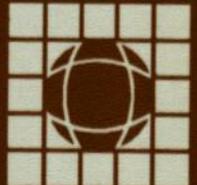
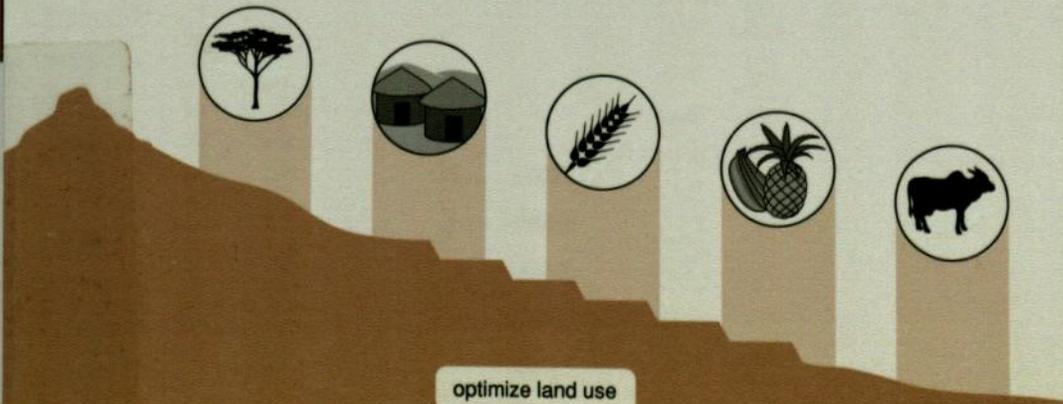
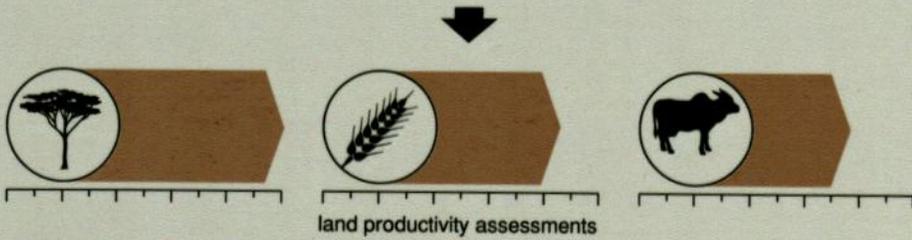
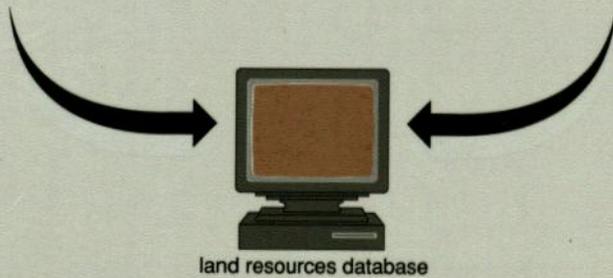


# Agro-ecological assessments for national planning: the example of Kenya



Food and Agriculture Organization of the United Nations



AGR



# Agro-ecological assessments for national planning: the example of Kenya



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## Chapter 1

# Introduction

The ability of land to produce is limited, and the limits to production are set by climate, soil and landform conditions, and the use and management applied to the land. Accordingly, knowledge of land resource endowment and its potential is an essential prerequisite to planning for optimal land use and subsequent sound agricultural and economic development that is sustainable in the long term.

In particular, in planning for optimal land use, answers are needed to a number of questions:

- is there sufficient land to meet future food and agricultural needs?
- where are the potentially utilizable areas and what are their extents?
- for which land uses are they suitable and what is the range of their potential?
- what level of technology is required under these various circumstances?
- what is the risk of degradation and what measures are required to minimize the risk?
- where can maximum returns from increased inputs be obtained and with what land uses?
- what levels of investment are needed to obtain these returns?
- what are the limitations to production increases?
- where should research, extension and education efforts be concentrated?

Aware of these facts, FAO began in 1976 the Agro-ecological Zones Project (AEZ) (FAO 1978-81) to assess production potential of land resources in the developing world, and to provide the physical data base necessary for planning future agricultural development. The innovative FAO study was valuable because it developed the concept and methodology to characterize tracts of land by quantified information on climate, soils and other physical factors which are used to predict the potential productivity for various crops according to their specific environmental and management needs. Climate, soil and landform data were combined into a 1:5 million scale land resources data base of several thousand unique agro-ecological cells. For each of these, crop requirements and crop growth models were applied to estimate rainfed yields and outputs for a range of agricultural input levels.

This subsequently made it possible for FAO to undertake, with support from UNFPA, and in collaboration with IIASA, assessments of the potential population supporting capacities of 117 developing nations, grouped into five regions — Africa, Southwest Asia, Southeast Asia, Central America and South America (FAO 1980, 1982). The methodology and the findings were discussed at the 1983 FAO Conference which, recognizing the importance of such work for development, recommended that future activities be concentrated at the national level (FAO 1984a). To do this, more refined methods have had to be developed for use at the larger scales required for national and sub-national studies. As in the original

global study, the methods are based on the same procedure of mapping climate (thermal and moisture regimes to indicate lengths of growing period) which is overlaid on the soil map to derive agro-ecological zones — tracts of land with unique combinations of climate and soil, and other factors, such as flooding risk, as necessary.

