temp. change	0	0	0	0	0	2	2	2	4	4	4
Rainfall change (%)	0	-10	-10	-30	-30	0	0	0	0	0	0
CO2 level (ppm.)	330	330	550	330	550	330	460	550	330	460	550
Crop	1000 MT	%	%	%	%	%	%	%	%	%	%
Maize	145451	-2.6	6.1	-11.1	-3.3	-7.5	-2.8	0.4	-14.9	-10.2	-7.2
Sorghum	94901	-1.1	7.7	-6.4	2.1	-6.8	-1.9	1.4	-13.5	-8.6	-5.5
Millet	74905	0.3	9.1	-1.6	7.1	-5.7	-0.7	2.7	-11.7	-6.9	-3.6
Rice	99518	-4.9	20.7	-18.0	4.5	-8.2	8.6	20.2	-17.1	-1.6	9.2
Cowpea	57252	-2.5	28.0	-10.9	16.4	-9.7	8.3	22.1	-19.9	-3.1	8.6
Groundnut	83515	-2.1	28.2	-10.3	17.3	-9.4	8.4	21.7	-19.5	-2.9	8.8
Soybean	49741	-1.8	29.1	-8.9	19.2	-12.3	5.4	18.5	-22.4	-6.3	5.4
Beans (Phaseolus)	383	3.9	64.8	11.0	72.6	-90.1	-83.3	-79.9	-99.7	-98.7	-97.9
Sweet Potato	477212	-3.4	26.2	-14.5	11.2	-7.5	10.3	23.5	-16.1	0.6	12.6
White Yam	391766	-8.0	19.3	-28.9	-8.1	-2.6	16.7	29.8	-8.5	9.4	22.6
Greater Yam	335936	-9.1	21.8	-34.1	-10.5	-9.6	10.0	24.4	-20.0	-2.1	11.2
Yellow Yam	93181	-17.0	21.2	-53.9	-30.7	-15.1	8.5	28.1	-28.8	-9.4	6.4
Cassava	155179	-11.1	27.1	-36.5	-7.6	-11.8	13.1	29.9	-23.6	-0.2	15.9
White Potato	75	12.0	81.3	34.7	120.0	-100.0	-97.3	-97.3	-100.0	-100.0	-100.0
Sugarcane	77433	-13.0	-0.1	-46.1	-35.9	-12.6	-4.8	0.2	-25.3	-17.6	-12.9
Banana	1200	-39.9	6.8	-87.7	-70.7	-36.1	-2.4	22.8	-57.4	-37.8	-20.2
Oilpalm	2101	-29.8	12.3	-75.6	-55.4	-24.4	4.2	27.4	-48.7	-23.3	-6.0
Cotton	28617	-1.2	28.2	-10.6	15.4	-2.4	16.6	30.6	-7.5	11.5	24.7

* = GCM derived

role. The latter is for example the case for long duration annual crops and perennials in the MPTR2-460 scenario.

The rainfall sensitivity analyses clearly show the positive impact of increasing rainfall on perennial crops and long-duration annuals, while the effect on short duration crops, although positive, is of much lower magnitude, merely because currently suitable LGP zones are simply shifted northwards. On the other hand, productivity of perennials suffers most when rainfall decreases. Just like the GCM-based scenario's, the positive impact of increased CO_2 levels on the production of C_3 crops is large, while it is limited for the C_4 group. Increases of temperature alone affect virtually all crops in a negative manner, but temperate and perennial crops most. In case of the former this is directly due to the temperature increase, but the perennials are affected by temperature induced reductions of the LGP. Negative effects of increased temperatures are less or even turned positive when CO_2 levels increase simultaneously. This balancing effect is again strongest for C_3 crops.

Tables 4.5 and 4.6 present the changes in extent of suitable land and of crop yields that determine changes of crop production potential. Changes of suitable area and crop yield are relatively minor for C_4 crops, but both, yield and extent of suitable land, may increase considerably for short duration C_3 crops, as long as the scenario includes increases of CO_2 level. The positive yield effect is less pronounced for long duration annual and perennial C_3 crops, in most GCM-based scenario's, because these at the same time imply reductions of LGP in the currently humid areas. Sensitivity scenario's, where both rainfall and CO_2 increase, show similar yield effects for short as well as long duration C_3 crops. The extent of land that is suitable for perennial crops varies very much with scenario and yield increases are limited, even when both rainfall and CO_2 levels increase, because the extension of suitable area is large in extent but refers to marginal conditions.

Annex 8 presents results of the same kind of analysis that accounts for possible contributions of multiple cropping to crop production potential. The conclusions are fairly similar to those for sole cropping conditions. However, potential production increases are higher when a scenario implies increases of LGP length.

Spatial representations of the changes of crop production potential for Millet, Maize and Cassava for selected scenario's are given in figs. 4.6-8. General map patterns reflect the effects of discrete soil mapping units, the soil specific available soil moisture capacity as well as effects of agro-climatic constraints, that are currently still applied in a discontinuous manner. For millet, both HCTR scenarios show a dispersed pattern of relatively minor productivity increases and decreases. The GFTR3-550 scenario generally produces productivity increases, which in the North of the country are due to increases of LGP length but in the South refer a reduction of humid conditions resulting in lower pest and disease pressures and less constraints on handling of wet produce. MPTR3-550 shows the same effect for south-west Nigeria, but in the north where millet is extensively grown at present, it shows extensive and large decreases of potential production caused by reduced LGP's. The sensitivity scenario with 30% reduction of rainfall at ambient levels of CO_2 (PM30-330) results in a rather dramatic shift of potential millet productivity from the north to the south. A rise of temperature with 4 °C in combination with doubling of greenhouse gasses (T40-550) gives higher production potentials at higher elevation in the centre and south-east of the country. Increases in the south-west are due to the above described effects of shortening currently long LGP's. In extensive areas of the north of the country production potentials decrease due to the temperature induced shortening of the LGP.

Overall patterns of change for maize are similar to those of millet, be it that the affected zones are shifted southward because of longer LGP requirements for maize (fig. 4.7). Cassava is a long-duration C_3 crop and therefore an entirely different picture evolves (fig. 4.8). In northern

Table 4.5 : Impacts on global change on extents of areas suitable for rainfed crops (% change for sole cropping systems

Scenario	Reference	GFTR-D2	GFTR-D3	HCTR-D2	HCTR-D3	MPTR-D2	MPTR-D3	PP10	PP10	PP30	PP30
Temp. change	0	*	*	*	*	*	*	0	0	0	0
Rainfall change (%)	0	*	*	*	*	*	*	10	10	30	30
CO2 level (ppm.)	330	460	550	460	550	460	550	330	550	330	550
Crop	100 ha	%	%	%	%	%	%	%	%	%	%
Maize	458284	-2.8	5.2	0.6	0.1	-13.8	-5.4	2.6	6.1	6.0	10.2
Sorghum	512225	-2.4	6.1	1.1	1.7	-11.8	-4.1	2.1	5.6	5.6	9.9
Millet	520127	-1.1	8.0	2.5	3.4	-8.3	-3.6	-0.9	2.6	-3.2	-0.3
Rice	452743	2.1	12.6	6.5	7.5	-9.5	-0.6	3.9	13.0	10.0	17.5
Cowpea	474135	1.6	11.5	4.9	9.2	-8.7	0.7	2.1	12.1	5.4	16.6
Groundnut	438903	1.3	11.2	5.2	7.8	-9.4	0.3	2.4	13.1	6.5	18.3
Soybean	445518	0.6	10.4	5.0	6.9	-10.3	0.1	2.2	12.2	4.9	16.0
Beans (Phaseolus)	3659	-61.4	-73.8	-7.6	-49.9	-76.5	-89.0	-0.1	103.4	-0.5	110.9
Sweet Potato	434417	2.3	13.1	4.3	7.2	-12.1	1.6	2.8	12.0	8.1	17.8
White Yam	247949	11.9	17.7	10.6	12.0	-8.7	10.6	6.6	13.1	15.7	22.0
Greater Yam	232095	9.8	18.5	14.8	14.8	-9.2	6.7	5.6	24.7	17.2	34.2
Yellow Yam	96369	9.6	10.6	28.0	39.5	-10.6	12.7	12.7	46.5	35.8	69.6
Cassava	188699	7.4	13.4	11.0	12.3	-11.1	5.1	6.2	20.3	14.8	32.2
White Potato	86	-93.0	-93.0	-76.7	-88.4	-94.2	-100.0	-14.0	111.6	-15.1	150.0
Sugarcane	130868	-0.9	-1.7	10.3	12.5	-19.2	-6.7	10.4	23.0	27.8	38.8
Banana	7494	5.1	-3.6	-34.6	-22.0	-40.5	-33.7	47.3	117.1	144.1	250.3
Oilpalm	22010	10.5	12.6	-10.0	12.1	-27.0	-9.0	34.4	92.5	102.2	158.1
Cotton	309217	12.5	23.3	13.1	11.0	-6.5	8.5	3.0	12.3	7.6	17.2

Scenario	Reference	PM10	PM10	PM30	PM30	T20	T20	T20	T40	T40	T40
Temp. change	0	0	0	0	0	2	2	2	4	4	4
Rainfall change (%)	0	-10	-10	-30	-30	0	0	0	0	0	0
CO2 level (ppm.)	330	330	550	330	550	330	460	550	330	460	550
Crop	100 ha	%	%	%	%	%	%	%	%	%	%
Maize	458284	-3.0	0.5	-12.4	-9.9	-2.8	-1.1	-0.2	-6.6	-4.2	-3.0
Sorghum	512225	-2.0	1.3	-9.3	-6.0	-2.5	-0.6	0.7	-6.0	-3.1	-1.8
Millet	520127	0.5	3.9	-3.6	-0.2	-1.6	0.7	2.0	-4.2	-1.9	-0.3
Rice	452743	-4.3	3.8	-14.6	-6.0	-4.0	3.0	6.8	-8.5	-1.5	2.5
Cowpea	474135	-2.9	6.0	-10.4	-2.6	-3.8	1.8	7.6	-8.9	-1.5	1.5
Groundnut	438903	-2.7	5.7	-11.1	-2.7	-3.6	1.7	5.9	-8.2	-1.8	1.4
Soybean	445518	-2.4	7.2	-11.0	-1.9	-4.8	1.7	6.2	-9.6	-3.2	1.0
Beans (Phaseolus)	3659	0.3	82.7	-1.0	84.1	-88.4	-76.2	-71.6	-99.2	-97.4	-95.5
Sweet Potato	434417	-3.5	5.1	-14.9	-7.4	-2.1	2.3	6.5	-5.4	-0.4	2.8
White Yam	247949	-8.7	-2.1	-30.7	-25.4	2.3	9.9	12.4	3.6	9.1	13.8
Greater Yam	232095	-6.2	10.0	-25.8	-10.7	-5.3	5.3	12.8	-12.0	-2.2	5.3
Yellow Yam	96369	-11.6	15.9	-43.2	-24.4	-9.3	6.7	21.9	-17.5	-5.2	6.1
Cassava	188699	-8.6	8.1	-29.0	-14.0	-7.6	4.9	10.4	-15.5	-1.9	4.8
White Potato	86	9.3	115.1	14.0	144.2	-100.0	-95.3	-93.0	-100.0	-100.0	-100.0
Sugarcane	130868	-10.2	-1.6	-40.5	-31.8	-8.5	-3.1	0.1	-18.3	-12.1	-8.7
Banana	7494	-38.9	1.2	-86.1	-68.7	-34.3	-4.0	17.0	-53.2	-36.6	-21.0
Oilpalm	22010	-27.7	6.4	-73.3	-54.5	-20.9	2.5	21.8	-44.5	-20.7	-6.4
Cotton	309217	-2.9	5.7	-14.6	-7.1	-0.2	6.4	11.1	-1.4	5.8	9.8

* = GCM derived

Table 4.6: Impacts of global change on crop yields of rainfed crops (% change for sole cropping systems)

Scenario	Reference	GFTR -D2	GFTR -D3	HCTR -D2	HCTR -D3	MPTR -D2	MPTR -D3	PP10	PP10	PP30	PP30
Temp. change	0	*	*	*	*	*	*	0	0	0	0
Rainfall change (%)	0	*	*	*	*	*	*	10	10	30	30
CO2 level (ppm.)	330	460	550	460	550	460	550	330	550	330	550
Crop	kg/ha	%	%	%	%	%	%	%	%	%	%
Maize	3174	2.8	3.9	3.3	3.5	-0.2	-0.4	-0.4	4.8	-0.9	3.9
Sorghum	1853	2.9	4.9	2.1	1.5	0.1	-0.3	-1.1	4.0	-3.0	1.7
Millet	1440	-0.8	1.3	0.3	1.8	0.3	-0.7	0.4	5.6	1.7	7.2
Rice	2198	9.7	13.5	11.4	17.6	5.0	13.2	0.3	17.6	1.0	19.9
Cowpea	1208	11.0	17.9	12.8	16.9	6.7	13.2	-0.2	20.0	-0.7	19.2
Groundnut	1903	11.4	18.3	12.8	18.1	8.0	13.9	-0.7	18.9	-2.0	17.2
Soybean	1116	8.2	16.3	9.5	15.2	5.5	10.3	-0.6	19.4	-1.4	18.1
Beans (Phaseolus)	1047	-24.5	-33.2	-7.2	-19.6	-25.5	-46.2	-3.2	-18.3	-8.0	-21.9
Sweet Potato	10985	12.0	16.8	14.2	19.9	10.4	15.1	-0.1	20.2	-0.6	19.9
White Yam	15800	7.7	14.6	11.6	21.7	8.4	13.6	-0.2	21.7	-0.2	22.3
Greater Yam	14474	4.0	4.1	8.2	18.1	2.9	9.2	2.2	16.1	4.3	21.0
Yellow Yam	9669	2.6	0.9	-2.6	1.6	-3.6	-0.4	4.2	15.4	10.5	24.3
Cassava	8224	8.9	12.5	11.8	22.8	6.2	14.3	3.0	26.9	8.6	32.5
White Potato	8735	-51.1	-50.4	-21.7	-48.5	-51.8	-100.0	2.6	-22.1	-5.8	-30.4
Sugarcane	5917	-0.5	-4.3	1.1	2.3	-3.6	-2.8	2.2	5.9	6.1	10.7
Banana	1602	1.6	2.2	1.5	0.4	1.4	-4.3	2.5	11.8	8.2	17.4
Oilpalm	955	2.1	2.1	-2.1	-2.0	-0.3	-2.1	1.6	10.4	5.7	18.3
Cotton	925	11.5	19.5	11.8	20.0	12.2	16.8	-1.1	18.3	-2.6	16.6

Scenario	Reference	PM10	PM10	PM30	PM30	T20	T20	T20	T40	T40	T40
Temp. change	0	0	0	0	0	2	2	2	4	4	4
Rainfall change (%)	0	-10	-10	-30	-30	0	0	0	0	0	0
CO2 level (ppm.)	330	330	550	330	550	330	460	550	330	460	550
Crop	kg/ha	%	%	%	%	%	%	%	%	%	%
Maize	3174	0.4	5.5	1.5	7.3	-4.9	-1.7	0.6	-8.9	-6.3	-4.3
Sorghum	1853	0.9	6.3	3.1	8.5	-4.4	-1.3	0.7	-8.0	-5.7	-3.7
Millet	1440	-0.1	5.1	2.1	7.4	-4.2	-1.4	0.6	-7.8	-5.1	-3.4
Rice	2198	-0.7	16.3	-4.0	11.2	-4.4	5.4	12.5	-9.4	-0.1	6.6
Cowpea	1208	0.3	20.7	-0.6	19.4	-6.0	6.3	13.5	-12.2	-1.7	6.9
Groundnut	1903	0.5	21.3	0.8	20.5	-6.0	6.6	14.9	-12.2	-1.2	7.3
Soybean	1116	0.7	20.4	2.3	21.6	-7.9	3.7	11.6	-14.2	-3.1	4.5
Beans (Phaseolus)	1047	3.6	-9.9	12.0	-6.2	-14.2	-29.5	-28.9	-56.4	-53.8	-52.3
Sweet Potato	10985	0.1	20.1	0.5	20.0	-5.6	7.8	16.0	-11.3	1.0	9.5
White Yam	15800	0.8	21.8	2.6	23.1	-4.8	6.2	15.5	-11.7	0.3	7.7
Greater Yam	14474	-3.0	10.8	-11.2	0.2	-4.5	4.5	10.3	-9.1	0.1	5.6
Yellow Yam	9669	-6.1	4.5	-18.8	-8.3	-6.3	1.7	5.2	-13.7	-4.4	0.3
Cassava	8224	-2.8	17.7	-10.6	7.4	-4.5	7.8	17.6	-9.7	1.7	10.6
White Potato	8735	1.2	-15.9	17.4	-10.2	-100.0	-52.0	-50.0	-100.0	-100.0	-100.0
Sugarcane	5917	-3.1	1.5	-9.4	-6.0	-4.5	-1.8	0.1	-8.6	-6.3	-4.6
Banana	1602	-1.8	5.4	-11.7	-6.4	-2.9	1.7	4.9	-9.1	-1.9	1.0
Oilpalm	955	-3.0	5.5	-8.5	-2.1	-4.5	1.6	4.5	-7.6	-3.4	0.3
Cotton	925	1.8	21.4	4.6	24.2	-2.2	9.7	17.6	-6.1	5.4	13.6

* = GCM derived

Fig. 4.6: Changes of millet productivity for six climate change scenario's, relative to reference conditions (kg/ha)