The regional assessments, in effect, ascertained country situations within a regional context; the national assessments of land productivity and population supporting capacity are intended to quantify sub-national situations within national contexts.

The specific requirements for growth of selected crops are matched with the physical conditions to provide an estimate of potential productivity. Although the concept is straightforward, the variety of combinations of climate, soil, and crop requirements makes this a complex and time-consuming undertaking. The zones identified as a result of the work are not mere arbitrary geographical regions, but have been systematically established and can be used with confidence by agricultural scientists and planners.

The programme of work used as the example for this *Soils Bulletin* was concerned with the development and implementation of a national-level methodology for the determination of land use potentials of land resources in each of the 41 districts of Kenya, as a tool in policy formulation and development planning. This case study was carried out by FAO and IIASA in collaboration with the Government of Kenya (FAO 1984b), and is part of the follow-up programme thrust to implement the 1983 FAO Conference recommendations. The work was reported in the form of a Main Report, from which this present volume is substantially derived, and eight Technical Annexes, under the title: 'Agro-ecological Land Resources Assessment for Agricultural Development Planning: A Case Study of Kenya: Resources Database and Land Productivity' (FAO/IIASA 1991).

The national methodology developed for Kenya was based on principles fundamental to any sound evaluation of land. These principles are described in 'A Framework for Land Evaluation' (FAO 1976). The methods used in the compilation of the national land inventory, as well as the land productivity models, have followed the philosophy and concepts developed in the AEZ regional assessments of land and population potentials of land resources of individual nations (FAO 1978-81, 1982).

The main objective of the national assessment was to apply the methodology to quantify:

- the extents of the various qualities of land in each district;
- what alternative kinds of land use can be considered for the different qualities of land in the various districts, and what are their productivity potentials at different levels of production inputs;
- how many people can be supported at those different levels of production inputs, and at what costs; and
- what are the policy implications of these land and population potentials for food and economic self-sufficiency, when examined against the background of present and future populations, food and agricultural demands, and socio-economic needs, opportunities and constraints.

This objective was addressed using methods and techniques that can operate within Kenya for future use, and are amenable to modification by national planners and experts in the light of increased knowledge.

This *Bulletin* presents the 1:1 million scale computerized land resources data base of Kenya, and the crop, livestock and fuelwood productivity models derived from land suitability assessments, which together provide the basis for the development of the model for the estimation of potential productivity of land resources. An overview of the methodology is presented in Chapter 2. The land resources data base is presented in Chapter 3, followed in Chapter 4 by the model to assess soil erosion hazard and its impact on productivity. Chapters 5, 6 and 7 present the crop, livestock and fuelwood productivity models respectively, which together comprise the land productivity model. The report ends with a worked example of a land productivity assessment for one area in Kenya, and a discussion, both of some of the factors that need to be taken into account when considering starting such a national-level AEZ assessment, and of the uses to which the results can be put in order to benefit the country as a whole.

Full technical details of the models and the computer application of them, are given in FAO/IIASA 1991.



## Chapter 2

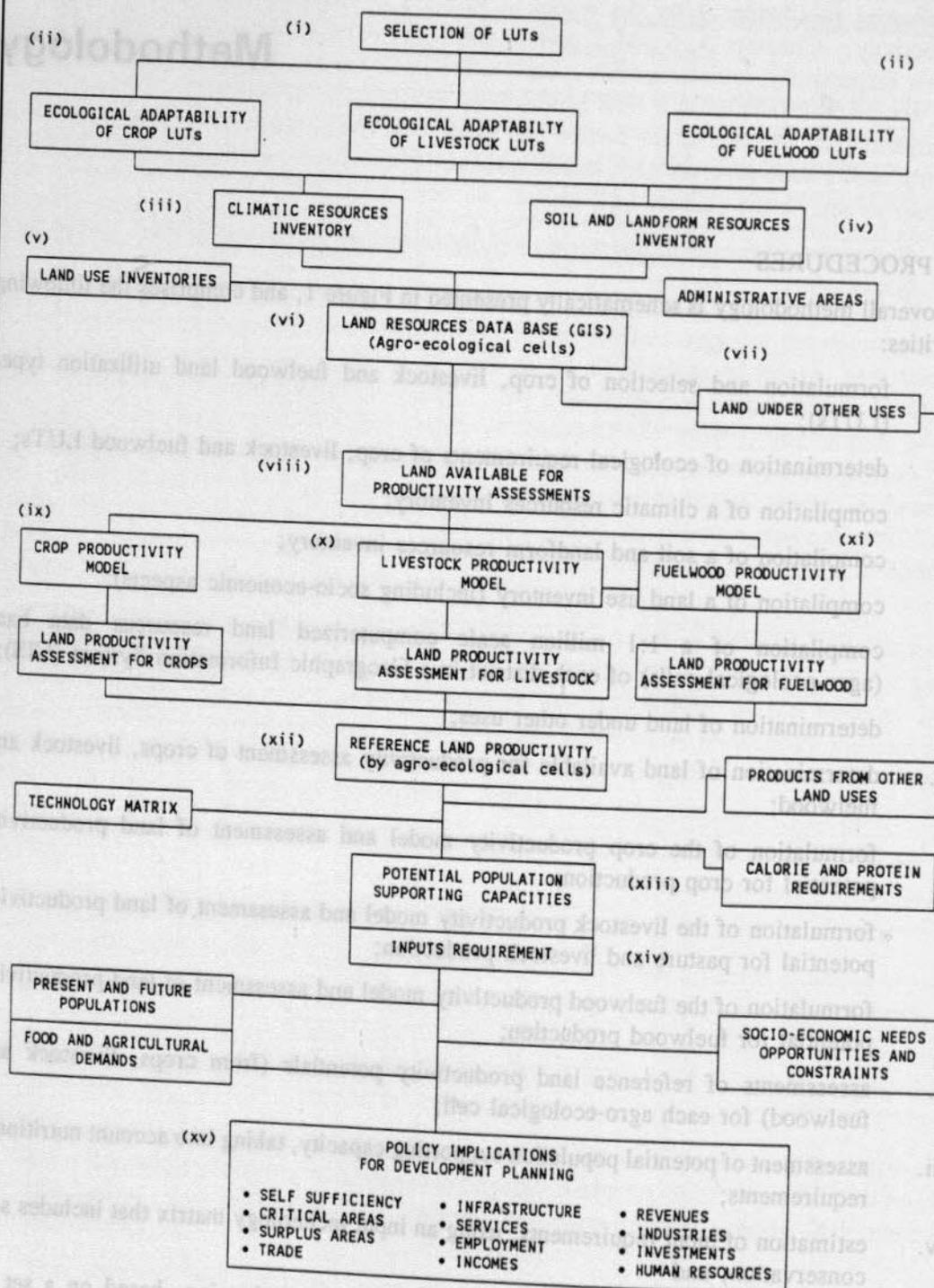
# Methodology

### 2.1 PROCEDURES

The overall methodology is schematically presented in Figure 1, and comprises the following activities:

- i. formulation and selection of crop, livestock and fuelwood land utilization types (LUTs);
- ii. determination of ecological requirements of crop, livestock and fuelwood LUTs;
- iii. compilation of a climatic resources inventory;
- iv. compilation of a soil and landform resources inventory;
- v. compilation of a land use inventory (including socio-economic aspects);
- vi. compilation of a 1:1 million scale computerized land resources data base (agro-ecological cells) of each district in a Geographic Information System (GIS);
- vii. determination of land under other uses;
- viii. determination of land available for productivity assessment of crops, livestock and fuelwood;
- ix. formulation of the crop productivity model and assessment of land productivity potential for crop production;
- x. formulation of the livestock productivity model and assessment of land productivity potential for pasture and livestock production;
- xi. formulation of the fuelwood productivity model and assessment of land productivity potential for fuelwood production;
- xii. assessments of reference land productivity potentials (from crops, livestock and fuelwood) for each agro-ecological cell;
- xiii. assessment of potential population supporting capacity, taking into account nutritional requirements;
- xiv. estimation of input requirements, using an input technology matrix that includes soil conservation; and
- xv. addressing a range of policy issues for development planning, based on a set of scenarios embodying present and future populations, food and agricultural demands, and socio-economic development needs, opportunities and constraints.

**FIGURE 1**  
Schematic presentation of methodology



The above 15 activities represent four groups of compound activities, namely:

- formulation of LUTs and their ecological requirements;
- compilation of a national land resources and land use data base;
- assessments of land productivity potentials; and
- development planning, involving assessments of potential population supporting capacities and input requirements to address policy issues.

Activities related to the formulation of LUTs and their ecological requirements overlap with those activities concerned with the compilation of the land resources data base. This is necessary to ensure that those land qualities that determine productivity are characterized in the land inventory and that land use requirements can be formulated in terms of such land qualities.

Subsequently, the productivity models of crops, livestock and fuelwood are applied to the land resources data base to estimate land productivity potentials of alternative LUTs. These land productivity potentials, in turn, form a basis for quantifying potential population supporting capacities and input requirements at several levels of geographical and administrative aggregation (e.g., sub-district, district, province, nation). When set against present and projected population distribution, food and agricultural demands, socio-economic development needs, opportunities and constraints, such assessments of land and population potentials provide a sound and coherent basis for national development planning.

This *Soils Bulletin* presents the first three groups of compound activities. The optimization of production to meet policy defined requirement scenarios or the investigation of alternative putative uses of the land for planners looking at 'What if...?' possibilities are not discussed here, nor are the estimation of potential population supporting capacities and related development issues.