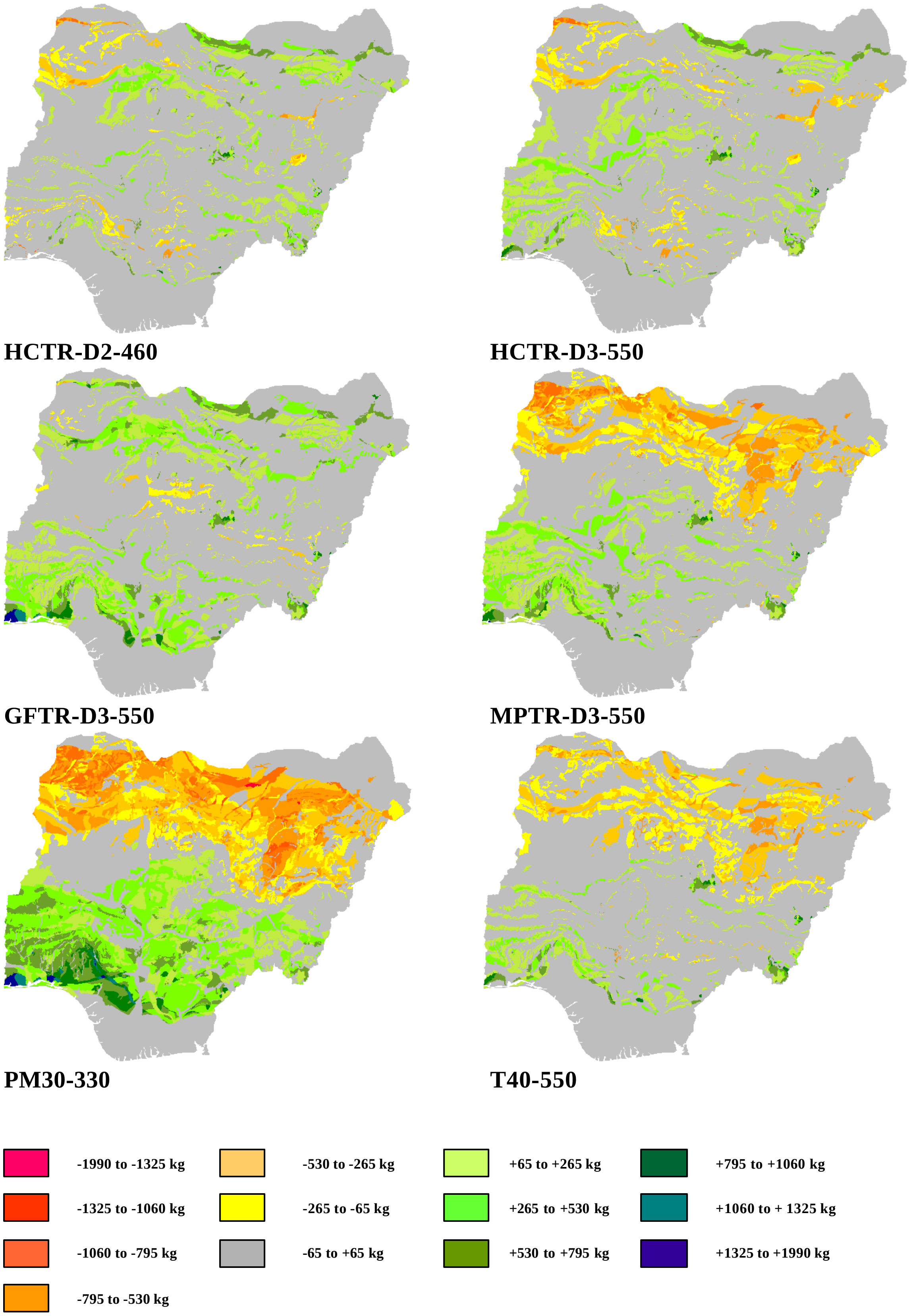


Fig. 4.7: Changes of Maize productivity for six climate change scenario's, relative to reference conditions (kg/ha)

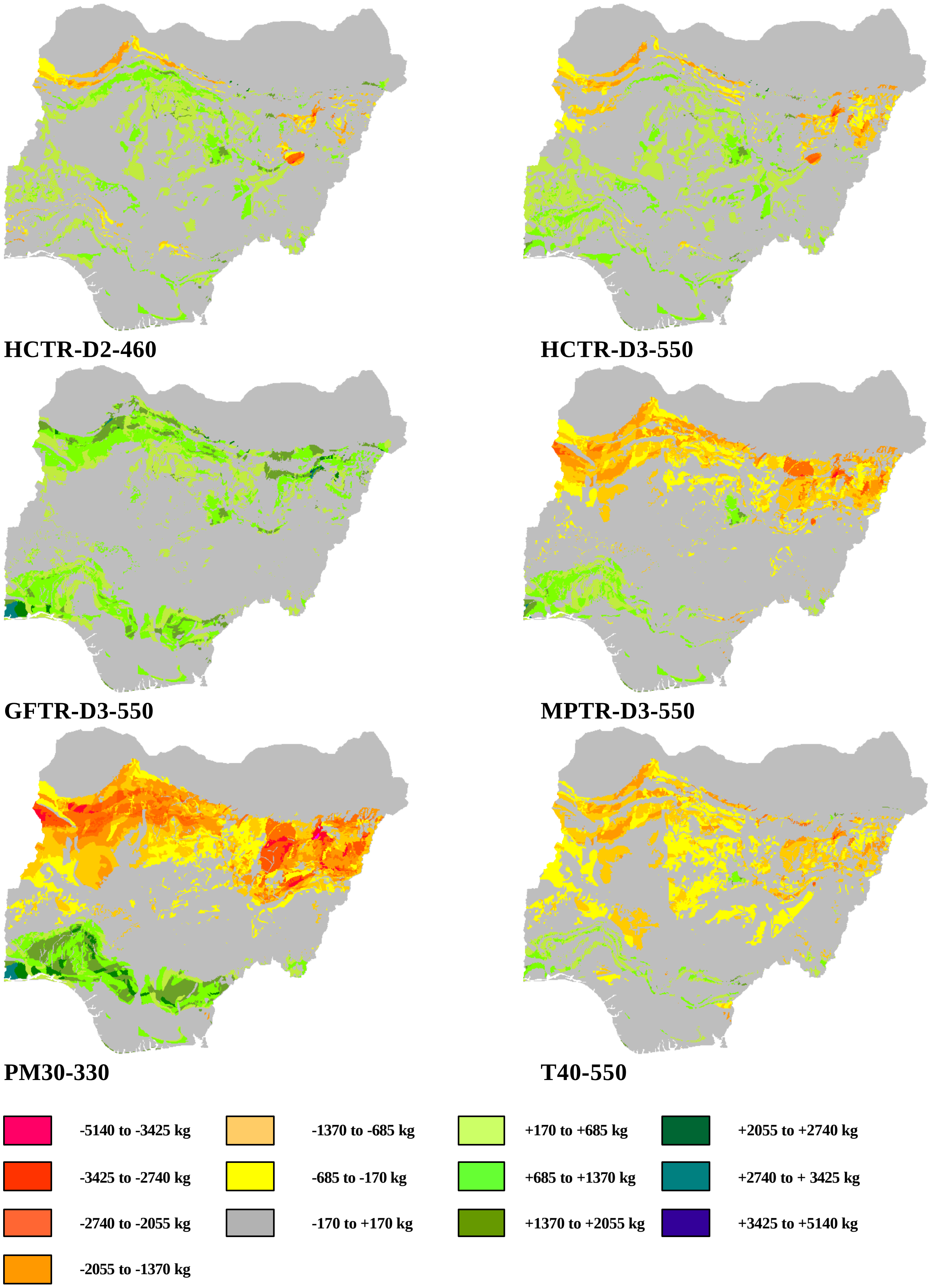
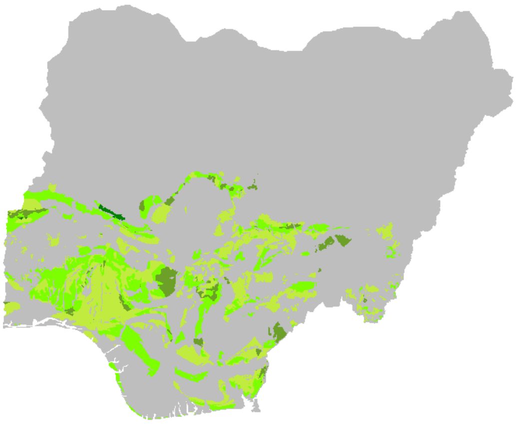
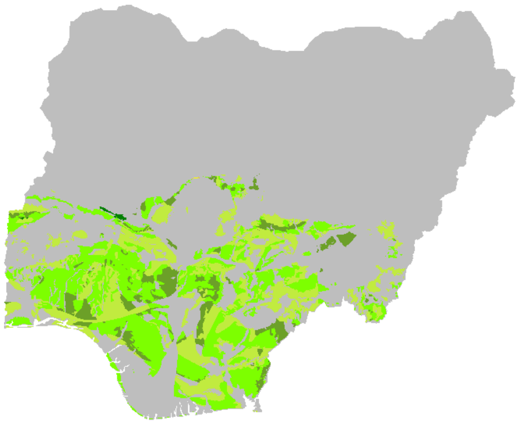


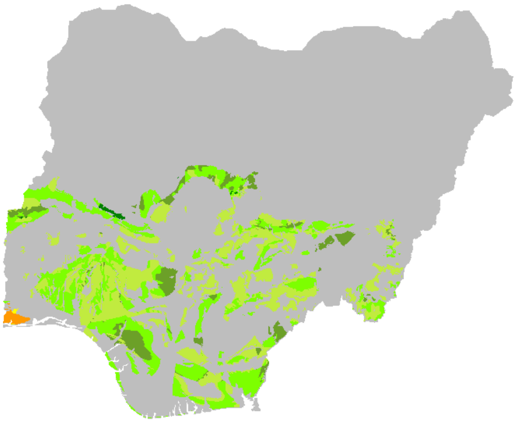
Fig. 4.8: Changes of Cassava productivity for six climate change scenario's, relative to reference conditions (kg/ha)



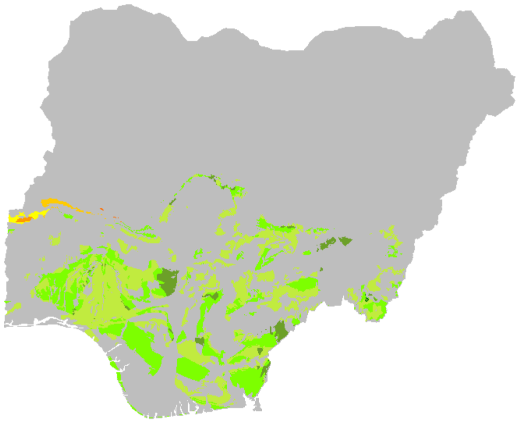
HCTR-D2-460



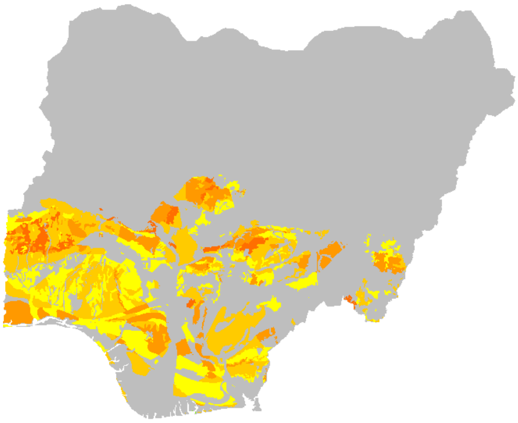
HCTR-D3-550



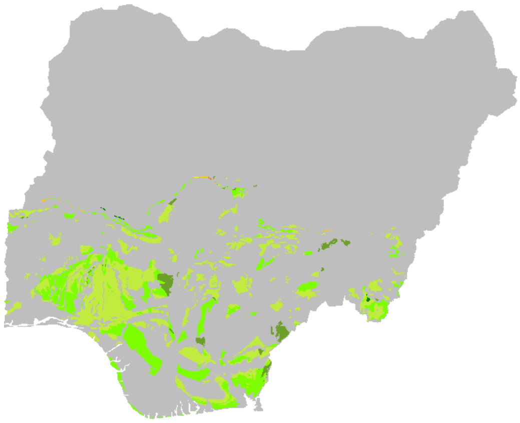
GFTR-D3-550



MPTR-D3-550



PM30-330



T40-550

Nigeria there is no change because the short LGP in both, baseline and scenario conditions, makes the area largely unsuitable. In the south, GCM-based scenarios generally show an increase of potential production, mainly due to the CO_2 fertilization effect. Extent and magnitude of increases of potential are further determined by changes of LGP length. Negative effects of reduced LGP's caused by lower rainfall levels are evident from the PM30-330 scenario. The T40-550 scenario shows that the positive CO_2 effects are limited in the northern part of the suitable area, because of the balancing effect of a reduced LGP. More southward, in the currently humid area, the effect of temperature increases on LGP length is limited and consequently the CO_2 effect is more pronounced.

4.2.2 Land productivity

The assessment of land productivity considers all crops and varieties of the study simultaneously. For each of the gridcells, the locally best performing crop combinations, in terms of the food production objective, are determined. The selection of these 'optimal' cropping patterns has been repeated for each of the climate change scenario's. It is therefore assumed that farmers are 'smart' and adapt cropping activities optimally in response to climate change, within the limits of the set of available cropping options. Land productivity is again assessed for GCM-based scenarios and sensitivity scenario's to enable separation of possible impacts of climate change from the effects of CO_2 fertilization and enhanced water-use efficiency. Results are presented as a percentage difference between scenario and baseline conditions. The productivity for each condition has been quantified by a weighted sum of extents of land with cultivation potential and their productivity.

Small scale maps with the results for GCM-based scenario's are presented in fig. 4.9 and six sensitivity examples are given in fig. 4.10. Compared with the results of single crops some of the discontinuities are somewhat enhanced, because of jumps from one crop to another and implications of this for the application of agro-climatic constraints, that are both crop and LGP specific.

All GCM-based scenario's show positive effects of global change on land productivity at higher elevations (Jos plateau, Mambilla range). The effect is least in extent and magnitude in an east-west belt in the middle of the country. The current LGP length and the limited range of predicted changes imply that farmers in this zone will be able to select crops and varieties that are well suited to the changed climatic conditions. In this area, the yield of C_4 cereals would be fairly similar to current levels, but production increases might be expected for C_3 crops (e.g. cowpea), due to CO_2 fertilization. The scenario's show a more widespread positive effect in the south of the country, because C_3 rootcrops are and will remain the most productive crops in this area and therefore CO_2 fertilization has a large impact. In northern Nigeria the possible effects of global change on land productivity vary with scenario and also regionally within scenario's. Concentrating on decade-3 conditions, it may be seen that land productivity generally improves in case of the GFTR scenario. Productivity changes are particularly large when increases of LGP length allow to shift from millet to maize, which has a higher genetic yield potential. The HCTR3-550 scenario shows similar increases in the north-east, although to a lesser geographic extent. In the north-west it indicates productivity decreases rather than increases. The MPTR scenario implies a widespread and serious land productivity decline throughout the north of Nigeria

Fig. 4.9: Changes of land productivity for six climate change scenario's, relative to reference conditions (%)

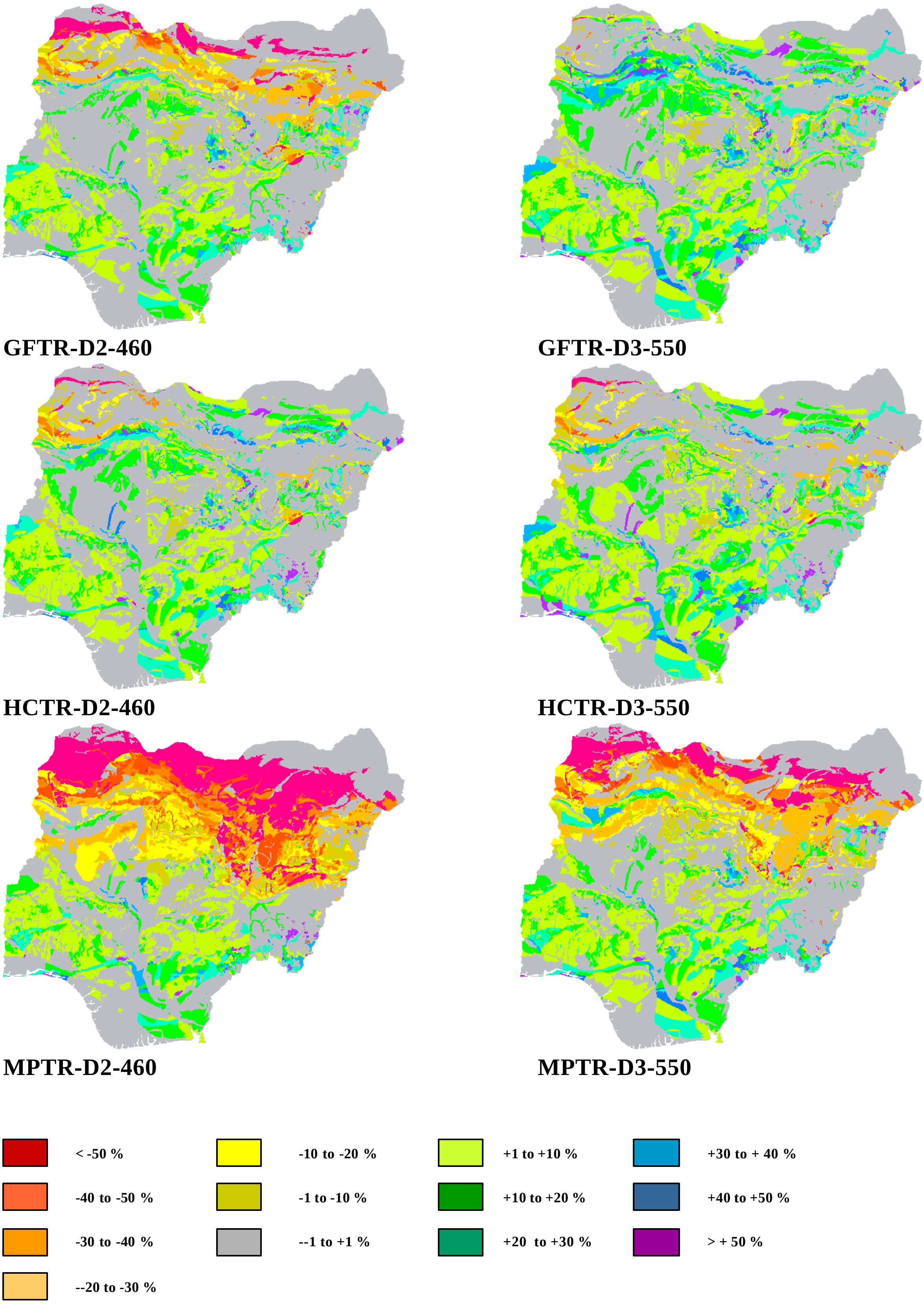
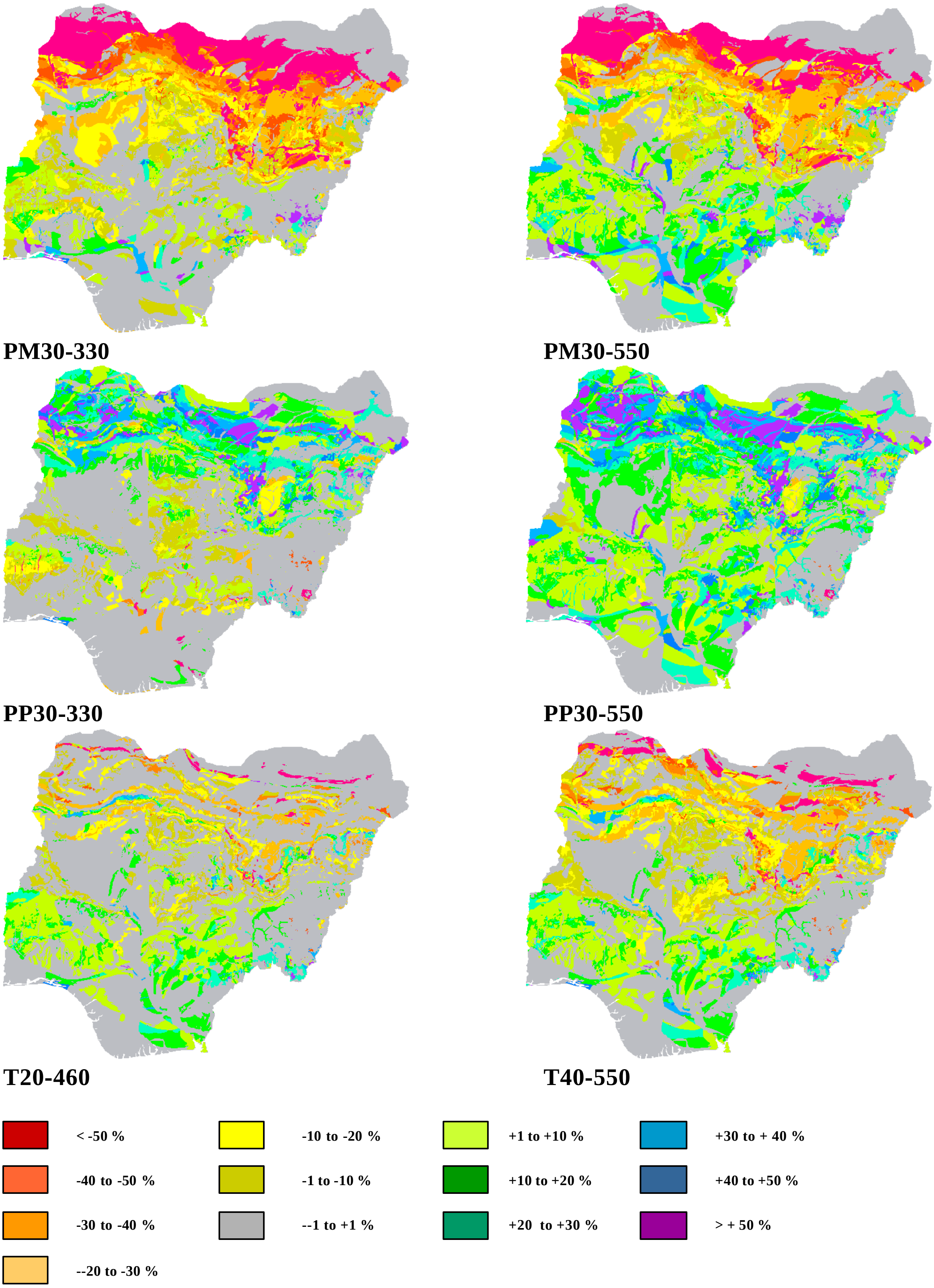