## 2.2 LUTs AND ECOLOGICAL REQUIREMENTS

For the crop productivity model, as elaborated in Chapter 5, a large number of possible crops — and alternative uses of the same crops — have to be considered, and combined with several levels of management and inputs. The present computer program allows for a large number of crop LUTs to be considered, but for the Kenya study only 25 crop species needed to be considered, differentiated into 64 crop types to account for differences within each species in ecotypic adaptation, crop phenology and growth cycles. The crops were seven cereals (wheat, barley, oats, rice, maize, pearl millet and sorghum); six grain legumes (cowpea, green gram, groundnut, *Phaseolus* bean, pigeon pea and soybean); three root and tuber crops (white potato, sweet potato and cassava); and nine 'cash' crops (banana, oil palm, sugarcane, coffee, cotton, pineapple, pyrethrum, sisal and tea).

Coffee, cotton, pineapple, pyrethrum, sisal and tea were considered in the model for Kenya to take account of the reported land area occupied by these crops as inventoried in the land use data base. The other 19 crops were differentiated into 58 crop types and each considered at three levels of input. In all, the crop productivity model considered 174 crop LUTs.

For the livestock productivity model outlined in Chapter 6, a large number of pasture and fodder species can be included and combined with a range of alternative livestock production regimes, but for Kenya it was sufficient to provide for 32 pasture and fodder species of both

grasses (20 pasture and 4 fodder types) and legumes (8 pasture and fodder types), and combine them with 6 livestock husbandry types.

The grass and legume species can be considered at various levels of input, and three levels of input were considered in Kenya. However, at this stage of model development and application, the full 96 combinations were not used, but rather productivity assessments were made for groups of pasture and fodder grasses and legumes at three levels of inputs.

The livestock productivity model allows for various livestock production systems to be considered with alternative husbandry regimes and levels of input. For the Kenya study the livestock groups were cattle, goats and sheep under both pastoral and non-pastoral regimes, camels under a pastoral regime only, and poultry and pigs, which were considered under intensive systems only. The non-pastoral systems comprised dairy and meat cattle, dairy and meat goats, and meat and wool sheep systems, each at three levels of inputs. Pastoral systems considered were cattle herds (nomadic distant, nomadic with market access, and semi-nomadic); goat herds (nomadic distant, and semi-nomadic); sheep herds (nomadic distant, and semi-nomadic); and camel herds (nomadic only). As the livestock model makes provision for a variable number of livestock LUTs, the 19 LUTs needed for Kenya could be easily accommodated.

In the fuelwood productivity model of Chapter 7, it was found sufficient for the Kenya study to consider some 31 fuelwood species, of which 15 had nitrogen fixing ability. The model considered the 31 species at three levels of inputs, so that the fuelwood model provided for 93 fuelwood LUTs.

The three levels of inputs used in the models are low, intermediate and high, and are detailed in Chapters 5, 6 and 7. The low-level conditions assume subsistence agriculture, with low capital input, the use of traditional cultivars of crops and local breeds of animals, hand labour only, no use of fertilizer or other agrochemicals, no large-scale conservation measures, and cultivation in rotation with bush fallow to maintain soil fertility. It can be compared to traditional systems of bush fallow rotations. The intermediate level assumes medium capital input, partly subsistence and partly commercial management practices, the use of improved cultivars and breeds of crops and animals (including crossbred animals), the use of improved hand tools and draught implements, some mechanization, some use of fertilizer and other agrochemicals, some soil conservation measures, and cultivation in rotation with sown grass fallow. The high level of input assumes capital-intensive management practices, full use of the most productive adapted cultivars of crops and breeds of animals (including exotic breeds), complete mechanization, optimum use of farm chemicals, and full soil conservation measures.

Determination of the climatic and edaphic (soil) requirements of crop, livestock and fuelwood LUTs used in the assessment was a major activity within the Kenya study. Previous attempts to quantify climatic requirements of crops, in the broadest sense and including pasture and fuelwood species, had not adequately recognized the importance of the time courses of temperature and soil moisture balances, including seasonal and between-year variations, in relation to crop growth (photosynthesis), development (phenology) and production (yield). It is considered that adequate emphasis has now been placed on these sets of parameters (temperature and soil moisture regimes) in the assessment model.

Of similar significance is the nature of the photosynthetic response to temperature and radiation, which determines crop yield and land productivity when the phenological requirements are met during the period when soil moisture is available for growth. Accordingly, for the Kenya study, an inventory of crop, pasture and fuelwood species was prepared, based on their climatic requirements, both photosynthetic and phenological. Four main climatic

adaptability groups of crops, pasture grasses and legumes, and fuelwood species could be recognized in the Kenya assessment, as detailed in Chapters 5, 6 and 7. Such an inventory gives, *inter alia*, ranges of temperature requirements for different aspects of growth and development. These are subsequently matched to existing thermal climatic conditions.

Once the photosynthetic and phenological thermal requirements are met, the agronomic (or silvicultural) yield potential of a crop, under constraint-free conditions, is governed by the number of days (or years) to maturity. This, in turn, is determined by the length and quality of growing period (including its year-to-year variation). Constraint-free yields are calculated for all crop, livestock and fuelwood LUTs for each length of growing period (LGP). The results provide the basis for the climatic suitability assessment, as described in Chapters 5, 6 and 7.

The edaphic requirements of LUTs are then assessed, and for each crop, pasture and fuelwood species, available data on soil characteristics considered meaningful for production are listed — soil depth, texture, salinity, stoniness, etc. For each LUT, each characteristic is then quantitatively subdivided into an optimum range and a (wider) acceptable range of values. When a value falls outside the acceptable range, the soil has to be considered as currently not suitable.

The information on optimal range and minimum or maximum values of soil properties for each LUT forms the basis for subsequent suitability rating of the soil units for production of crops, pasture and fuelwood, as discussed more fully in Chapters 5, 6 and 7.

### 2.3 COMPILATION OF THE NATIONAL LAND RESOURCES AND LAND USE DATABASES

The information on climatic and soil requirements of crop, pasture and fuelwood LUTs is used as a guide in the compilation of the land resources inventory, as detailed in Chapter 3.

Temperature and soil moisture availability are key factors in determining the distribution of rainfed crops in both space and time. In combination with solar radiation pattern (day length), which is latitude related and so with little variation in Kenya as it straddles the equator, these climatic factors condition photosynthesis and hence both accumulation of biomass and development, according to the species-specific ecophysiological rates and patterns. The temperature attributes are quantified by defining thermal zones. To cater for the range of temperature requirements of the various crops, pasture and fuelwood species, nine reference thermal zones were identified for Kenya, based on 2.5°C intervals in daily mean temperature.

Moisture attributes are quantified using the concept of a reference LGP, defined as the duration, in days, of the period during which the supply of available soil moisture from precipitation, and from storage in the soil profile (set at a reference 100 mm), is greater than half the potential evapotranspiration.

For the Kenya study, LGPs were computed from historical data sets of some 435 stations, and derived from average data sets of some 1500 stations. With the historical data set, LGPs were computed for individual years, and frequency distributions for each mean length were computed for the historical series. Where there was more than one LGP per year, the total mean length as well as the individual mean lengths (e.g., two, three) and their frequency distributions were calculated. These computations represented the information on the LGP. Fifteen mean LGP zones (0, 30, .... 330 at intervals of 30 days, 365<sup>-</sup> & 365<sup>+</sup>) were delineated in the climatic inventory of Kenya, as explained in Chapter 3.

To inventory the year-to-year variation in the number of LGPs per year, a historical profile is compiled showing groups of years each with a different number of growing periods per year.

The proportional representation of each group in the total historical series is then computed, giving the pattern of length of growing period (LGP-pattern). Twenty-two such LGP-pattern zones were recognized in the climatic inventory of Kenya.

For each LGP zone delineated, average values of major climatic elements (radiation, day and night temperature, humidity, etc.) are inventoried to characterize the climate during the growing period. These together, with the information on the year-to-year variation in the number of LGPs per year and in each component LGP, form the basis for subsequent matching and productivity estimation. Details of climatic resources inventory are given in Chapter 3.

A soil inventory is compiled which maps the different soil units to be found within the area under consideration. For Kenya, information came primarily from the 1:1 million scale Exploratory Soil Map of Kenya (KSS 1982a), which has 390 different soil map units. For each map unit, information on landform, geology/parent material, soil unit (with implied characteristics), slope-gradient, soil texture and soil phases, in terms of description, classes and extents, is transferred to form the soil resources inventory for the assessment.

On completion of the climatic inventory, the three layers (thermal zone, LGP zone and LGP-pattern zone) are superimposed on the soil map. For Kenya, the different layers of climate and soil information were digitized and the information was converted to a data base of about 575 000 grid cells on the map, each of 1 mm square and corresponding to 1 km<sup>2</sup> (100 ha) on the ground. The resultant map output created an inventory of about 91 000 unique agro-ecological cells, whose land attributes, defined by climate, soil and landform, were known and quantified. This information, compiled at the national level by province and district, constitutes the physical land resources data base of the country.

Additional layers of information can also be digitized and overlaid on the land resources inventory. For Kenya there are six such additional layers, containing information on cash crop zones, forest zones, parkland areas, irrigation schemes, tse-tse infestation areas and administrative boundaries (provinces and districts).

The climate, soil and land-use inventories make up the computerized data base for the assessment, and allow any desired geographical and administrative aggregation to be made of inventoried parameters and results.

#### 2.4 ASSESSMENT OF POTENTIAL LAND PRODUCTIVITY

The assessment of land productivity starts by the identification of crop, livestock and fuelwood LUTs (shown at the head of the flow chart in Figure 1), and their ecological (climatic, edaphic and landform) requirements (ii).

Then, from the agro-ecological cells in the land resources inventory (iii, iv, v, vi), district by district, land used or required for irrigation, cash crops and for non-agricultural purposes (vii) is deducted. The remainder is an inventory of land potentially available for rainfed cultivation, and for productivity assessments (viii).