Fig. 4.10: Changes of land productivity for six climate change scenario's, relative to reference conditions (%)



The sensitivity scenario's (fig. 4.10) show that decreases of rainfall at current CO_2 levels mainly affect the north of the country. In the south and middle, this kind of reduction of rainfall does affect LGP length much less and the effect on land productivity is therefore limited. Negative changes in this area refer to a curtailment of LGP where short duration annuals are most productive. Positive changes in this zone mainly refer to a shortening of the humid period. The same decrease of rainfall with elevated CO_2 (PM30-550) shows that increased CO_2 does have little effect in the north, because the shortening of LGP is overruling and because the most productive crops belong to the less responsive C_4 group. Positive impacts of enhanced CO_2 on the productivity of C_3 crops is evident in the south. Increased rainfall without CO_2 increase (PP30-330) results in large productivity increases in extensive areas of the north, while in the south there is hardly an effect. Increasing CO_2 under these conditions (PP30-550) increases land productivity in the south on a similar basis as for reduced rainfall. In the northern parts we now also observe an additional effect of CO_2 fertilization. Both temperature sensitivity scenario's (with CO_2 effect) show land productivity increases at higher elevation and in the south of the country. In the north there is a negative trend in both cases.

4.3 Sensitivity to global change

Relative changes of land productivity for each scenario at the sub-national state level are presented in table 4.7 . These results are used, in combination with the maps, to analyze which of the current conditions are particularly sensitive to climate change and enhanced CO_2. As already noted earlier, the areas of higher elevation are very sensitive to global change because temperature increases at these elevations imply a decline of land suitability for temperate crops and consequently the loss of production opportunities for special crops that cannot be grown elsewhere in Nigeria. Land productivity itself is not necessarily affected in this case because the areas concerned become more suitable for tropical crops. Areas with currently short growing periods are also very sensitive to global change as may be evident from the figures referring to northern states in table 4.7. Here, small changes in rainfall amount result in drastic reductions or improvements of land productivity. This sensitivity mainly operates through the effect of changes of rainfall on LGP length, while the CO_2 fertilization effect is limited because the highest productivity is obtained from C_4 crops.

At the other extreme of LGP length, the currently humid zone, we also find important sensitivities to global change. Reductions of LGP length, as most GCM-based scenario's imply, have large impacts on the productivity of perennial crops. Here again the overall land productivity may not be affected, but the extent of optimal growing conditions for yet another group of special crops is at stake. For south-west Nigeria, as exemplified by Lagos state (table 4.7), large differences in land productivity change between the scenario's may be observed. Rainfall patterns in this area have a bimodal tendency which implies that land productivity is particularly sensitive to changes of rainfall. Currently, based on mean rainfall data, there is one relatively long LGP. Decreases of rainfall however, accentuate the bimodality and may result in two separate short seasons. Whether or not this occurs depends on the pattern and magnitude of the change of rainfall in combination with the available soil moisture holding capacity that may become decisive in this respect. Similar effects are at play in rainshadow areas, like north-east of the Jos plateau and inland areas at low altitudes, associated with the main rivers Niger and Benue (Keyzer et al., 1997).

Table 4.7: Impacts of global change on potental land productivity by state (% change**)**

Scenario	GFTR-D2	GFTR-D3	HCTR-D2	HCTR-D3	MPTR-D2	MPTR-D3	PP10	PP10	PP30	PP30
Temp. change	*	*	*	*	*	*	0	0	0	0
Rainfall change (%)	*	*	*	*	*	*	10	10	30	30
CO2 level (ppm.)	460	550	460	550	460	550	330	550	330	550
North-West										
Sokoto	-16.5	10.5	-2.4	-3.5	-46.5	-28.8	6.7	14.7	19.7	30.8
Kebbi	-9.0	9.6	-2.7	-3.6	-34.4	-20.9	7.9	17.2	19.1	27.4
North-Central										
Katsina	-15.7	8.1	2.8	2.6	-54.4	-29.1	6.0	13.2	15.5	25.7
Kano	-10.9	11.0	4.2	1.3	-45.1	-18.1	10.9	20.6	22.5	29.5
Jigawa	-20.6	10.2	9.0	7.8	-71.9	-31.0	10.5	21.0	31.7	37.3
Bauchi	-4.3	6.0	3.8	2.9	-43.6	-17.2	4.2	12.4	15.6	23.1
North-East										
Borno	-4.0	5.6	4.3	1.6	-21.6	-12.8	4.1	8.1	10.4	13.7
Yobe	-15.4	6.8	5.1	3.1	-44.8	-30.0	4.7	8.1	11.8	15.5
Mid-West										
Niger	1.7	4.5	4.1	4.8	-4.9	-0.1	1.0	7.6	1.8	8.2
Kwara	6.0	7.9	7.3	9.2	4.3	5.2	-0.1	9.7	0.1	9.2
Kogi	3.3	5.6	4.6	7.2	2.5	5.2	-0.4	6.7	-1.1	6.6
Mid-Central										
Kaduna	3.8	6.3	4.8	4.0	-11.6	0.5	2.3	6.4	4.2	8.8
Abuja	1.0	1.4	1.0	2.1	4.9	1.8	-1.2	2.4	-2.7	1.2
Plateau	4.1	6.1	4.7	7.9	-4.3	2.2	1.0	8.1	0.8	10.2
Mid-East										
Adamawa	4.1	4.3	2.9	4.6	-10.7	-0.1	2.0	7.3	3.4	8.2
Taraba	2.6	7.2	6.0	7.9	1.4	5.4	-0.6	7.5	-0.9	6.1
Benue	8.5	11.7	10.3	17.0	6.6	11.2	-0.2	16.5	-1.8	16.0
South-West										
Ogun	4.0	8.7	4.9	12.4	5.3	6.5	-0.8	11.8	-0.4	9.3
Ondo	4.3	6.2	4.8	6.0	4.2	5.7	0.3	6.8	0.3	6.7
Osun	2.6	4.8	3.1	4.6	2.9	4.2	-0.2	4.6	-0.5	4.5
Oyo	6.6	8.9	7.1	10.4	6.0	8.0	-1.1	10.1	-3.6	9.4
Lagos	5.0	17.4	4.8	32.3	13.3	14.8	-4.8	14.6	3.2	13.8
Edo	4.3	7.7	5.0	6.8	5.5	6.8	-1.4	7.4	-3.2	6.9
South-East										
Abia	5.9	13.6	9.3	14.0	7.2	12.8	-0.8	12.3	-3.8	10.1
Akwa-Ibom	10.1	12.3	12.1	12.5	9.6	12.4	-0.6	12.3	-1.0	12.3
Anambra	6.6	16.7	7.2	14.5	12.9	11.1	-2.6	13.4	-3.6	14.4
Enugu	9.0	12.7	9.3	10.4	11.3	9.9	-0.8	10.6	-2.9	9.0
Imo	4.4	13.6	6.9	15.2	3.8	15.5	0.0	15.0	0.0	14.3
Rivers	1.3	2.9	1.7	4.6	1.6	2.3	0.0	3.6	0.0	3.1
Delta	3.2	3.7	3.6	3.7	2.9	3.7	0.1	3.6	-0.1	3.6
Cross River	9.9	14.6	11.1	14.9	8.8	12.7	-1.0	14.4	-1.0	13.7
Temp. change	0	0	0	0	2	2	2	4	4	4
Rainfall change (%)	-10	-10	-30	-30	0	0	0	0	0	0
CO2 level (ppm.)	330	550	330	550	330	460	550	330	460	550
North-West										
Sokoto	-10.4	-4.6	-45.9	-40.3	-10.4	-4.7	-1.9	-20.9	-16.3	-12.6
Kebbi	-5.5	1.6	-34.6	-29.1	-7.3	-4.4	-1.3	-14.2	-9.3	-7.2

Table 4.7 (cont.): Impacts of global change on potental land productivity by state (% change**)**

Scenario	GFTR-D2	GFTR-D3	HCTR-D2	HCTR-D3	MPTR-D2	MPTR-D3	PP10	PP10	PP30	PP30
North-Central										
Katsina	-10.4	-2.6	-46.9	-40.1	-10.0	-5.9	-2.6	-26.2	-17.4	-14.0
Kano	-8.0	-0.2	-36.8	-29.8	-10.0	-6.4	-3.6	-18.7	-14.0	-12.1
Jigawa	-17.5	-8.4	-63.7	-54.6	-11.2	-5.5	-3.1	-27.5	-20.2	-14.2
Bauchi	-8.2	0.1	-34.3	-25.5	-10.8	-5.2	-2.0	-22.3	-16.6	-13.1
North-East										
Borno	-5.0	0.0	-19.9	-15.2	-5.0	-2.8	-0.6	-10.1	-7.6	-6.0
Yobe	-15.0	-3.3	-39.7	-34.1	-15.4	-7.7	-3.0	-25.4	-21.7	-17.4
Mid-West										
Niger	-0.9	5.8	-8.4	-1.4	-3.3	-0.1	3.1	-7.7	-3.1	-0.9
Kwara	-0.2	8.5	-1.7	8.4	-4.9	3.7	8.2	-7.7	-4.1	1.7
Kogi	0.3	7.0	-0.1	6.9	-3.1	2.2	6.0	-5.3	-1.0	3.0
Mid-Central										
Kaduna	-1.6	2.3	-7.1	-2.8	-4.5	-0.5	2.3	-12.0	-5.4	-1.9
Abuja	0.8	2.1	4.3	8.1	-10.0	-0.8	1.7	-12.8	-8.9	-6.1
Plateau	-1.4	5.9	-6.1	0.8	-6.1	-0.6	4.8	-11.1	-7.4	-3.8
Mid-East										
Adamawa	-1.2	3.9	-10.0	-4.3	-3.5	-1.1	1.0	-7.3	-4.1	-1.8
Taraba	-0.1	8.4	-0.8	6.0	-2.4	3.6	6.8	-4.4	-0.6	3.4
Benue	0.5	16.3	2.0	14.7	-0.2	7.5	11.8	-4.1	0.7	9.3
South-West										
Ogun	1.5	12.2	7.6	13.3	-4.2	2.9	6.3	-6.5	1.7	3.3
Ondo	-0.4	6.4	0.4	10.3	-4.0	3.4	5.4	-9.8	0.6	4.0
Osun	0.4	5.0	-0.2	5.5	-7.2	2.0	4.4	-13.2	0.2	2.6
Oyo	0.8	10.5	0.6	9.7	-3.3	5.8	9.2	-6.8	0.9	7.1
Lagos	3.9	29.7	21.8	28.0	-1.5	4.4	9.1	-11.0	4.8	5.2
Edo	1.3	8.3	5.3	11.8	-2.8	2.5	6.9	-4.2	0.0	3.3
South-East										
Abia	-0.1	14.5	3.3	15.2	-2.8	4.5	12.5	-3.6	0.6	6.6
Akwa-Ibom	0.3	12.3	0.7	12.8	-4.5	9.3	12.3	-6.3	1.2	10.4
Anambra	4.5	16.2	14.0	21.4	-3.3	4.2	11.1	-4.3	-0.4	7.5
Enugu	1.0	13.8	1.9	16.7	-3.1	6.2	10.7	-3.6	0.5	6.9
Imo	0.0	11.5	2.4	14.6	-1.0	4.5	15.4	-7.9	0.2	9.5
Rivers	0.7	4.7	1.4	5.2	-1.0	0.8	2.4	-2.5	0.0	1.1
Delta	-0.1	3.8	-0.8	3.9	-1.2	3.0	3.6	-1.4	1.0	3.2
Cross River	0.6	15.5	0.9	15.5	-4.5	7.3	13.7	-5.9	0.5	9.1

The above described four different types of sensitive areas together roughly cover 50% of Nigeria. We observe that in 3 out of 4 cases the sensitivity is related to changes of rainfall for which the GCM's provide a diverging picture.

Section 5

Conclusions

Nigeria currently comprises a wide variety of agro-ecological conditions based on large differences in both climate and soils. The revised and expanded agro-ecological zones approach appears appropriate to capture the diverse impacts that may affect agricultural production potential in different ecological conditions. It provides a comprehensive and suitable framework for integrating the impacts of enhanced CO_2, climatic changes and altered crop physiology in terms of single crop production, extents of cultivable lands, crop yields and productivity enhancements obtained from multiple cropping. It has been shown how it can serve a spatially explicit analysis at national level that could highlight issues of national policy relevance.

However, drawing firm conclusions of immediate policy relevance is hampered by uncertainty due to a number of issues. First, there is uncertainty with respect to the total impact of all variables involved in global change which, at the ecosystem level, operate simultaneously and in an integrated manner. The possible occurrences and effects of a number of feedback mechanisms is not yet fully understood and knowledge on the effects of global change on soil properties is still poorly developed (Annex 1). Secondly, climate has changed since about 1970. There has been little change in the middle of the country, in the coastal areas there was much less rain but with little effect on the LGP and in the north the decrease of rainfall increased with latitude and has large impacts on LGP and yield potential (Voortman, 1998). These patterns show a fair resemblance to some of the GCM experiments but it is uncertain if such changes are forced by increased levels of greenhouse gasses. This issue further poses the important question as to what baseline period to use. Thirdly, we have noted that GCM implied patterns of change diverge particularly with respect to rainfall and it is exactly rainfall that is the single most important factor that, through its effect on LGP, determines agricultural potentials. Such weaknesses of GCM's are well known and results should be dealt with as broad scale sets of possible changes rather than predictions (IPPC, 1994), but at the same time it should be realized that only GCM's offer the possibility to provide estimates of regional climate change. Lastly, there are some limitations due to the use of mean rainfall data. Albersen et al. (1998), merely applied mean GCM implied changes to individual years of a time series and show that in parts of Nigeria, a shortening LGP coincides with an increasing frequency of occurrence of extreme events from 10 to 50 percent of the years. This will have considerable implications for farming systems and the use of mean data therefore does not fully capture the possible impacts of global change on food security.

Nevertheless, if we take a cautionary band width with respect to possible real world events, we may draw the following conclusions:

- Temperature increases are very likely and these will reduce the extent of cool areas and consequently the possibilities for growing temperate crops. It does not necessarily affect land productivity negatively because productivity of tropical crops will increase in the areas concerned.
- Land productivity in the middle belt of Nigeria will be hardly affected by global change. GCM scenario's consistently result in minor changes of climate and this confirms the patterns of historic climate change. Due to this, but also because of current LGP length, adaptation is easy by switching of crops or varieties in order to reduce productivity losses. C_4

crop yields will be fairly similar to current conditions and C_3 crop yields (e.g. pulses) are likely to increase.

- The south of the country is expected to systematically benefit from global change, as long as changes of precipitation do not exceed the expected band width. C_3 crops are and will remain the most productive crops and their yields will be positively affected by CO_2 fertilization. Global change effects on production potentials of perennial crops are somewhat uncertain, varying from minor increases to rather large decreases. Land productivity may be maintained in the latter case by switching to long duration annual crops.
- The effects of global change on northern Nigeria are more uncertain. The benefits of CO_2 fertilization will be limited because C_4 crops are and remain the most productive crops. The main impacts are therefore to be expected from changes in temperature and particularly precipitation. The temperature sensitivity scenario's systematically show decreases of land productivity because higher temperatures further shorten the already short LGP's. The latter also causes that impacts of increased or decreased rainfall are very large. The GCM based scenarios show some tendency towards decreased productivity in at least parts of this zone and historic climate change has already seriously affected potentials. A cautious conclusion is therefore that global change may have important negative impacts on land productivity in northern Nigeria.
- The possible negative impact in the North may have important social consequences as large parts of this area are currently densily populated. It may therefore require outmigration to areas further south, where land resource conditions are quite different. The likely simultaneous productivity increase in the South of the country will further increase within-country disparities in opportunities of enhancing land productivity.