For each of the agro-ecological cells in this inventory, the next stage is to determine the potential rainfed yield or output of crops, livestock and fuelwood at one or more levels of inputs (ix, x, xi) in order to find out which LUTs (cropping patterns and rotations, livestock systems or fuelwood land uses) are most productive, stable and sustainable in the unique conditions of the cell. The land productivity potentials can then be calculated (xii), either in a reference manner or within the context of a set of planning scenarios.

The crop, livestock and fuelwood models (Chapters 5, 6 and 7) are all designed to operate with the computerized land resources data base. The models permit quantitative land suitability assessments to be made based on growth and yield predictions for each LUT or combinations of LUTs in each agro-ecological cell. All three productivity models include a provision for quantifying the soil erosion hazard inherent in each LUT in terms of productivity loss. This is achieved through the soil erosion and productivity model described in Chapter 4. The model also estimates 'tolerable' soil loss, and costs of alternative conservation measures.

The crop productivity model (Chapter 5) explicitly formulates options in respect of individual crops, annual cropping patterns and crop rotations, and quantifies their production potentials. The model formulates optimum cropping patterns and output therefrom to meet a reference or given food demand, taking into account the desired level of production stability.

The livestock productivity model (Chapter 6) quantifies primary productivity potential, which is then converted into secondary production (milk, meat, wool, draught power) for pastoral and non-pastoral herds.

The fuelwood model (Chapter 7) quantifies wood biomass productivity potential in terms of mean annual increments over the rotation age of each fuelwood LUT.

The crop, livestock and fuelwood productivity models are interlinked with each other, thus allowing land productivity to be optimized for a given set of development constraints and demands.

## 2.5 DEVELOPMENT PLANNING

The next stage in the assessment process allows for development planning applications, which involves the calculation of the quantities of edible calories and protein that could be produced by the different crops, livestock, and products from other land uses, using information on the nutritional composition of the products. The crops or crop mixes, including grassland, that can produce the largest or desired quantity and quality of calories and protein in each agro-ecological cell are then selected, and the results from each cell in each climatic zone in each district are added to determine the optimal maximum potential production of calories and protein from each climatic zone in each district, from whole districts and groups of districts, and from whole provinces and the country.

Dietary and other constraints, such as minimum protein requirements, are applied to estimate potential population supporting capacity (xiii) at various desired levels of geographical and administrative aggregation. Similarly, by applying an extended technology matrix, analogous to that prepared in the FAO work for Kenya, and that includes conservation inputs, the associated input requirements (xiv) can be quantified (Bruinsma *et al.* 1983).

The potential population supporting capacity (xiii) is computed as potential population density in persons per hectare, which is then compared with the present and projected population densities, and examined against food and agriculture demands, and socio-economic needs, opportunities and constraints, to address a range of policy issues for development planning. These relate, for example, to food and economic self-sufficiency, areas with surplus potential and areas that are critical, domestic and export trade possibilities, infrastructure needs, services, employment, incomes, revenues, industries, investments, and human resources development (xv).

These considerations are briefly addressed in Chapter 8.

## Chapter 3

# Land resources

The land resources inventory brings together two layers of information on physical environmental resources (climate and soil) and allows the creation of unique ecological land units (agro-ecological cells) within which soil, landform and climatic conditions are quantified. This information, compiled at the national level by province and district, constitutes the inventory of the physical land resources.

To create a computerized inventory of land resources, the individual climate and soil inventories are compiled in map form, which for Kenya was at 1:1 million scale, and digitized.

The climatic resources inventory consist of three separate thematic layers: thermal zones, LGP zones, and LGP-pattern zones. The Exploratory Soil Map of Kenya (KSS 1982a), provided the soil base, giving information on soils, landform and geology/parent material, with additional layers of information at the same scale also digitized and overlaid on the land resources inventory.

The individual map layers were digitized using the Comprehensive Resource Inventory and Evaluation System (CRIES 1983), a geographical information system (GIS) developed at Michigan State University. The digitized information derived from the individual map layers was converted to a data base of 576 072 grid cells. Each cell is 1 mm square on the original map and corresponds to 1 km<sup>2</sup> (100 ha) on the ground.