Although there is some uncertainty with respect to the above conclusions we can more certainly identify areas that are sensitive to climate change, irrespective of direction and magnitude of global change, because of their current characteristics. These are:

- Areas at high altitude, where increased temperatures call for changes of cropping patterns.
- Areas where currently growing periods are short, where temperature increases alone shorten the LGP and where the impact of rainfall changes, for better or worse, is large.
- Areas with currently very long LGP's, where decreases in rainfall may impact upon perennial crop production potentials.
- Areas with a bimodal tendency in rainfall patterns, where the interplay between changes of rainfall and temperature together with soil waterholding capacities determines whether there will be one continuous long season or two short ones.

In the present study we have compared crop production potentials and land productivity for identical input/management levels (intermediate) with and without the possible effects of global change, but it should be realized that the impact of improving technology can be much larger than global change effects. However, although technology generally can enhance land productivity, it cannot deal with the need to change crops in areas at higher altitudes or a possible shift in crops where currently perennials are grown, if so required. More importantly, higher technology levels under rainfed conditions cannot compensate for reductions of the length of the growing period in the northern parts of the country, if this occurs.

The uncertainty associated with projections of climate change and assessments of impacts on agricultural potential calls for attentive preparedness, that includes the monitoring of current climate, 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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Annex 1

Possible effects of climate change and enhanced atmospheric CO_2-levels on the environment, crop yields and land productivity

(Voortman, 1998)

This annex is a copy of a SOW-VU internal document prepared for the purpose of this study after attendance of the GCTE-LUCC Open Science Conference on Global Change, 'The Earth's Changing Land', 14-18 March, Barcelona, Spain.

A1.1 Introduction

Global change due to increasing levels of greenhouse gasses in the atmosphere has a number of interrelated effects on plant growth, and consequently on land productivity. First, the increase of atmospheric CO_2 itself affects plant growth directly in terms of phenology and biomass production. Secondly, elevated CO_2-levels induce stomatal closure, leading to higher water use efficiencies. The effect of both phenomena varies with crop species and is related to their photosynthetic pathway. In addition, global change is expected to affect climatic variables such as temperature, precipitation, humidity and consequently evapotranspiration. Changes in terms of these variables impact on plant growth either directly, e.g. through effects of temperature on photosynthesis, or indirectly through changes in the water balance and consequently the time duration of moisture availability that allows plant growth. The effect of changing basic climatic variables is again crop specific and related to both their photosynthesis pathway and growth cycle length. Global change may also have important indirect impacts, because it will affect occurrence and vigor of weeds, pests and diseases. Crop growth and yield levels under conditions of global change will thus be determined by the simultaneous operation of a number of individual phenomena. Net effects will depend on their interactions, in combination with plant nutrient availability, and of course input use and agricultural management. Clearly, the complexity and nature of the issue at hand, suggest that assessments of possible effects of global change on crop yields and land productivity may benefit from an ecosystem functioning perspective.

This paper summarizes, without trying to be exhaustive, general trends of experimental research findings in order to facilitate the selection of parameters to be used for assessing global change impacts on land productivity. However, from the onset it should be stressed that the importance of an ecosystem perspective was emphasized only recently (e.g. Körner, 1998). Much of the research on possible effects of atmospheric and climate change has been conducted under artificial conditions in controlled environments, where the effects of only one or a few variables have been studied in isolation (Soussana et al., 1998). Research findings therefore do not always lead to convergence of evidence regarding the possible total impacts of the combination of different phenomena. To some extent, it therefore remains uncertain what will happen under real-world conditions, where all variables are at play simultaneously, and where a 'myriad of unknown feedback's determines responses' (Körner, 1998). Another point that calls for cautiousness is that research has often been conducted with annual plants in their early stages of development, while there is considerable evidence that effects disappear with time, because acclimation takes place. Moreover, responses are often non-linear (Körner, 1998; Grünzweig and Körner, 1998), highly species specific (Ellsworth, 1998; Coffin, 1998; Körner, 1998; Jones,

1998) and the response of the same species may vary with the properties of the ecosystem in which it occurs (Körner, 1998; Norby et al., 1998). The effects of global change at the level of individual ecosystems may further be influenced significantly by land and crop management (Lüscher et al., 1998; Niinemets et al., 1998; Walker et al., 1998). All this emphasizes the need for a careful examination of global change research findings for the purpose of designing a study on its possible effects on crop yields and land productivity.

In the following sections we first summarize research findings on the effect of elevated CO_2-levels on crop growth and then on crop water use. Next we describe possible effects of changing basic climatic variables. In section 5 we briefly touch upon possible indirect impacts of weeds, pests and diseases. Section 6 deals with effects on soil properties and soil suitability. In section 7 we summarize our findings.

A1.2 Effects of increased atmospheric CO_2-levels on crop growth

Biomass production and yield

The general picture emanating from research is that increases of atmospheric CO_2-levels lead to increased biomass production and higher crop yields. Observed responses of C_3 plants are considerably stronger if compared to plants with a C_4 photosynthetis pathway. These differences are related to photorespiration occurring in C_3 plants, which for C_4-plants is negligible (Driessen and Konijn, 1992). During photorespiration a portion of the initially fixed carbohydrates are re-oxidized to CO_2, thus explaining the higher productivity of C_4 -plants under current conditions. The incurred losses due to photorespiration normally increase with rising temperatures, but the process is equally sensitive to CO_2-levels, being readily suppressed when CO_2 concentrations increase. C_3-plants therefore benefit more from CO_2 fertilization and the beneficial effects increase with rising temperatures (Idso et al., 1987; Kimball et al., 1993; Reddy et al., 1998).

The photosynthetic rate of C_3-crops under doubled CO_2-levels increases roughly with some 50-70 percent, but the numerous steps between carbohydrate production in leaves and the transformation into plant tissue, temper the effect in terms of biomass and crop yield (Allen, 1991; Kimball at al., 1993). Many studies indicate that C_3-plant productivity, at ambient temperatures and doubled CO_2-levels, is raised with about 30 percent on average (e.g. Cure, 1985; Kimball, 1983, 1986; Morgan et al., 1998; Nagakawa et al., 1998; Reddy et al., 1998; De Luis et al., 1998 and Wall et al., 1998). Yield increases in individual experiments, however, also depend on factors like temperature, moisture stress and nutrient availability.

The quantification of the temperature dependent benefits of CO_2 fertilization under doubled CO_2 concentrations can be derived from experimental data obtained with a variety of C_3-species These data suggest the following linear relationship between relative growth increase and temperature (Kimball et al., 1993):

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

where f_y is relative growth increase and T is temperature (ºC)

Changes in CO_2-levels also affect temperature optima for photosynthesis, in particular in C_3-species, which show an upward shift with increasing CO_2 concentrations (Allen et al., 1990, 1991; Manderscheid et al., 1998). The effect of CO_2-levels on growth and maintenance respiration seem uncertain (Fischer and Van Velthuizen, 1996).

The amount of data on CO_2-induced yield increases for C_4-crops is limited, but effects are generally much less if compared to C_3-crops. Reported magnitudes of change vary with experiments. The photosynthetic rate at doubled CO_2 would increase by some 4 percent only (Kimball et al., 1993), but also general figures, referring to total biomass increases, of 22 to 28 percent have been observed (Walker at al., 1998; Poorter, 1993; Navas et al., 1998). Reports by Kimball (1996) and Cure (1985) take an intermediate position with figures for biomass accumulation of Maize and Sorghum at 9%.

Phenology

Elevated CO_2-levels generally accelerate phenological development of plants. Exposure to higher CO_2-levels is mostly followed by an immediate response, reflected in increased biomass and a higher Leaf Area index (LAI). The increased rate of photosynthesis in early development stages results in an earlier complete light interception, which in turn stimulates biomass production. However the effect on a total growth cycle is limited because the initial strong response to CO_2 tends to disappear with time because acclimation takes place, even in the case of short-duration annuals (Nakagawa et al., 1998). Acclimation may be related to a sink limitation of the plant (Manderscheid et al., 1998), but has also been attributed to CO_2-induced nutrient stress (Pinter et al., 1998). Indeed, it was found that higher LAI's occur only when nutrients are not limiting (Hiroze and Bazzaz, 1998). Moreover, the initial higher leaf area production leads to earlier self shading and coincides with decreased specific leaf areas (e.g. Lüscher et al., 1998; Grunzweig and Körner, 1998). Both reduce photosynthesis per amount of leaf material and leaf turn-over rates are increased. These effects may put a break on accelerated growth and the effect of higher LAI on biomass production may therefore be limited.

Partitioning

Increased atmospheric CO_2-concentrations affect the partitioning of assimilates within the plant. Generally, an increase of the root/shoot ratio has been found (e.g. Lüscher et al., 1998; Wechsung et al., 1998). This might be particularly beneficial for C_3-root crops where the economically useful yield is located in the below-ground parts. The relative increase of root production has been related to the development of nutrient deficiencies under elevated CO_2-levels. A higher investment in roots would be made to exploit available soil nutrients more fully. Contrasting findings have been obtained in arid ecosystems, where root/shoot ratio's decreased rather than increased (Friedlingstein et al., 1998). This has been attributed to the reduction of water stress caused by increased water use efficiency, thus reducing the need for assimilate allocation to roots. Friedlingstein et al. (1998) formulate the hypothesis that carbon investments are partitioned so as to maximize the most limiting resources. This indeed would explain the observed differences.

By contrast, Walker et al. (1998) observed no effect of elevated CO_2 on carbon allocation in a case of C_4-grasses and Soussana et al. (1998) found additional carbon sequestration in roots even under high fertility conditions. Although elevated CO_2 generally raises yields and changes assimilate allocation patterns there is insufficient convergence of evidence that yield quantities in relation to total biomass, and consequently Harvest Indexes, would change.

In summary, the most prominent effect of increased atmospheric CO_2-levels on crop growth, of relevance to the present study, is the effect on photosynthetic rates and photorespiration and consequently crop yields and that, in the case of C_3-crops, the magnitude of change is temperature dependent. The effect on growth and maintenance respiration is uncertain and can therefore not be included in the present stage of model development. The impact on crop phenology is small, particularly because we deal with tropical conditions. Leaf Area Indexes may increase, but the impact in terms of crop yield is likely to be limited, because of a number feedback mechanisms and because of decreasing returns from further increases of LAI. There is also insufficient evidence to indicate that Harvest Indexes need to be adapted for elevated CO_2 conditions.

A1.3 Effects of increased atmospheric CO_2-levels on crop water use

Water use efficiency

Many studies report increased water use efficiencies under elevated CO_2-conditions: more dry matter is produced per unit of water transpired (e.g. Elsworth, 1998). This reflects the combined effect of higher photosynthetic rates and a simultaneous decrease of transpiration, caused by the reduction of stomatal conductance. At doubled CO_2-levels, these reductions are in the order of 40-50 percent, both for C_3 and C_4-species (Morison, 1987; Kergoat et al., 1998; de Bruin & Jacobs, 1993). However, stomatal conductance is measured at the leaf level and changes of whole plant respiration were found to be considerably less (Polley et al., 1998). Jarvis (1998) argues that the effect of reduced stomatal conductance at the leaf level may, at canopy level, be balanced by simultaneous increases of biomass and LAI. The effects may be even further limited when water use over an entire season is considered because the speed up of phenology in the early stages of development.

Nevertheless, CO_2-effects on water use have been observed and were found to be greatest under dry conditions (Hättenschwiler et al., 1998). Crops become more drought resistant (De Luis et al., 1998) and soil moisture levels remain higher under elevated CO_2-conditions (Morgan et al., 1998; Grunzweig and Körner, 1998). The reduction of transpiration rates has to be implemented in the model by changing canopy resistance as used to calculate potential evapotranspiration. 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 stomatal resistance of a single leaf [$s\ m^{-1}$] ≈ 100

LAI = leaf area index

The magnitude of changes of stomatal resistance to be applied has to be a conservative one, because LAI's are kept unchanged in the calculation of biomass/potential yield for reasons as previously explained and because of the effects that upscaling from leaf to canopy and season may have, as described in this section.

Leaf temperature

Reduced transpiration may cause an increase of leaf temperatures because of the cooling effect of that transpiration has and higher leaf temperatures in turn affect the rate of photosynthesis. Leaf temperature increases of about 1 °C were found for cotton (Idso et al., 1987) while increases of 0.6-1.1 °C have been reported for wheat (Kimball et al., 1998). The net effect on crop yields depends on ambient temperatures and whether, in combination with additional warming, the resulting leaf temperatures are close to or exceed optimal values for photosynthesis (Kimball et al., 1993). Increases of leaf temperature may also cause accelerated ageing of leaf tissue and therefore reduce photosynthetic efficiency of canopies, if LAI's are sub-optimal which is commonly found in low input tropical agriculture. The additional effects of increased leaf temperatures due to reduced transpiration are very minor under tropical circumstances and therefore need not be taken into account.

A1.4 The effect of changing climatic variables

Global change, apart from increased CO_2 levels, entails a change of climate and the possible changes in temperatures, rainfall and radiation are produced by experiments with General Circulation Models. The AEZ approach standardly deals with these variables and provides the framework to do so in an integrated manner. We therefore will only briefly discuss the possible effects of climate change on the geography and productivity of agriculture.

Temperature

Temperature has a direct effect on crop growth and phenological development, the latter particularly in the temperate zones. A rise of temperature may strongly interact with the effects of CO_2 fertilization and either enhance or neutralize it, depending on current conditions. Clearly, crop yields will be increased when current temperatures are sub-optimal for the species concerned. However, rising temperatures may also imply that the ceiling of optimal temperature is exceeded, causing a decline of yield. The latter effect may operate through a reduction of biomass production, but also through problems related to phenological development. Elevated CO_2 in combination with high temperatures for instance causes spikelet sterility in rice (Nakagawa et al., 1998) and is detrimental to boll retention and growth in the case of cotton (Reddy et al., 1998).

A rise of temperature may lead to an expansion of the growing season, if currently its duration is temperature-limited. Thus, cropping options may emerge in cool areas at high latitudes and altitudes, that were hitherto not suitable for the production of (certain) crops. Higher temperatures may therefore cause important geographic shifts in cropping patterns.

Rainfall and Moisture availability

Changes of rainfall pattern and amount need to be considered in combination with for instance changes of temperature and crop water use efficiency to determine its effects on moisture availability and consequently crop yield. This integration is achieved through the concept of the Length of the Growing Period (LGP).

The net effect of LGP changes depends on current length and the predicted direction and magnitude of change. If a currently short LGP is further reduced in length, it may imply that crops can not be grown satisfactorily any longer, unless the yield reduction due to a shortening LGP is small and offset by other positive effects (e.g. increased photosynthetic rate or accelerated phenological development). A shortening of LGP in currently humid areas, may seriously reduce the potentials for perennial crops, but the suitability for long-duration annual crops may improve, due to lower pest and disease pressures and better conditions for handling of produce. Increases of rainfall amount are likely to extend the LGP, particularly when it is short at present. In the latter case productivity is likely to increase but a further extension of currently prolonged LGP's may reduce the suitability for the crops currently grown (pests/diseases, mechanization). More generally, changes of LGP, in combination with other global change phenomena, may imply that crops commonly grown at present are out-yielded by others.

A1.5 Indirect effects of global change: weeds, pests and diseases

Similar to crops, higher CO_2 levels also affect photosynthesis, water use efficiency and root/shoot ratios in weeds. As for crops, the effect is more pronounced in C_3-species and therefore C_3-weeds may gain in competitive advantage over C_4 crop species. This may lead to yield reductions for C_4 -crops, if weeds are not adequately dealt with or to increased costs of capital and labour to achieve the full potential of crops. Yield effects are likely to be more prominent under low input circumstances because of labour constraints.

With respect to insect pests, climate change may profoundly influence their mortality, reproduction and geographic distribution. In general, pests as well as diseases tend to follow the distribution of their hosts. If conditions change for a crop, for better or worse, it may be expected that the same applies for its pests and diseases. Unfortunately, global change research on the interaction of weeds, pests and diseases with crop productivity has focused primarily on single insects, weeds, or diseases and often in relation to one environmental variable only (Coakley et al., 1998). The effect of pests, diseases and weeds is currently taken into account in AEZ through LGP specific agro-climatic constraints. As yet, there is insufficient evidence for a systematic change of the relationship between environmental characteristics and incidence of pests, diseases and weeds.

A1.6 Effects on soils and soil suitability

Temperature increases and changes in precipitation amount and distribution will, by themselves, as well as through their effect on above and below-ground biomass production, inevitably affect soil properties. This may cause a chain reaction due to the continuously changing substrate-living biomass interaction until equilibrium conditions are reached. The latter may not be expected for some time to come, given the expected levels of greenhouse gas emissions. The previously described CO_2-induced increase of biomass production and the greater allocation of assimilates to roots supposedly leads directly to increased amounts of organic materials in the soil. Whether or not these can be maintained depends for instance on soil moisture, temperature and the degradability of litter and roots. Changes in rainfall alone may also influence the upward or downward movement of plant nutrients and toxic elements. However, what the net effect of global change on soil properties and through these on crop yields will be, within the time frame of the present study, is rather uncertain.

Dominant soil forming factors, that act slowly, will not change significantly within a time frame of 50-100 years and with the exception of some fragile, ‘ecotonal’, conditions, most soils are expected to remain in the same genetic group (Sombroek, 1990). It therefore seems justified to continue current AEZ practice where the effect of soils on crop yields is implemented through the genetic soil class.

The main, within soil class, changes are expected to refer to topsoil properties, in particular with respect to soil organic matter and its dynamics. An increase of organic matter may be expected due to the stimulating effect of CO_2 on biomass production and the changes of assimilate allocation patterns in favour of roots. The increase of organic matter could have a positive influence on soil fertility, soil structure and rainfall infiltration (Brinkman and

Sombroek, 1993) and hence it may increase crop yields and reduce erosion hazard. But, a simultaneous rise of temperature may cause litter decomposition rates to increase (a.o. Rustad et al., 1998), although this effect may be limited if higher temperatures at the same time reduce the moisture content of the litter layer (Verburg and Van Breemen, 1998; Kamp et al., 1998).