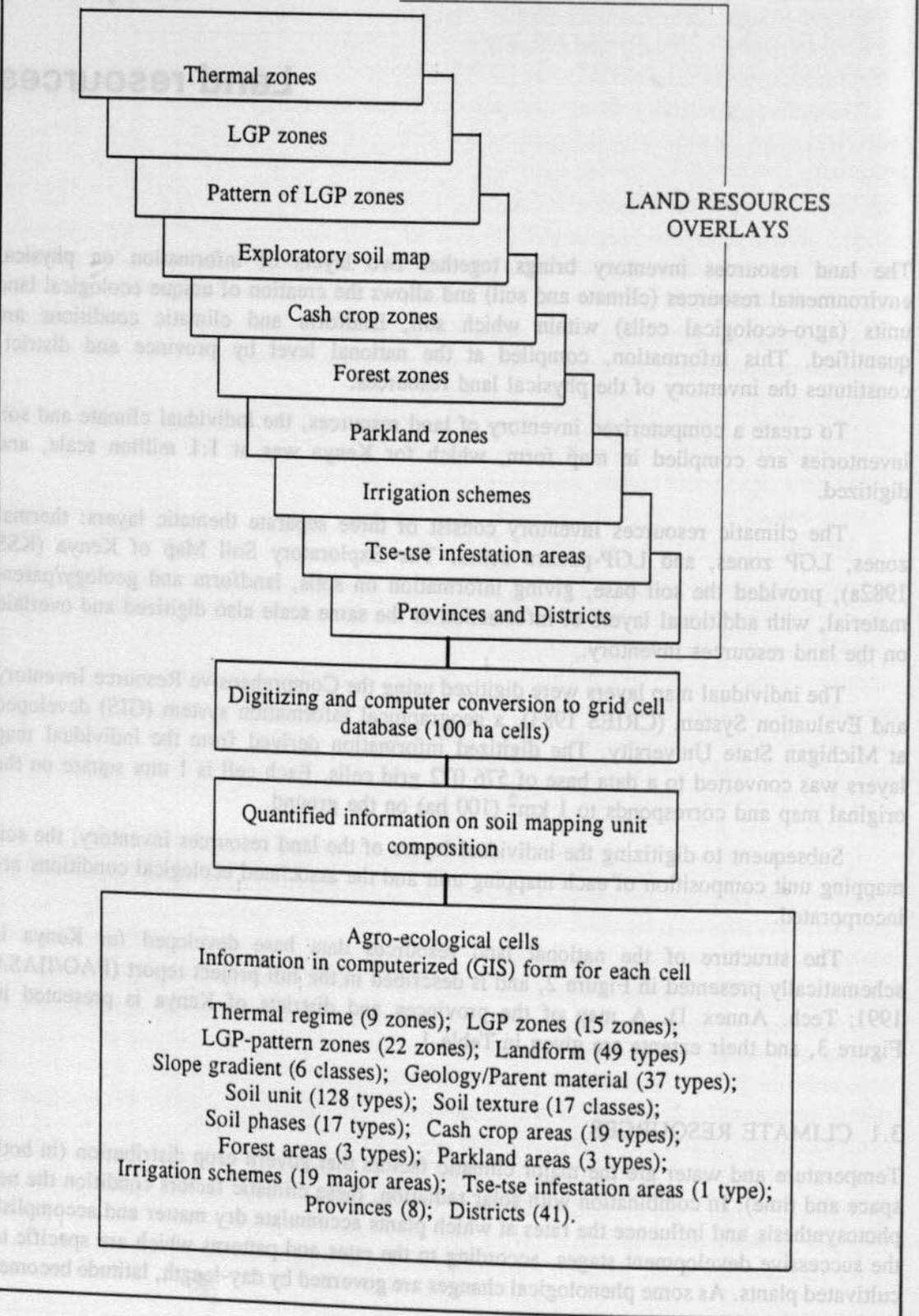
Subsequent to digitizing the individual layers of the land resources inventory, the soil mapping unit composition of each mapping unit and the associated ecological conditions are incorporated.