Organic matter dynamics may further be affected by changes of the chemical properties of litter. Increases in primary production under elevated CO_2 are frequently associated with a changes of specific leaf area and chemical composition of herbage (e.g. Lüscher et al., 1998; Newton and Clark, 1998; Niinemets et al., 1998). The chemistry change is characterized by decreases of foliage protein content and increases of water soluble carbohydrates (e.g. Manderscheid et al., 1998). Decomposers are thus faced with an unfavourable high C/N ratio (e.g. Gitay and Murphy, 1998) and this would slow down nutrient cycling. It may imply that scarce plant nutrients, even more than at present, are fixed in living biomass, litter and soil organic matter. In fact, actual biomass production may therefore be reduced due to the paucity of available (micro-) nutrients. This effect may be particularly important when soil acidity already inhibits organic matter decomposition and nutrient mineralization. The (temporary) unavailability of scarce nutrients may have important implications for fallow period requirements under conditions of low input agriculture. In natural and pasture ecosystems, the expected increase of C/N ratios may, to some extent, be compensated by an increase of N-fixing legumes in the species composition (Hartwig et al., 1998; Lüscher et al., 1998).

There is, however, quite some uncertainty associated with research on C/N ratios and its effect on decomposition rates when CO_2-levels increase. Sowerby et al. (1998) emphasize that much of the contradictory nature of research on plant litter degradability can be explained by differences in methodology used. They found the commonly expected, namely that litter grown under elevated CO_2-levels shows decreased mineralization rates based on significant differences in the C/N and lignin/N ratio's. It has also been emphasized that current knowledge on C and N cycles and organic matter dynamics is limited to extent that even the direction of change of Carbon levels stored in soil organic matter is uncertain (Van de Geijn and Van Veen, 1993). Only few models deal adequately with the return to and incorporation of organic matter into the soil and its impact on crop yields (Hunt et al., 1998).

More in general, current models hardly consider plant nutrients other than Nitrogen, because knowledge on the effect of other elements is insufficiently developed (Hunt et al., 1998), let alone on the often complex interactions between plant nutrients, that determine their availability to plants (e.g. Boyer, 1972) . We tend to agree with Van der Geijn and Van Veen (1993) and Hunt et al. (1998), who argue that the current state of knowledge on the effect of global change on soil fertility does not allow to draw firm conclusions of relevance to crop yield assessments. Nevertheless common principles currently used also seem to apply under elevated CO_2. Niinemets et al. (1998) found that the greatest biomass under elevated CO_2-levels was associated with the highest soil Nitrogen (N) content. Pinter et al. (1998) and Wall et al. (1998) found that the CO_2-effect was limited when N availability was restricted. In a number of experiments on the effect of elevated CO_2 , it was observed that C_3-grasses showed N deficiency symptoms while these were absent in legumes. In general, if compared to other C_3-plants, legumes respond stronger to elevated CO_2 , supposedly because they can draw from an unlimited supply of Nitrogen (Hartwig et al., 1998; Lüscher et al., 1998). In this study we therefore must assume that soil fertility will not change and hence that soils, under conditions of global change, will affect crop yields in a similar manner as they do at present. The current relative yield reduction factor for soils that is applied to climatic potentials is consequently maintained, implying that the full effect of CO_2 fertilization can only be achieved when soil fertility is not limiting and that yield reductions are proportionate to fertility constraints of current soil genetic groups.

A1.7 Conclusions

The main impact of global change derives from the positive response of photosynthesis to enhanced CO_2 levels, resulting in increased biomass production and crop yield. These responses have been widely observed and can be quantified with reasonable accuracy. In case of C_3-species the temperature dependency of growth rates, related to higher photorespiration rates at higher temperatures as well its inhibition at raised CO_2 levels, has to be accounted for.

With respect to crop phenology we observed a number of feedbacks (acclimation, decreased specific leaf areas, self-shading and leaf turn-over rates), that are likely to largely balance effects of CO_2-induced acceleration of early development. Leaf Area Indexes (LAI) may thus be higher, but less efficient in producing biomass. We therefore maintain currently used maximum Leaf Area Indexes (LAI) and their relation to crop growth.

Changes of assimilate partitioning patterns under elevated CO_2, expressed in root/shoot ratio's, have been extensively documented, but whether this is a direct effect of increased CO_2 itself seems uncertain. The impression exists that such changing patterns are contingent on other factors that become the most limiting resource such as nutrients and water. Although elevated CO_2 generally raises yields and changes assimilate allocation patterns, there is insufficient convergence of evidence that yield quantities in relation to total biomass would change. We therefore maintain currently applicable Harvest Indexes.

Higher water use efficiencies due to both, increased biomass production and reduced water use, have frequently been observed. Reduced water use is caused by increased stomatal resistance under higher atmospheric CO_2 concentrations. Clearly, this phenomenon needs to be accounted for and there is a considerable amount of quantitative information to allow this. However, stomatal resistance is measured at the leaf level and when scaling-up to crop canopy and season level, the reduction of water use observed for leaves may to some extent be balanced by simultaneous increases of biomass and LAI. Because of this, and since LAI's have been kept unchanged, we apply conservative changes to the canopy resistance term used to calculate potential evapotranspiration.

Global change, apart from increased CO_2 levels, entails a CO_2 level-specific change of climate. Possible changes of temperatures, rainfall and radiation are produced by experiments with General Circulation Models (GCM). The AEZ approach standardly deals with these variables and provides the framework to do so in an integrated manner. Thus, new waterbalances are calculated to determine the Length of the Growing Period (LGP) and temperature and radiation characteristics are calculated for its duration. This information is used in a crop growth model to calculate potential biomass production and crop yields under conditions of elevated CO_2. Specific constraints due to very high or too low temperatures are taken into account through thermal zone constraints.

The effect of pests, diseases and weeds is currently taken into account in AEZ through LGP specific agro-climatic constraints. As yet, there is insufficient evidence for a systematic change of the relationship between environmental characteristics (LGP) and incidence of pests, diseases and weeds.

In AEZ the impact of soils on crop yield is assessed by soil genetic group/class. It is unlikely that, within the time frame of concern in this study, soils would change in any significant extent from one group to another due to global change effects. Most changes may be expected in terms of topsoil properties as caused by organic matter dynamics. This might imply a change of soil class, but current knowledge on effects of global change on C and N cycles, organic matter dynamics and numerous feedbacks is limited to extent that even the direction of change of Carbon levels stored in soil organic matter is uncertain. Thus, the current state of knowledge does not allow to draw firm conclusions with respect to soil fertility changes that could be of relevance to crop yield assessments. Nevertheless common principles currently observed also seem to apply under elevated CO_2. In this study we therefore must assume that soil classes remain unaltered and that soil fertility will affect crop yields in a similar manner as it does at present. Maintaining the soil class and crop specific yield reductions of AEZ implies that the full effect of CO_2 fertilization can only be achieved when soil fertility is not limiting and that yield reductions are proportionate to the currently used soil constraints in AEZ methodology.

Annex 2

Observed baseline climate data and their spatial representation

Observed climatic data are derived from 324 stations within and close to Nigeria. These include 52 synoptical stations, 46 agro-meteorological stations and 226 rainfall stations. Time series of monthly rainfall for the period 1940-1992 were available for the first two categories. The synoptic stations in addition provide long term monthly averages for all other climatic parameters, that are required to calculate potential evapotranspiration. Agro-meterological stations usually record only a variable selection of these. The data from rainfall stations mostly refer to mean monthly rainfall, but 53 had a time series of limited duration. The climate data base further includes daily rainfall records from 1970 onwards for synoptic stations within Nigeria.

Data concerning synoptic and agro-meteorological stations within Nigeria were mostly obtained from the original sources of the Department of Meteorological Services at Oshodi. FAO provided data from synoptic and agro-meteorological stations outside Nigeria from a data set later used for the FAOCLIM database (FAO, 1995). Mean monthly data for rainfall stations within Nigeria were obtained from Kowal and Knabe (1972) and also FAO. These data refer to the period before 1970. Time series for the period 1980-1989 were available for rainfall stations of the hydrological network (NWRMP, 1993.). The Federal Department of Agricultural Land Resources collected time series of monthly rainfall for selected stations in areas where spatial coverage of other data sources was poor. Additional information for the period up to 1982 was available from Akintola (1986).

The data were first thoroughly checked and the overlapping data sources were systematically compared. The Meteorological Department assisted in solving most of the doubtful cases. All unsolved observations have been rejected for further use. This initial visual checking was followed by data-screening of time series of annual rainfall using software developed by Dahmen and Hall (1990). This software for hydrological studies tests the stability of time series, variously expressed as stationarity, consistence and homogeneity, to detect data irregularities that may be caused by extraneous influences. It was indeed found that, in parts of the study area, the time series are not stationary. Extent and magnitude of change of statistical properties of time series occurs in a coherent geographical pattern, that cross-cuts national boundaries. This can not be explained by extraneous influences and it was concluded that climate has changed in recent history (Voortman, 1998).

The present study uses the mean values for the period 1961-1990 as baseline conditions. These were calculated for the stations with full time series. The rainfall station data originate from different time periods and were adjusted. The stations with complete time series allowed to calculate mean values for the periods of observation of rainfall stations. These values were regressed with the means of the 1961-1990 period. Linear relations between rainfall of two periods, that also include latitude as independent variable, usually gave r-square values well above 0.95 and for rainy season months they were mostly around 0.98. The regression formula’s were used to obtain values, that are representative for the 1961-1990 period.

Mean climatic parameters for observation points were, on a monthly basis, interpolated in a GIS to constitute a grid of 2 by 2 km size. The interpolation was directly applied to observed values in case of sunshine duration, windspeed, relative humidity and global radiation. For maximum and minimum temperatures a different approach was followed. Observed temperatures were converted to sea level, using the relation between temperature and altitude (a decrease of about 0.6 °C with 100 meter increase in altitude). The sea-level temperatures were interpolated and the interpolated values were, for each gridcell, again used to recalculate altitude specific temperatures on the basis of a Digital Elevation Model and the relation of altitude and temperature.

All calculations referring to current climate, like potential evapotranspiration, length of growing period etc. have been conducted on a gridcell basis. Monthly values of average daily reference evapotranspiration (ET_0) were calculated with the modified Penman-Monteith equation, as recommended by FAO (FAO, 1992b). Details of the calculation procedure are described in Annex 3.

Annex 3

Calculation of reference evapotranspiration

(Fischer and van Velthuizen, 1996)

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

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

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

$$ET_o = ET_{ar} + ET_{ra} \quad (1)$$

where the aerodynamic term can be approximated by

$$ET_{ar} = \frac{g}{J + g*} \cdot \frac{900}{T_a + 273} \cdot U2 \cdot (e_a - e_d) \quad (2)$$

and the radiation term by

$$ET_{ra} = \frac{J}{J + g*} \cdot (R_n - G) \cdot \frac{1}{l} \quad (3)$$

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

γ	...	psychrometric constant (kPa $ºC^{-1}$)
$\gamma*$	..	modified psychrometric constant (kPa $ºC^{-1}$)
ϑ	...	slope vapor pressure curve (kPa $ºC^{-1}$)
T_a	...	average daily temperature (ºC)
e_a	...	saturation vapor pressure (kPa)
e_d	...	vapor pressure at dew point (kPa)
$(e_a - e_d)$		vapor pressure deficit (kPa)
U2	...	wind speed measurement (ms^{-1})
R_n	...	net radiation flux at surface (MJ m^{-2} d^{-1})
G	...	soil heat flux (MJ m^{-2} d^{-1})
λ	...	latent heat of vaporization (MJ kg^{-1})

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

Average daily temperature:

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

Latent heat of vaporization:

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

Atmospheric pressure (kPa) at elevation A:

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

Psychrometric constant:

$$g = 0.0016286 \cdot \frac{P}{l} \tag{7}$$

Aerodynamic resistance:

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

Crop canopy resistance:

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

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

Modified psychrometric constant:

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

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

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

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

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

Vapor pressure at dew point, e_d:

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

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

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

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

$$\boldsymbol{J} = 0.5\left(\boldsymbol{J}_x + \boldsymbol{J}_n\right) \tag{17}$$

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

Latitude expressed in rad:

$$\boldsymbol{j} = \frac{L\boldsymbol{p}}{180} \tag{18}$$

Solar declination (rad):

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

Relative distance Earth to Sun:

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

Sunset hour angle (rad):

$$\boldsymbol{y} = arc\ \cos\ (-\tan\ \boldsymbol{j}\ \tan\ \boldsymbol{d}) \tag{21}$$

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

$$R_a = 37.586\ d\ (\boldsymbol{y} \sin\ \boldsymbol{j} \sin\ \boldsymbol{d} + \cos\ \boldsymbol{j} \cos\ \boldsymbol{d} \sin\ \boldsymbol{y}) \tag{22}$$

Maximum daylight hours:

$$DL = \frac{24}{\boldsymbol{p}}\, \boldsymbol{y} \tag{23}$$

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

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

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

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

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

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

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

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

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

$$R_n = R_{ns} - R_{nl} \quad (29)$$

Finally, soil heat flux is approximated using

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

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

Annex 4

Determination of growing period

(Fischer and van Velthuizen, 1996)

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

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

Average day-time temperature, T_d (ºC):

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

Average night-time temperature, T_n (ºC)

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

where

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

T_{max} ... maximum daily temperature (ºC)

T_{min} ... minimum daily temperature (ºC)

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

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

with

R ... monthly rainfall (mm)

A ... elevation (m)

CD2 ... the smaller of distance to coast and 200 (km)

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

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

$$SD = SD_{rel} \cdot DL / 100 \quad (6)$$

Reference evapotranspiration, ET_0 (mm), is calculated according to the combination method of Penman-Monteith, as described in Appendix 1:

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

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

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

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

where

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

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

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

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

for at least LGPmin days[3] A growing period ends on the day when first

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

In this way all the growing periods are fully determined with starting and ending dates, length and ETa values. The procedure also records the dates and length of any humid phase, of each growing period defined as days where moisture supply exceeds potential evapotranspiration, i.e., with

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

Keeping exact records of moisture and temperature profiles then allows a more accurate calculation of potential biomass production as detailed in Appendix 3.

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

Annex 5

Calculation of potential net biomass and potential yield

(Fischer and van Velthuizen, 1996)

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

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

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

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

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

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

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

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

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

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

where:

- F = the fraction of the daytime the sky is clouded, F = (A_c - 0.5 R_g) / (0.8 A_c), where A_c (or PAR) is the maximum active incoming short-wave radiation on clear days (de Wit 1965), and R_g is incoming short-wave radiation (both in cal $cm^{-2}.day^{-1}$)
- b_o = gross dry mater production rate of a standard crop for a given location and time of the year on a completely overcast day, (kg ha^{-1} day^{-1}) (de Wit, 1965)
- b_c = gross dry mater production rate of a standard crop for a given location and time of the year on a clear overcast day, (kg ha^{-1} day^{-1}) (de Wit, 1965)

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

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

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

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

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

$$r_m = k\,b_{gm} + c\,B_m \text{ kg ha}^{-1}\text{ day}^{-1} \quad (7)$$

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

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

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

$$B_m = 0.25\,b_{nm} \times N \quad (9)$$

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

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

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

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

where:

b_{gm}	=	maximum rate of gross biomass production at leaf area index (LAI) of 5
L	=	maximum growth ratio, equal to the ratio of b_{gm} at actual LAI to b_{gm} at LAI of 5
N	=	length of normal growth cycle
C_t	=	maintenance respiration, dependent on both crop and temperature according to equation (8)

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

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

where:

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

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

Annex 6

Soil and terrain inventory

A nation-wide soil and terrain inventory was made to obtain a spatial representation of soil and land form data, which complies with the selected methodologies for assessment of agricultural production and water erosion hazard. The soil and land form data are stored in a Geographical Information System to facilitate data logistics and processing and consists of three thematic layers: soil associations, slope and altitude. In this annex the sources of information, methods used and data formats are described. The compilation of the soil resources inventory is fully documented in Sonneveld (1998).

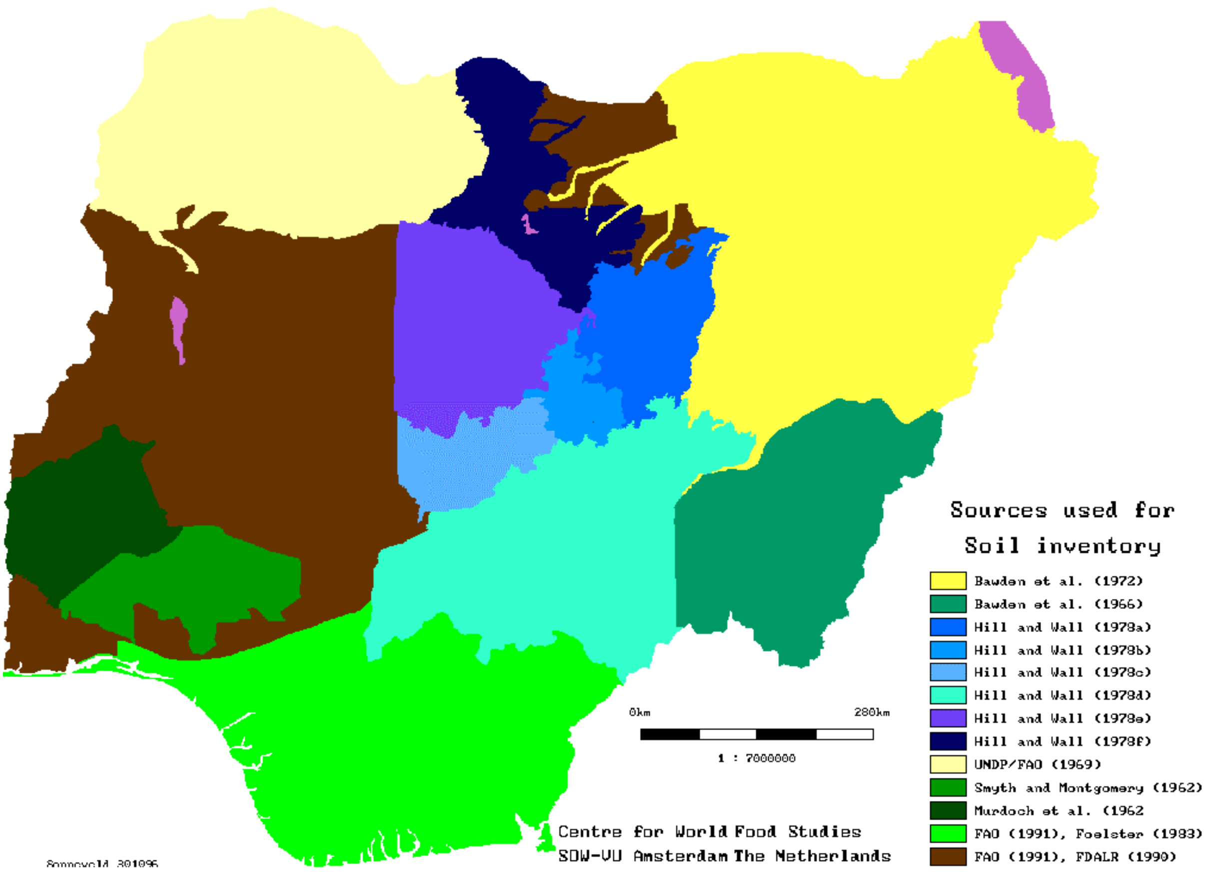

Figure 1

A6.1 Data Sources

Soil information was obtained from published regional and national soil surveys. Information on slope and altitude was derived from a Digital Elevation Model.

Published regional soil resource inventories, typically at a scale of 1:250 000-1:500 000, cover large parts of the Nigerian territory and have been used to compile the nation-wide map. Most of these studies use land systems or similarly defined entities as mapping units. Such units are described with respect to their composition in terms of individual soil types. Each soil type is described in detail in combination with the presentation of typical profiles and results of chemical an physical analysis of individual soil horizons. This detailed information allows the classification of soils in terms of FAO/UNESCO units (FAO/UNESCO, 1974, FAO/UNESCO/ISRIC,1994) and the inventory of soil attributes.

The regional inventories used are the following:

- Bawden et al. (1972).This study covers a large part of north-eastern Nigeria with land systems mapped at a scale of 1 : 500 000. It uses the French system to classify the soil units and presents a key for conversion into the FAO/UNESCO (1974) classification. Representative soil profile descriptions and results of the physical and chemical analysis are provided.
- Bawden et al. (1966).The areas concerned are Adamawa and Sardauna in the Eastern part of Nigeria and land systems are mapped at a scale of 1: 1 000 000. However, in agreement with the mapping scale, the description of the composition of the mapping units is less detailed than Bawden (1972). These general descriptions were used in combination with information on map unit compositions of FAO/UNESCO (1978) and FDALR (1991).
- Hill and Wall (1978a-f.) Six reconnaissance studies resulting in land systems maps at a scale of 1 : 250 000 cover most of Central Nigeria. A land system approach similar to that of Bawden et al. (1972) is used and the soil units are classified according to FAO/UNESCO (1978). In addition a description of typical soil profiles and results of physical and chemical analysis are presented.
- UNDP/FAO (1969). The study consists of reconnaissance survey (1 : 250 000) of Sokoto state and semi-detailed soil surveys of the alluvial areas. A physiographic approach is used in which soil units and their properties are correlated with geological and land form conditions. Typical profiles and analysis results are provided together with the USDA soil class of the individual soil units.
- Smyth and Montgomery (1962). The survey deals with the western part of Nigeria (South of the study area of Murdoch et al., 1978) and is presented as a reconnaissance map of land systems at a scale 1 : 250 000). Map unit composition is presented in terms of soil associations which again are defined in terms of soil series composition. The description of the individual soil series includes representative soil profile characteristics together with physical and chemical soil analysis.
- Murdoch. (1978). The results of this survey are presented in a reconnaissance soil inventory of the Western Part of Nigeria at a scale of 1 : 500 000. The basic mapping unit of land systems is linked to land facets and soil series in terms of composition and character. A full description of the the soils units is given by typical profiles and their physical and chemical properties.
- Fölster et al. (1983) present a generalized description of the soils found in Southern Nigeria together with information on representative soil profiles and their physical and chemical properties.

For about 30% of the Nigerian territory there was no other systematic information than the FAO Soil Map of the World a scale of 1:5 000 000 and the FDALR national map at scale 1: 1000 000 (FDALR,1991). The FDALR reports give a full documentation of about 200 soil profiles. The location map pertaining to these observations was supplied by FDALR and the information used to update the FAO/UNESCO map in terms of spatial extent of mapping units, their composition and soil classification.

Altitude and slope characteristics have been derived from a Digital Elevation Model (DEM) with a 30-arc-second intervals altitude observation (Earth Resources Observation Systems Data Centre in Sioux Falls, USA). The DEM was created from 1:1,000,000 scale Digital Chart of the World (DCW). The Australian National University Digital Elevation Model (ANUDEM) generation program was used to generate a grid at 30-arc-second intervals with altitude observation. Maps derived from the DEM were geo-referenced and masked with the national boundaries of Nigeria.

A6.2 Methods

The maps of the regional studies have been photographically reduced to a mapping scale of 1: 2 000 000. The Integrated Land and Water Information System (ILWIS) GIS version 1.4 was used to digitize the soil and land form information. Some mapping units were combined in case that spatial detail of the map unit could not be digitised seperately. In accordance with the other inventories of the study the gridded soil and landform database has a pixel size of 2 * 2 km^2 on a Albers Conical Equal Area Projection.

From the information given in the studies concerned, the mapping unit composition was derived. Based on profile descriptions as well as chemical and physical analysis the FAO/UNESCO soil type (FAO/UNESCO/ISRIC, 1996) and soil phase, if present, were determined for each of the constituent units. The classification includes some intergrades between the basic soil types. For each soil type within a mapping unit the following properties were tabulated: texture, soil drainage condition, soil depth, total available water capacity and slope. In addition an assessment for each soil type was made of the soil erodibility and topographic factor for erosion hazard. The tabulated information on soil characteristics is linked to the mapping units by means of an attribute table.

A6.3 Soil and terrain attributes

The soil attribute table links the mapping units to the composition in terms of areal extent of individual soil units as well as their FAO/UNESCO class. A number of additional observed and calculated properties of individual components of mapping units are stored in this file. The attribute information is briefly summarized below.

Soil phase. The FAO/UNESCO/ISRIC (1994) phase definitions have been used to assess if individual soil units qualify for a phase designation.

Texture classes. For each soil unit, both a five and twelve textural classification was determined. The subdivision in five classes is used to assess the water holding capacity of the soil. The twelve texture classification is an input for the calculation of the soil erodibility factor K.

Drainage. The description of the soil drainage classes given in the reports have been converted to the classification used by FAO (1977) and extended with the intergrade ‘poorly/imperfectly drained’ in order to improve suitability assessment in this range that is critical for many crops. The soil drainage class is used directly for the purpose of land suitability evaluation and thus in this study is disconnected from the drainage class that is supposedly implied by the soil type.

Soil depth. The information on soil depth corresponds with the potential rooting zone and was categorized into five depth classes. This information was used to estimate the total available water capacity.

TAWC. The present study uses the soil-specific length of growing period to assess climatic yield potential. To this effect the total available water capacity (TAWC) is calculated on the basis of Batjes (1996). Values for TAWC are presented in mm/m for a FAO/UNESCO (1974) soil units for each of three textural classes. The soil properties within the rooting zone as determined by soil depth and the occcurrence of soil phases have been used for this purpose.

Slope. The slope gradient of the land for each pixel was derived from the DEM using standard algorithms of the ILWIS program (ITC, 1993). The slope ranges are presented per soil map unit.

Soil erodibility (K factor). The soil erodiblity factor was calculated according to the formula presented in Wischmeyer and Smith (1978). It has been assumed that erosion losses are reduced if a rudic phase occurs and the K-value, in these cases, is consequently multiplied by 0.5. (Kassam, 1991). Further, pedo-transfer rules developed by Mitchell (1983), were applied, in case one of the required variables in the equation was missing.

Topography (Factor LS). A topography factor to be used for the assessment of water erosion hazard has been calculated according to Mutchler and Murphy (1981), using an assumed relation between slope length and slope gradient.

Annex 7

Soil ratings and land suitability assessment for Nigeria

The soil assessment rules previously used in AEZ essentially derive from Sys and Riquier (1984) and consists of ratings applicable to FAO/UNESCO soil class that were largely determined through expert knowledge, based on inherent properties of these classes. However, increasingly quantitative information on the properties of FAO/UNESCO soil classes becomes available and knowledge and insights on crop requirements is also improving (e.g. Sys et al.1993, Voortman, 1985). Matching such knowledge and insights with quantitative information on FAO soil class properties, as presented in the WISE 2.1 data base (Batjes, 1995), suggests that the existing rating systems need revision. A new system of soil ratings was therefore developed, which also allowed to reduce the discontinuities of the previously used rating systems.

The crop- and soil-specific maximum attainable yields were calculated as follows:

$$Y_{ep} = Y_c * (R_s - R_t) * R_d * R_o * R_p - Y_p$$

where:

Y_{ep}	=	Ecological yield potential
Y_c	=	Climatic yield potential
R_s	=	Soil class rating with emphasis on soil fertility
R_t	=	Soil texture rating
R_d	=	Soil depth rating
R_o	=	Oxygen availability rating (soil drainage class)
R_p	=	Phase rating
Y_p	=	Economic yield needed as planting material

R_t	=	0.1 for coarse texture, else 0.0
Y_p	=	1 ton DM for yams, else 0.0

The assessments of soil depth and soil drainage class are input level independent. The effect of soil phases differs for low and high inputs and for intermediate inputs the low level has been applied. The methods used to arrive at the soil rating (R_s) are the most innovative and will be reported in this annex.

The soil rating (R_s)

The soil rating is established separately for low and high input conditions, because under low inputs it is natural fertility that is of importance, while under high input conditions the nutrient retention properties of soils are more important. For intermediate input levels the impact of the soil may be taken as intermediate between high and low levels. The final rating of the effect of soil-type-implied limitations is arrived at in two steps. First 6 factors relevant for general fertility conditions are considered and their assessment takes into account both the most limiting factor, but also that substitution may take place. Then a number of additional factors referring to soil chemistry and structure are considered and due to their usually overruling character the maximum limitation is selected. This is combined with assessment of general soil fertility by selecting the effect of the most limiting factor of the two.

General fertility levels

The mean of chemical properties were, by soil class, calculated from WISE 2.1. and used to arrive at a general soil fertility rating based on the criteria and class limits proposed by Voortman (1985). This system of land evaluation was developed for Basement Complex soils (without extreme soil acidity) and considers Total Nitrogen and available Phosphate in de topsoil and Total Exchangeable Bases (TEB), the cation ratio's (Ca/Mg and Mg/K) and pH of the subsoil as important indicators of soil fertility (for low input conditions and independent of crop type). For each variable there is a score from 1 to 4, where 1 implies no yield reductions due to soil fertility, 2 gives a deduction of 20%, etc.

The final score on the basis of these 6 variables is derived from the most limiting factor:

$$R_f = \min [R_N, R_P, R_{TEB}, R_{Ca/Mg}, R_{Mg/K}, R_{pH}]$$

If there is only one variable that scores in the lowest class, the overall rating is one higher than the lowest in order to allow for possible substitution. However, if TEB is the single variable that scores lowest than the lowest score is maintained. In case of very acid soils these ratings were adjusted to account for negative effects of Al-saturation.

Crop sensitivity to chemical and physical factors

We now still have to account for a number of chemical and physical factors implied by the soil class and not dealt with through separate ratings such as soil phase and soil drainage class. Moreover the general fertility rating has to be converted into a crop specific one. To this effect we have rated the individual crops in terms of their sensitivity to a number of soil factors including general fertility, presence of Ca-carbonate, Alkalinity, Salinity, Presence of Gypsum. We also consider soil depth and soil texture as implied by soil class (not covered by phases and topsoil texture specifications), workability and rooting conditions. All these sensitivities were developed relatively to a reference crop. General sensitivities to soil fertility were adjusted on the basis of crop cycles to account for the fact that longer duration varieties are less sensitive to lower fertility, if compared low sensitivity short duration crops. The sensitivity ratings are presented in table A7.1. The rating is relative to the reference crop and if positive the crop is less sensitive and if negative it is more sensitive than the reference crop.

Low input conditions

Based on the sensitivity of individual crops to general fertility conditions and the previously established soil fertility ratings a soil and crop specific score for general soil fertility is established. The general fertility rating for low inputs is upgraded for crops with a lower sensitivity than the reference crop. If the general soil fertility rating is 3 or poorer, the upgrading is 0.5 if the sensitivity is +1 and 1.0 if it is +2, etc. The resulting ratings that have a scale from 1 to 5 are converted into a fraction that corresponds to the part of the climatically attainable yield that can be obtained in the absence of yield limiting factors other than general soil fertility.

Table A7.1 : Crop specific sensitivities to ecological factors

	Mai	Sor	Mil	Ric	Cow	Grn	Bns	Soy	Cas	Swp	Why	Gry	Yey	Pot	Cot	Sug	Oil	Ban	Relative to
Fertility (general)	0	1	2	2	0	0	0	0	2	0	2	2	2	0	-1	0	1	-1	Maize
Fertility (+length)	0	1	2	2	0	0	0	0	2	0	1	1	1	0	0	0	2	0	Maize
CaCO3	0	1	1	0	-2	1	0	0	-3	0	-3	-3	-3	-2	1	1	-3	-2	Maize
Alkalinity	-1	0	1	0	-2	-2	-2	-2	-2	-1	-1	-1	-1	-1	0	-1	-2	-2	Sorghum
Salinity	0	1	0	-1	-1	-1	-2	-1	-1	0	-1	-1	-1	0	1	1	-1	-1	Maize
Gypsum	0	1	0	0	-2	0	-2	0	-2	0	-2	-2	-2	-1	0	1	-2	-1	Maize
Sandy texture	-2	-1	0	-4	-1	0	-2	-2	0	-2	0	0	0	-1	-1	-1	-1	-2	Millet
Workability	0	0	0	1	0	-1	0	0	-1	0	-1	-1	-1	0	0	0	-1	0	General
Rooting cond.	0	0	0	0	0	0	0	0	-2	-1	-2	-2	-2	-1	0	0	-2	-1	Maize
Depth	-1	-1	-1	-1	-1	-1	-1	-1	-2	-1	-2	-2	-2	-1	-2	-2	-3	-2	Maize

For the other soil properties given in table A7.1 (e.g. presence of $CaCO_3$), first a rating of the severity of such factors was established on the basis of both the soil properties implied by the FAO soil classification and the evidence provided by the WISE database. A soil rating of 1 implies that there are no soil constraints, if it is 5 the soil is considered not suitable for the reference crop. Next we again take into account the sensitivity of the crop in a manner similar to how general soil fertility was dealt with. Adjustments are only made when the crop considered is particularly sensitive or tolerant to the soil constraint. The presence of thionic properties are dealt with separately and are considered over-ruling constraints. Next the maximum of the limiting factors (not including workability) is selected and again converted to a ratio, that corresponds to the part of the agroclimatic yield that can be attained on the basis of these soil properties.

In the next step the strongest constraint is selected (either the minimum of the general fertility rating or the maximum of the other factors. This provides a crop and soil specific soil suitability (based on soil fertility conditions) for low input conditions expressed as a fraction of the climatic yield that can be attained.

High inputs

The general fertility rating for high inputs combines the general fertility rating for low inputs with a separately established rating for nutrient retention capacity that operates through subsoil TEB (Voortman, 1985). The latter was also derived from the WISE database. The low input rating stands for general ecological conditions and the high input rating expresses what one can do about soil limitations. If the rating for high input conditions is 5, it implies that even under such conditions very little can be done about the prevailing soil limitations and consequently the general fertility rating is equal to the one for low inputs. If conditions for high input agriculture are better then the fertility rating for low inputs then the latter is upgraded: in case of rating 4 the low input rating is reduced with 0.5 and if it is 3 the reduction is 1.0 In the remaining cases the basic fertility rating is 1, implying that there may be natural fertility constraints, but these can be adequately dealt with by inputs and appropriate management.

The severity of the ratings for the other soil chemical and physical properties has been relaxed by one point if the limitation can be corrected under high input circumstances.The rest of the procedures applied is identical to low inputs.

Examples of the resulting ratings of R_s for high and low input agriculture are presented in table A7.2. These are used in combination with similarly derived ratings for soil texture, soil depth, soil drainage class and soil phases to calculate the attainable yields. In case of Yams a part of the economically useful yield is substracted in order to account for reservations to be made for planting in the next season.

Table A7.2: Soil ratings with emphasis on soil fertility (Rs) for high and low input conditions

Input level	Soil code	Crops of the Nigeria study																	
		Mai	**Mil**	**Ric**	**Sor**	**Cow**	**Grn**	**Bns**	**Sob**	**Cas**	**Swp**	**Pot**	**Wiy**	**Gry**	**Yey**	**Ban**	**Oil**	**Suc**	**Cot**
Low	ACf	0.4	0.6	0.6	0.5	0.4	0.4	0.4	0.4	0.6	0.4	0.4	0.5	0.5	0.5	0.4	0.6	0.4	0.4
Low	ACg	0.6	0.8	0.8	0.7	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
Low	ACh	0.4	0.6	0.6	0.5	0.4	0.4	0.4	0.4	0.6	0.4	0.4	0.5	0.5	0.5	0.4	0.6	0.4	0.4
Low	ACp	0.1	0.4	0.4	0.3	0.1	0.1	0.1	0.1	0.4	0.1	0.1	0.3	0.3	0.3	0.1	0.4	0.1	0.1
Low	ALf	0.4	0.6	0.6	0.5	0.4	0.4	0.4	0.4	0.6	0.4	0.4	0.5	0.5	0.5	0.4	0.6	0.4	0.4
Low	ALg	0.6	0.8	0.8	0.7	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
Low	ALh	0.4	0.6	0.6	0.5	0.4	0.4	0.4	0.4	0.6	0.4	0.4	0.5	0.5	0.5	0.4	0.6	0.4	0.4
Low	ALp	0.1	0.4	0.4	0.3	0.1	0.1	0.1	0.1	0.4	0.1	0.1	0.3	0.3	0.3	0.1	0.4	0.1	0.1
Low	ARa	0.1	0.3	0.1	0.2	0.1	0.1	0.1	0.1	0.3	0.1	0.1	0.2	0.2	0.2	0.1	0.3	0.1	0.2
Low	ARb	0.3	0.5	0.2	0.4	0.3	0.4	0.3	0.3	0.5	0.3	0.4	0.4	0.4	0.4	0.3	0.5	0.3	0.4
Low	ARc	0.4	0.6	0.2	0.6	0.5	0.6	0.4	0.4	0.4	0.5	0.4	0.5	0.5	0.5	0.4	0.4	0.5	0.6
Low	ARg	0.5	0.7	0.2	0.6	0.5	0.6	0.5	0.5	0.7	0.5	0.6	0.6	0.6	0.6	0.5	0.7	0.5	0.6
Low	ARh	0.5	0.7	0.2	0.6	0.5	0.6	0.5	0.5	0.7	0.5	0.6	0.6	0.6	0.6	0.5	0.7	0.5	0.6
Low	ARI	0.3	0.5	0.2	0.5	0.3	0.5	0.3	0.3	0.5	0.3	0.5	0.4	0.4	0.4	0.3	0.5	0.3	0.4
Low	ARo	0.2	0.3	0.1	0.3	0.2	0.2	0.2	0.2	0.3	0.2	0.2	0.2	0.2	0.2	0.1	0.3	0.2	0.2
Low	CLI	0.6	0.7	0.6	0.7	0.4	0.7	0.6	0.6	0.3	0.6	0.4	0.3	0.3	0.3	0.4	0.3	0.7	0.7
Low	CLp	0.4	0.5	0.4	0.5	0.1	0.5	0.4	0.4	0.1	0.4	0.1	0.1	0.1	0.1	0.1	0.1	0.4	0.4
Low	CMc	0.8	0.8	0.8	0.8	0.6	0.8	0.8	0.8	0.5	0.8	0.6	0.5	0.5	0.5	0.6	0.5	0.8	0.8
Low	CMd	0.6	0.8	0.8	0.7	0.6	0.6	0.6	0.6	0.8	0.6	0.6	0.7	0.7	0.7	0.6	0.8	0.6	0.6
Low	CMe	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
Low	CMg	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
Low	CMo	0.4	0.6	0.6	0.5	0.4	0.4	0.4	0.4	0.6	0.4	0.4	0.5	0.5	0.5	0.4	0.6	0.4	0.4
Low	CMx	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
Low	FLc	0.6	0.8	0.8	0.7	0.6	0.6	0.6	0.6	0.5	0.6	0.6	0.5	0.5	0.5	0.6	0.5	0.6	0.6
Low	FLd	0.4	0.6	0.6	0.5	0.4	0.4	0.4	0.4	0.6	0.4	0.4	0.5	0.5	0.5	0.4	0.6	0.4	0.4
Low	FLe	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
Low	FLt	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Low	FLu	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
Low	FRh	0.4	0.6	0.4	0.5	0.4	0.4	0.4	0.4	0.6	0.4	0.4	0.5	0.5	0.5	0.4	0.6	0.4	0.4
Low	FRp	0.4	0.6	0.4	0.5	0.4	0.4	0.4	0.4	0.6	0.4	0.4	0.5	0.5	0.5	0.4	0.6	0.4	0.4
Low	FRu	0.4	0.6	0.4	0.5	0.4	0.4	0.4	0.4	0.6	0.4	0.4	0.5	0.5	0.5	0.4	0.6	0.4	0.4
Low	FRx	0.4	0.6	0.4	0.5	0.4	0.4	0.4	0.4	0.6	0.4	0.4	0.5	0.5	0.5	0.4	0.6	0.4	0.4
Low	GLd	0.6	0.8	0.8	0.7	0.6	0.6	0.6	0.6	0.8	0.6	0.6	0.7	0.7	0.7	0.6	0.8	0.6	0.6
Low	GLe	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
Low	GLk	0.6	0.7	0.6	0.7	0.4	0.7	0.6	0.6	0.3	0.6	0.4	0.3	0.3	0.3	0.4	0.3	0.7	0.7
Low	GLm	1	1	1	1	1	1	1	1	0.6	0.7	0.6	0.6	0.6	0.6	1	1	1	1
Low	GLu	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
Low	LPd	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Low	LPe	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.1	0.3	0.3	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Low	LPm	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.1	0.3	0.3	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Low	LPq	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Low	LVa	0.6	0.8	0.4	0.7	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
Low	LVf	0.6	0.8	0.8	0.7	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
Low	LVg	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.6	0.7	0.7	0.6	0.6	0.6	0.7	0.6	0.8	0.8
Low	LVh	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.6	0.7	0.7	0.6	0.6	0.6	0.7	0.6	0.8	0.8
Low	LVk	0.8	0.8	0.8	0.8	0.6	0.8	0.8	0.8	0.5	0.7	0.6	0.5	0.5	0.5	0.6	0.5	0.8	0.8
Low	LVx	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.6	0.7	0.7	0.6	0.6	0.6	0.7	0.6	0.8	0.8
Low	LXf	0.6	0.8	0.8	0.7	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
Low	LXg	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.6	0.7	0.7	0.6	0.6	0.6	0.7	0.6	0.8	0.8
Low	LXh	0.6	0.8	0.8	0.7	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
Low	LXp	0.4	0.6	0.6	0.5	0.4	0.4	0.4	0.4	0.6	0.4	0.4	0.5	0.5	0.5	0.4	0.6	0.4	0.4

Input level	Soil code	Crops of the Nigeria study																	
		Mai	**Mil**	**Ric**	**Sor**	**Cow**	**Grn**	**Bns**	**Sob**	**Cas**	**Swp**	**Pot**	**Wiy**	**Ban**	**Oil**	**Suc**	**Cot**		
Low	NTh	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
Low	NTr	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
Low	NTu	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Low	PHc	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.6	0.7	0.6	0.6	0.6	0.6	0.8	0.8	0.8	0.8
Low	PHg	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.6	0.7	0.6	0.6	0.6	0.6	0.8	0.8	0.8	0.8
Low	PHh	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.6	0.7	0.6	0.6	0.6	0.6	0.8	0.8	0.8	0.8
Low	PHI	0.8	0.8	0.6	0.8	0.8	0.8	0.8	0.8	0.6	0.7	0.6	0.6	0.6	0.6	0.7	0.6	0.8	0.8
Low	PLe	0.6	0.8	0.8	0.7	0.6	0.6	0.6	0.6	0.8	0.6	0.6	0.7	0.7	0.7	0.6	0.8	0.6	0.6
Low	PTd	0.1	0.4	0.4	0.3	0.1	0.1	0.1	0.1	0.4	0.1	0.1	0.3	0.3	0.3	0.1	0.4	0.1	0.1
Low	PTe	0.4	0.6	0.6	0.5	0.4	0.4	0.4	0.4	0.6	0.4	0.4	0.5	0.5	0.5	0.4	0.6	0.4	0.4
Low	RGd	0.4	0.6	0.6	0.5	0.4	0.4	0.4	0.4	0.6	0.4	0.4	0.5	0.5	0.5	0.4	0.6	0.4	0.4
Low	RGe	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
Low	SCg	0.1	0.1	0.1	0.3	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.3	0.3
Low	SNg	0.1	0.3	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Low	SNh	0.1	0.3	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Low	SNj	0.1	0.3	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Low	SNk	0.1	0.3	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Low	VRd	0.4	0.6	0.7	0.5	0.4	0.3	0.4	0.4	0.1	0.3	0.3	0.1	0.1	0.1	0.3	0.1	0.4	0.4
Low	VRe	0.6	0.6	0.7	0.6	0.6	0.5	0.6	0.6	0.1	0.3	0.3	0.1	0.1	0.1	0.3	0.1	0.6	0.6
Low	VRk	0.4	0.5	0.5	0.5	0.2	0.4	0.4	0.4	0.1	0.3	0.2	0.1	0.1	0.1	0.2	0.1	0.5	0.5
High	ACf	0.5	0.7	0.7	0.6	0.5	0.5	0.5	0.5	0.7	0.5	0.5	0.6	0.6	0.6	0.5	0.7	0.5	0.5
High	ACg	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
High	ACh	0.5	0.7	0.7	0.6	0.5	0.5	0.5	0.5	0.7	0.5	0.5	0.6	0.6	0.6	0.5	0.7	0.5	0.5
High	ACp	0.1	0.4	0.4	0.3	0.1	0.1	0.1	0.1	0.4	0.1	0.1	0.3	0.3	0.3	0.1	0.4	0.1	0.1
High	ALf	0.5	0.7	0.7	0.6	0.5	0.5	0.5	0.5	0.7	0.5	0.5	0.6	0.6	0.6	0.5	0.7	0.5	0.5
High	ALg	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
High	ALh	0.6	0.8	0.8	0.7	0.6	0.6	0.6	0.6	0.8	0.6	0.6	0.7	0.7	0.7	0.6	0.8	0.6	0.6
High	ALp	0.1	0.4	0.4	0.3	0.1	0.1	0.1	0.1	0.4	0.1	0.1	0.3	0.3	0.3	0.1	0.4	0.1	0.1
High	ARa	0.2	0.4	0.2	0.3	0.2	0.2	0.2	0.2	0.4	0.2	0.2	0.3	0.3	0.3	0.2	0.4	0.2	0.3
High	ARb	0.4	0.6	0.3	0.5	0.4	0.5	0.4	0.4	0.6	0.4	0.5	0.5	0.5	0.5	0.4	0.6	0.4	0.5
High	ARc	0.7	0.9	0.3	0.9	0.8	0.9	0.7	0.7	0.7	0.8	0.7	0.8	0.8	0.8	0.7	0.7	0.8	0.9
High	ARg	0.8	1	0.3	0.9	0.8	0.9	0.8	0.8	1	0.8	0.9	0.9	0.9	0.9	0.8	1	0.8	0.9
High	ARh	0.8	1	0.3	0.9	0.8	0.9	0.8	0.8	1	0.8	0.9	0.9	0.9	0.9	0.8	1	0.8	0.9
High	ARI	0.5	0.7	0.3	0.7	0.5	0.7	0.5	0.5	0.7	0.5	0.7	0.6	0.6	0.6	0.5	0.7	0.5	0.6
High	ARo	0.3	0.4	0.2	0.4	0.3	0.3	0.3	0.3	0.4	0.3	0.3	0.3	0.3	0.3	0.2	0.4	0.3	0.3
High	CLI	0.8	0.9	0.8	0.9	0.6	0.9	0.8	0.8	0.5	0.8	0.6	0.5	0.5	0.5	0.6	0.5	0.9	0.9
High	CLp	0.5	0.5	0.5	0.5	0.4	0.5	0.5	0.5	0.3	0.5	0.4	0.3	0.3	0.3	0.4	0.3	0.4	0.4
High	CMc	1	1	1	1	0.8	1	1	1	0.7	1	0.8	0.7	0.7	0.7	0.8	0.7	1	1
High	CMd	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
High	CMe	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
High	CMg	1	1.1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
High	CMo	0.4	0.6	0.6	0.5	0.4	0.4	0.4	0.4	0.6	0.4	0.4	0.5	0.5	0.5	0.4	0.6	0.4	0.4
High	CMx	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
High	FLc	1	1	1	1	0.8	1	1	1	0.7	1	0.8	0.7	0.7	0.7	0.8	0.7	1	1
High	FLd	0.6	0.8	0.8	0.7	0.6	0.6	0.6	0.6	0.8	0.6	0.6	0.7	0.7	0.7	0.6	0.8	0.6	0.6
High	FLe	1	1	1	1	1	1	1.1	1	1	1	1	1	1	1	1	1	1	1
High	FLt	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
High	FLu	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
High	FRh	0.6	0.8	0.6	0.7	0.6	0.6	0.6	0.6	0.8	0.6	0.6	0.7	0.7	0.7	0.6	0.8	0.6	0.6
High	FRp	0.5	0.7	0.6	0.6	0.5	0.5	0.5	0.5	0.7	0.5	0.5	0.6	0.6	0.6	0.5	0.7	0.5	0.5
High	FRu	0.5	0.7	0.6	0.6	0.5	0.5	0.5	0.5	0.7	0.5	0.5	0.6	0.6	0.6	0.5	0.7	0.5	0.5
High	FRx	0.4	0.6	0.6	0.5	0.4	0.4	0.4	0.4	0.6	0.4	0.4	0.5	0.5	0.5	0.4	0.6	0.4	0.4

Input	Soil	Crops of the Nigeria study																	
level	code	Mai	Mil	Ric	Sor	Cow	Grn	Bns	Sob	Cas	Swp	Pot	Wiy	Ban	Oil	Suc	Cot		
High	GLd	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
High	GLe	1	1.1	1.1	1	1	1	1	1	1	1	1	1	1.1	1	1	1	1	1
High	GLk	0.8	0.9	0.8	0.9	0.6	0.9	0.8	0.8	0.5	0.8	0.6	0.5	0.5	0.5	0.6	0.5	0.9	0.9
High	GLm	1	1	1	1	1	1	1	1	0.6	0.7	0.6	0.6	0.6	0.6	1	1	1	1
High	GLu	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
High	LPd	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
High	LPe	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
High	LPm	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
High	LPq	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
High	LVa	0.8	1	0.6	0.9	0.9	1	0.8	0.8	0.8	0.8	0.9	0.8	0.8	0.8	0.8	0.8	0.9	0.9
High	LVf	1	1	1	1	1	1	1	1	0.8	0.9	0.9	0.8	0.8	0.8	0.9	0.8	1	1
High	LVg	1	1	1	1	1	1	1	1	0.8	0.9	0.9	0.8	0.8	0.8	0.9	0.8	1	1
High	LVh	1	1	1	1	1	1	1	1	0.8	0.9	0.9	0.8	0.8	0.8	0.9	0.8	1	1
High	LVk	1	1	1	1	0.8	1	1	1	0.7	0.9	0.8	0.7	0.7	0.7	0.8	0.7	1	1
High	LVx	1	1	1	1	1	1	1	1	0.8	0.9	0.9	0.8	0.8	0.8	0.9	0.8	1	1
High	LXf	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
High	LXg	1	1	1	1	1	1	1	1	0.8	0.9	0.9	0.8	0.8	0.8	0.9	0.8	1	1
High	LXh	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
High	LXp	0.5	0.7	0.7	0.6	0.5	0.5	0.5	0.5	0.7	0.5	0.5	0.6	0.6	0.6	0.5	0.7	0.5	0.5
High	NTh	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
High	NTr	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
High	NTu	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
High	PHc	1	1	1	1	1	1	1	1	0.6	0.7	0.6	0.6	0.6	0.6	1	1	1	1
High	PHg	1	1	1	1	1	1	1	1	0.6	0.7	0.6	0.6	0.6	0.6	1	1	1	1
High	PHh	1	1	1	1	1	1	1	0.6	0.7	0.6	0.6	0.6	0.6	1	1	1	1	
High	PHI	1	1	1	1	1	1	1	1	0.6	0.7	0.6	0.6	0.6	0.6	0.9	0.8	1	1
High	PLe	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
High	PTD	0.1	0.4	0.4	0.3	0.1	0.1	0.1	0.1	0.4	0.1	0.1	0.3	0.3	0.3	0.1	0.4	0.1	0.1
High	PTe	0.6	0.8	0.8	0.7	0.6	0.6	0.6	0.6	0.8	0.6	0.6	0.7	0,7	0.7	0.6	0.8	0.6	0.6
High	RGd	0.4	0.6	0.6	0.5	0.4	0.4	0.4	0.4	0.6	0.4	0.4	0.5	0.5	0.5	0.4	0.6	0.4	0.4
High	RGe	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
High	SCg	0.4	0.4	0.3	0.5	0.3	0.3	0.1	0.3	0.3	0.4	0.4	0.3	0.3	0.3	0.3	0.3	0.5	0.5
High	SNg	0.3	0.5	0.4	0.4	0.1	0.1	0.1	0.1	0.1	0.3	0.3	0.3	0.3	0.3	0.1	0.1	0.3	0.4
High	SNh	0.3	0.5	0.4	0.4	0.1	0.1	0.1	0.1	0.1	0.3	0.3	0.3	0.3	0.3	0.1	0.1	0.3	0.4
High	SNj	0.3	0.5	0.4	0.4	0.1	0.1	0.1	0.1	0.1	0.3	0.3	0.3	0.3	0.3	0.1	0.1	0.3	0.4
High	SNk	0.3	0.5	0.4	0.4	0.1	0.1	0.1	0.1	0.1	0.3	0.3	0.3	0.3	0.3	0.1	0.1	0.3	0.4
High	VRd	0.6	0.6	0.7	0.6	0.6	0.5	0.6	0.6	0.3	0.5	0.5	0.3	0.3	0.3	0.5	0.3	0.6	0.6
High	VRe	0.8	0.8	0.9	0.8	0.8	0.7	0.8	0.8	0.3	0.5	0.5	0.3	0.3	0.3	0.5	0.3	0.8	0.8
High	VRk	0.6	0.7	0.7	0.7	0.4	0.6	0.6	0.6	0.2	0.5	0.4	0.2	0.2	0.2	0.4	0.2	0.7	0.7

Annex 8

Changes of land productivity, extent of suitable land, crop yields and multiple cropping index at national level including the effect of multiple cropping

Table A8.1 : Change in land productivity (%) at national level for including multiple cropping increments

Scenario	Reference	GFTR-D2	GFTR-D3	HCTR-D2	HCTR-D3	MPTR-D2	MPTR-D3	PP10	PP10	PP30	PP30
Temp. change	0	*	*	*	*	*	*	0	0	0	0
Rainfall change	0	*	*	*	*	*	*	10	10	30	30
CO2 level	330	460	550	460	550	460	550	330	550	330	550
Crop	1000 MT	%	%	%	%	%	%	%	%	%	%
Maize	176215	2.9	12.8	6.4	7.8	-12.1	-1.2	3.0	12.9	7.2	17.7
Millet	101067	3.1	15.9	4.9	6.1	-6.4	-1.1	-0.1	9.1	-0.5	8.5
Rice	126252	14.9	30.4	21.3	31.3	-3.2	17.1	5.2	36.1	13.8	46.7
Sorghum	111611	4.4	17.8	5.7	7.8	-8.7	1.4	1.0	11.2	3.0	13.5
Cowpea	74388	15.9	35.6	21.2	32.4	-0.1	19.0	2.6	36.7	6.9	43.1
Groundnut	108412	16.2	36.2	21.9	32.7	0.6	19.7	2.1	36.9	5.8	42.8
Beans (Phaseolus)	497	-70.8	-83.9	-13.1	-58.6	-83.5	-95.2	-2.6	56.5	-7.6	55.5
Soybean	62454	13.8	35.6	19.3	29.8	-1.7	17.1	1.8	37.7	3.9	41.8
Cassava	155179	17.0	27.6	24.2	37.9	-5.6	20.2	9.4	52.6	24.7	75.2
Sweet Potato	522224	16.1	31.5	20.5	31.3	-3.0	19.9	4.1	37.0	10.4	45.6
White Potato	81	-97.5	-97.5	-82.7	-95.1	-97.5	-100.0	-17.3	70.4	-25.9	70.4
White Yam	391766	20.5	34.9	23.5	36.3	-1.0	25.7	6.4	37.7	15.4	49.3
Greater Yam	335936	14.2	23.4	24.2	35.5	-6.6	16.5	7.9	44.9	22.2	62.4
Yellow Yam	93181	12.5	11.5	24.7	41.7	-13.8	12.3	17.4	69.0	50.0	110.8
Banana	1200	6.8	-1.4	-33.6	-21.6	-39.7	-36.6	51.0	142.9	164.3	311.5
Oilpalm	2101	12.9	15.0	-11.9	9.9	-27.2	-10.9	36.7	112.6	113.8	205.6
Sugarcane	77433	-1.4	-5.9	11.5	15.1	-22.1	-9.3	12.8	30.3	35.6	53.8
Cotton	28617	25.3	47.2	26.4	33.1	4.9	26.6	1.8	32.6	4.7	36.6

Scenario	Reference	PM10	PM10	PM30	PM30	T20	T20	T20	T40	T40	T40
Temp. change	0	0	0	0	0	2	2	2	4	4	4
Rainfall change	0	-10	-10	-30	-30	0	0	0	0	0	0
CO2 level	330	330	550	330	550	330	460	550	330	460	550
Crop	1000 MT	%	%	%	%	%	%	%	%	%	%
Maize	176215	-3.9	5.7	-15.1	-6.6	-4.8	0.5	4.1	-10.1	-4.9	-1.2
Millet	101067	0.3	9.6	-1.6	7.6	-4.1	1.2	4.8	-8.8	-3.7	-0.2
Rice	126252	-5.9	21.4	-21.7	1.3	-6.3	12.0	24.4	-14.0	3.2	15.1
Sorghum	111611	-1.5	8.5	-7.8	1.5	-3.6	2.0	6.0	-7.8	-2.0	1.8
Cowpea	74388	-3.3	28.2	-15.4	11.5	-7.4	11.5	26.0	-16.0	2.0	14.6
Groundnut	108412	-2.7	29.1	-14.4	13.0	-7.1	11.9	26.0	-15.3	2.6	15.3
Beans (Phaseolus)	497	0.6	52.3	-3.0	47.9	-89.5	-83.9	-81.1	-99.8	-99.0	-98.4
Soybean	62454	-2.2	31.2	-11.5	17.9	-10.8	9.7	24.2	-19.4	-0.4	12.9
Cassava	155179	-11.1	27.1	-36.5	-7.6	-11.8	13.1	29.9	-23.6	-0.2	15.9
Sweet Potato	522224	-5.3	24.1	-19.0	5.5	-5.5	13.0	26.7	-12.7	5.1	17.6
White Potato	81	16.0	87.7	29.6	111.1	-100.0	-97.5	-97.5	-100.0	-100.0	-100.0
White Yam	391766	-8.0	19.3	-28.9	-8.1	-2.6	16.7	29.8	-8.5	9.4	22.6
Greater Yam	335936	-9.1	21.8	-34.1	-10.5	-9.6	10.0	24.4	-20.0	-2.1	11.2
Yellow Yam	93181	-17.0	21.2	-53.9	-30.7	-15.1	8.5	28.1	-28.8	-9.4	6.4
Banana	1200	-39.9	6.8	-87.7	-70.7	-36.1	-2.4	22.8	-57.4	-37.8	-20.2
Oilpalm	2101	-29.8	12.3	-75.6	-55.4	-24.4	4.2	27.4	-48.7	-23.3	-6.0
Sugarcane	77433	-13.0	-0.1	-46.1	-35.9	-12.6	-4.8	0.2	-25.3	-17.6	-12.9
Cotton	28617	-1.2	28.2	-10.6	15.4	-2.4	16.6	30.6	-7.5	11.5	24.7

* = GCM derived

Table A8.2 : Change in extent of suitable land (%) at national level including multiple cropping increments

Scenario	Reference	GFTR-D2	GFTR-D3	HCTR-D2	HCTR-D3	MPTR-D2	MPTR-D3	PP10	PP10	PP30	PP30
Temp. change	0	*	*	*	*	*	*	0	0	0	0
Rainfall change	0	*	*	*	*	*	*	10	10	30	30
CO2 level	330	460	550	460	550	460	550	330	550	330	550
Crop	100 ha	%	%	%	%	%	%	%	%	%	%
Maize	458284	-2.8	5.2	0.6	0.1	-13.8	-5.4	2.6	6.1	6.0	10.2
Millet	520127	-1.1	8.0	2.5	3.4	-8.3	-3.6	-0.9	2.6	-3.2	-0.3
Rice	452743	2.1	12.6	6.5	7.5	-9.5	-0.6	3.9	13.0	10.0	17.5
Sorghum	512225	-2.4	6.1	1.1	1.7	-11.8	-4.1	2.1	5.6	5.6	9.9
Cowpea	474135	1.6	11.5	4.9	9.2	-8.7	0.7	2.1	12.1	5.4	16.6
Groundnut	438903	1.3	11.2	5.2	7.8	-9.4	0.3	2.4	13.1	6.5	18.3
Beans (Phaseolus)	3659	-61.4	-73.8	-7.6	-49.9	-76.5	-89.0	-0.1	103.4	-0.5	110.9
Soybean	445518	0.6	10.4	5.0	6.9	-10.3	0.1	2.2	12.2	4.9	16.0
Cassava	188699	7.4	13.4	11.0	12.3	-11.1	5.1	6.2	20.3	14.8	32.2
Sweet Potato	434417	2.3	13.1	4.3	7.2	-12.1	1.6	2.8	12.0	8.1	17.8
White Potato	86	-93.0	-93.0	-76.7	-88.4	-94.2	-100.0	-14.0	111.6	-15.1	150.0
White Yam	247949	11.9	17.7	10.6	12.0	-8.7	10.6	6.6	13.1	15.7	22.0
Greater Yam	232095	9.8	18.5	14.8	14.8	-9.2	6.7	5.6	24.7	17.2	34.2
Yellow Yam	96369	9.6	10.6	28.0	39.5	-10.6	12.7	12.7	46.5	35.8	69.6
Banana	7494	5.1	-3.6	-34.6	-22.0	-40.5	-33.7	47.3	117.1	144.1	250.3
Oilpalm	22010	10.5	12.6	-10.0	12.1	-27.0	-9.0	34.4	92.5	102.2	158.1
Sugarcane	130868	-0.9	-1.7	10.3	12.5	-19.2	-6.7	10.4	23.0	27.8	38.8
Cotton	309217	12.5	23.3	13.1	11.0	-6.5	8.5	3.0	12.3	7.6	17.2

Scenario	Reference	PM10	PM10	PM30	PM30	T20	T20	T20	T40	T40	T40
Temp. change	0	0	0	0	0	2	2	2	4	4	4
Rainfall change	0	-10	-10	-30	-30	0	0	0	0	0	0
CO2 level	330	330	550	330	550	330	460	550	330	460	550
Crop	100 ha	%	%	%	%	%	%	%	%	%	%
Maize	458284	-3.0	0.5	-12.4	-9.9	-2.8	-1.1	-0.2	-6.6	-4.2	-3.0
Millet	520127	0.5	3.9	-3.6	-0.2	-1.6	0.7	2.0	-4.2	-1.9	-0.3
Rice	452743	-4.3	3.8	-14.6	-6.0	-4.0	3.0	6.8	-8.5	-1.5	2.5
Sorghum	512225	-2.0	1.3	-9.3	-6.0	-2.5	-0.6	0.7	-6.0	-3.1	-1.8
Cowpea	474135	-2.9	6.0	-10.4	-2.6	-3.8	1.8	7.6	-8.9	-1.5	1.5
Groundnut	438903	-2.7	5.7	-11.1	-2.7	-3.6	1.7	5.9	-8.2	-1.8	1.4
Beans (Phaseolus)	3659	0.3	82.7	-1.0	84.1	-88.4	-76.2	-71.6	-99.2	-97.4	-95.5
Soybean	445518	-2.4	7.2	-11.0	-1.9	-4.8	1.7	6.2	-9.6	-3.2	1.0
Cassava	188699	-8.6	8.1	-29.0	-14.0	-7.6	4.9	10.4	-15.5	-1.9	4.8
Sweet Potato	434417	-3.5	5.1	-14.9	-7.4	-2.1	2.3	6.5	-5.4	-0.4	2.8
White Potato	86	9.3	115.1	14.0	144.2	-100.0	-95.3	-93.0	-100.0	-100.0	-100.0
White Yam	247949	-8.7	-2.1	-30.7	-25.4	2.3	9.9	12.4	3.6	9.1	13.8
Greater Yam	232095	-6.2	10.0	-25.8	-10.7	-5.3	5.3	12.8	-12.0	-2.2	5.3
Yellow Yam	96369	-11.6	15.9	-43.2	-24.4	-9.3	6.7	21.9	-17.5	-5.2	6.1
Banana	7494	-38.9	1.2	-86.1	-68.7	-34.3	-4.0	17.0	-53.2	-36.6	-21.0
Oilpalm	22010	-27.7	6.4	-73.3	-54.5	-20.9	2.5	21.8	-44.5	-20.7	-6.4
Sugarcane	130868	-10.2	-1.6	-40.5	-31.8	-8.5	-3.1	0.1	-18.3	-12.1	-8.7
Cotton	309217	-2.9	5.7	-14.6	-7.1	-0.2	6.4	11.1	-1.4	5.8	9.8

* = GCM derived

Table A8.3 : Change in crop yield per hectare (%) at national level including multiple cropping increments

Scenario	Reference	GFTR-D2	GFTR-D3	HCTR-D2	HCTR-D3	MPTR-D2	MPTR-D3	PP10	PP10	PP30	PP30
Temp. change	0	*	*	*	*	*	*	0	0	0	0
Rainfall change	0	*	*	*	*	*	*	10	10	30	30
CO2 level	330	460	550	460	550	460	550	330	550	330	550
Crop	kg/ha	%	%	%	%	%	%	%	%	%	%
Maize	3845	5.8	7.2	5.7	7.7	2.0	4.4	0.4	6.4	1.2	6.9
Millet	1943	4.3	7.3	2.4	2.6	2.1	2.6	0.8	6.3	2.7	8.9
Rice	2789	12.5	15.7	13.8	22.1	7.0	17.7	1.2	20.5	3.4	24.8
Sorghum	2179	7.0	11.0	4.5	6.0	3.5	5.7	-1.1	5.3	-2.4	3.3
Cowpea	1569	14.1	21.5	15.6	21.2	9.4	18.1	0.5	21.9	1.4	22.8
Groundnut	2470	14.7	22.6	15.9	23.1	11.1	19.4	-0.2	21.1	-0.6	20.7
Beans (Phaseolus)	1357	-24.5	-38.9	-5.9	-17.4	-29.8	-55.1	-2.4	-22.9	-7.1	-26.2
Soybean	1402	13.1	22.8	13.6	21.4	9.6	16.9	-0.4	22.8	-0.9	22.3
Cassava	8224	8.9	12.5	11.8	22.8	6.2	14.3	3.0	26.9	8.6	32.5
Sweet Potato	12021	13.5	16.2	15.5	22.6	10.3	18.1	1.3	22.3	2.1	23.7
White Potato	9476	-54.9	-54.2	-24.5	-52.6	-55.6	-100.0	-4.8	-20.0	-13.2	-32.1
White Yam	15800	7.7	14.6	11.6	21.7	8.4	13.6	-0.2	21.7	-0.2	22.3
Greater Yam	14474	4.0	4.1	8.2	18.1	2.9	9.2	2.2	16.1	4.3	21.0
Yellow Yam	9669	2.6	0.9	-2.6	1.6	-3.6	-0.4	4.2	15.4	10.5	24.3
Banana	1602	1.6	2.2	1.5	0.4	1.4	-4.3	2.5	11.8	8.2	17.4
Oilpalm	955	2.1	2.1	-2.1	-2.0	-0.3	-2.1	1.6	10.4	5.7	18.3
Sugarcane	5917	-0.5	-4.3	1.1	2.3	-3.6	-2.8	2.2	5.9	6.1	10.7
Cotton	925	11.5	19.5	11.8	20.0	12.2	16.8	-1.1	18.3	-2.6	16.6

Scenario	Reference	PM10	PM10	PM30	PM30	T20	T20	T20	T40	T40	T40
Temp. change	0	0	0	0	0	2	2	2	4	4	4
Rainfall change	0	-10	-10	-30	-30	0	0	0	0	0	0
CO2 level	330	330	550	330	550	330	460	550	330	460	550
Crop	kg/ha	%	%	%	%	%	%	%	%	%	%
Maize	3845	-0.9	5.2	-3.0	3.6	-2.1	1.6	4.3	-3.7	-0.7	1.8
Millet	1943	-0.2	5.5	2.0	7.8	-2.6	0.5	2.8	-4.8	-1.9	0.1
Rice	2789	-1.8	17.0	-8.3	7.7	-2.4	8.7	16.4	-6.0	4.7	12.2
Sorghum	2179	0.5	7.1	1.6	7.9	-1.2	2.6	5.3	-2.0	1.1	3.7
Cowpea	1569	-0.4	21.0	-5.6	14.4	-3.8	9.5	17.2	-7.8	3.6	12.9
Groundnut	2470	0.0	22.1	-3.8	16.1	-3.6	10.0	19.1	-7.7	4.5	13.6
Beans (Phaseolus)	1357	0.5	-16.6	-1.9	-19.5	-9.3	-32.3	-33.2	-66.3	-64.3	-63.2
Soybean	1402	0.3	22.3	-0.6	20.1	-6.3	7.8	17.0	-10.8	2.9	11.8
Cassava	8224	-2.8	17.7	-10.6	7.4	-4.5	7.8	17.6	-9.7	1.7	10.6
Sweet Potato	12021	-1.9	18.1	-4.8	13.9	-3.5	10.4	18.9	-7.7	5.5	14.4
White Potato	9476	4.5	-13.3	13.0	-13.7	-100.0	-55.7	-53.9	-100.0	-100.0	-100.0
White Yam	15800	0.8	21.8	2.6	23.1	-4.8	6.2	15.5	-11.7	0.3	7.7
Greater Yam	14474	-3.0	10.8	-11.2	0.2	-4.5	4.5	10.3	-9.1	0.1	5.6
Yellow Yam	9669	-6.1	4.5	-18.8	-8.3	-6.3	1.7	5.2	-13.7	-4.4	0.3
Banana	1602	-1.8	5.4	-11.7	-6.4	-2.9	1.7	4.9	-9.1	-1.9	1.0
Oilpalm	955	-3.0	5.5	-8.5	-2.1	-4.5	1.6	4.5	-7.6	-3.4	0.3
Sugarcane	5917	-3.1	1.5	-9.4	-6.0	-4.5	-1.8	0.1	-8.6	-6.3	-4.6
Cotton	925	1.8	21.4	4.6	24.2	-2.2	9.7	17.6	-6.1	5.4	13.6

* = GCM derived

Table A8.4 : Change in crop yield per hectare (%) at national level for sole crops

Scenario	Reference	GFTR-D2	GFTR-D3	HCTR -D2	HCTR -D3	MPTR -D2	MPTR -D3	PP10	PP10	PP30	PP30
Temp. change	0	*	*	*	*	*	*	0	0	0	0
Rainfall change	0	*	*	*	*	*	*	10	10	30	30
CO2 level	330	460	550	460	550	460	550	330	550	330	550
Crop	MCI	%	%	%	%	%	%	%	%	%	%
Maize	1.48	4.1	3.4	2.7	2.7	2.0	4.1	0.7	1.4	2.7	2.7
Millet	1.47	4.1	5.4	0.7	0.0	1.4	2.0	0.7	0.7	2.0	2.7
Rice	1.47	3.4	3.4	1.4	2.0	1.4	4.1	0.7	2.0	2.0	4.8
Sorghum	1.36	8.1	11.8	3.7	6.6	5.9	9.6	-1.5	4.4	-1.5	2.9
Cowpea	1.48	3.4	2.7	2.0	1.4	0.7	3.4	0.7	0.7	2.7	2.0
Groundnut	1.48	3.4	3.4	2.0	2.0	2.0	4.1	0.7	1.4	1.4	2.0
Beans (Phaseolus)	1.47	-8.2	-21.8	-4.8	-10.9	-17.7	-27.9	0.0	-15.6	-1.4	-15.6
Soybean	1.47	5.4	6.1	4.1	3.4	2.7	4.8	0.0	2.7	0.0	3.4
Cassava	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Sweet Potato	1.17	0.9	-2.6	1.7	1.7	-0.9	2.6	1.7	0.9	3.4	3.4
White Potato	1.2	-16.7	-16.7	-10.8	-16.7	-16.7	-100.0	-15.0	0.8	-16.7	-10.8
White Yam	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Greater Yam	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Yellow Yam	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Banana	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Oilpalm	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Sugarcane	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Cotton	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Scenario	Reference	PM10	PM10	PM30	PM30	T20	T20	T20	T40	T40	T40
Temp. change	0	0	0	0	0	2	2	2	4	4	4
Rainfall change	0	-10	-10	-30	-30	0	0	0	0	0	0
CO2 level	330	330	550	330	550	330	460	550	330	460	550
Crop	MCI	%	%	%	%	%	%	%	%	%	%
Maize	1.48	-0.7	0.0	-5.4	-4.1	2.0	2.0	2.7	3.4	3.4	4.1
Millet	1.47	-0.7	0.0	0.7	1.4	0.7	0.7	1.4	2.0	2.0	2.0
Rice	1.47	-1.4	0.7	-5.4	-4.1	1.4	2.7	2.7	2.7	4.1	4.8
Sorghum	1.36	0.0	5.1	-1.5	5.9	2.2	5.9	8.1	4.4	9.6	11.0
Cowpea	1.48	-0.7	0.0	-5.4	-4.7	2.0	2.0	2.0	4.1	3.4	3.4
Groundnut	1.48	0.0	0.7	-4.1	-4.1	2.0	2.7	2.7	4.1	4.1	4.1
Beans (Phaseolus)	1.47	-4.1	-16.3	-17.7	-23.8	1.4	-15.6	-18.4	-32.0	-32.0	-32.0
Soybean	1.47	-0.7	1.4	-2.0	-1.4	-0.7	2.7	3.4	0.7	4.1	4.8
Cassava	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Sweet Potato	1.17	-3.4	-3.4	-8.5	-8.5	2.6	2.6	1.7	4.3	4.3	4.3
White Potato	1.2	7.5	0.0	14.2	-0.8	-100.0	-16.7	-16.7	-100.0	-100.0	-100.0
White Yam	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Greater Yam	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Yellow Yam	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Banana	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Oilpalm	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Sugarcane	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Cotton	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

* = GCM derived

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