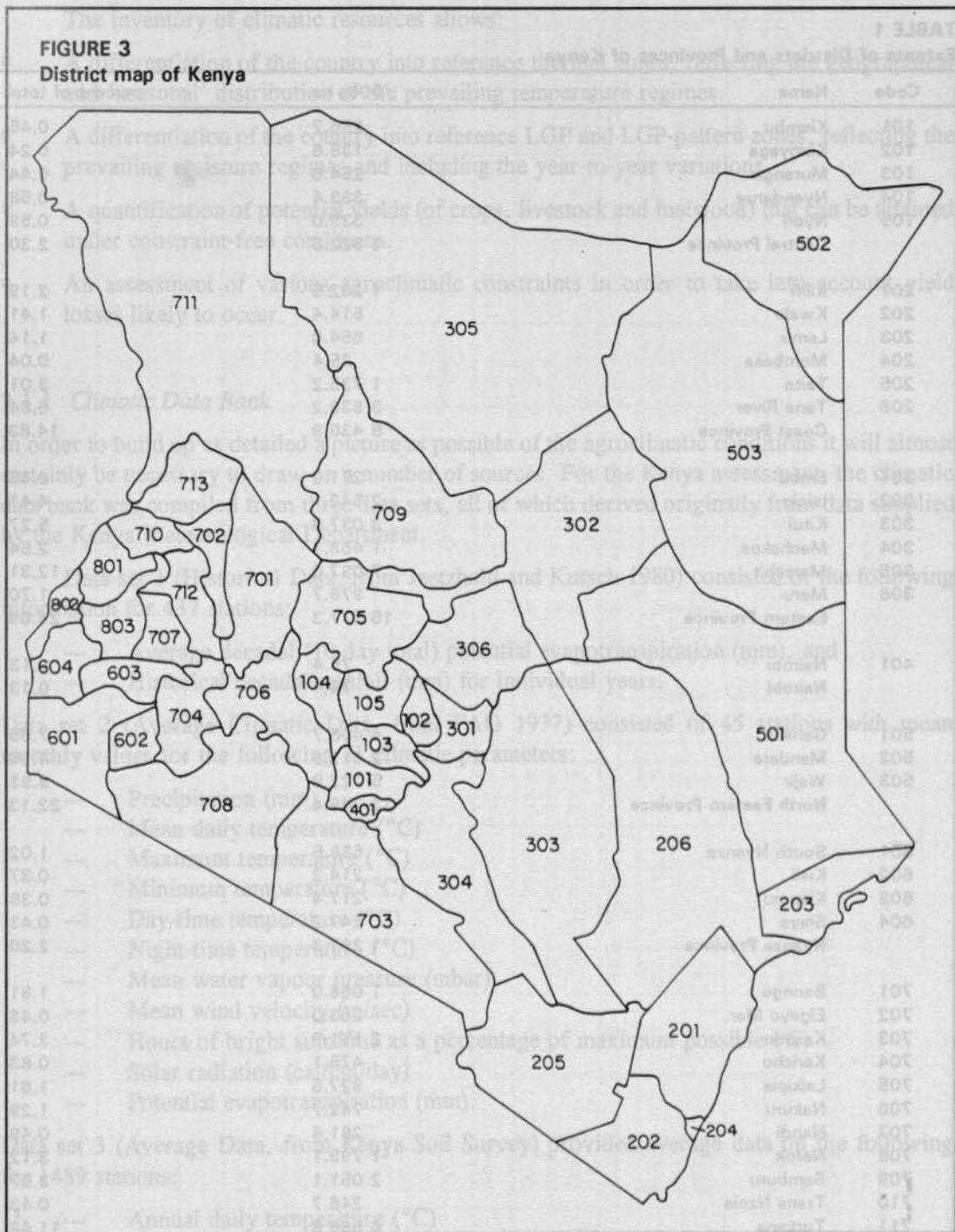
The structure of the national land resources data base developed for Kenya is schematically presented in Figure 2, and is described in the full project report (FAO/IIASA 1991: Tech. Annex 1). A map of the provinces and districts of Kenya is presented in Figure 3, and their extents are given in Table 1.

### 3.1 CLIMATE RESOURCES

Temperature and water are the major climatic factors that govern crop distribution (in both space and time). In combination with solar radiation, these climatic factors condition the net photosynthesis and influence the rates at which plants accumulate dry matter and accomplish the successive development stages, according to the rates and patterns which are specific to cultivated plants. As some phenological changes are governed by day-length, latitude becomes

**FIGURE 2**  
Schematic structure of the land resources database for Kenya





more and more important the further one goes from the equator, but that was not a significant factor in the Kenya study as Kenya straddles the equator.

The growing period has been used as a framework for the assessment of climatic resources (FAO 1978-81). It is defined as the period in which temperature and moisture permit crop growth. Prevailing temperature regimes have been inventoried by identification of thermal zones in order to take into account the varied temperature requirements of different crops (including pasture and fuelwood species).

**TABLE 1**  
Extents of Districts and Provinces of Kenya

Code	Name	'000s ha	percent of total
101	Kiambu	256.7	0.45
102	Kirinyaga	138.6	0.24
103	Muranga	254.6	0.44
104	Nyandarua	333.4	0.58
105	Nyeri	339.0	0.59
	<b>Central Province</b>	<b>1 322.3</b>	<b>2.30</b>
201	Kilifi	1 262.5	2.19
202	Kwale	814.4	1.41
203	Lamu	654.0	1.14
204	Mombasa	25.4	0.04
205	Taita	1 735.2	3.01
206	Tana River	3 939.2	6.84
	<b>Coast Province</b>	<b>8 430.9</b>	<b>14.63</b>
301	Embu	271.2	0.45
302	Isiolo	2 542.1	4.41
303	Kitui	3 037.2	5.27
304	Machakos	1 463.1	2.54
305	Marsabit	7 087.0	12.31
306	Meru	976.7	1.70
	<b>Eastern Province</b>	<b>15 377.3</b>	<b>26.69</b>
401	Nairobi	75.4	0.13
	<b>Nairobi</b>	<b>75.4</b>	<b>0.13</b>
501	Garissa	4 408.7	7.65
502	Mandera	2 617.8	4.55
503	Wajir	5 722.9	9.93
	<b>North Eastern Province</b>	<b>12 749.4</b>	<b>22.13</b>
601	South Nyanza	588.5	1.02
602	Kisii	214.2	0.37
603	Kisumu	217.4	0.38
604	Siaya	247.2	0.43
	<b>Nyanza Province</b>	<b>1 267.3</b>	<b>2.20</b>
701	Baringo	1 066.0	1.81
702	Elgeyo Mar.	263.0	0.46
703	Kajiado	2 151.9	3.74
704	Kericho	478.1	0.83
705	Laikipia	927.5	1.61
706	Nakuru	742.7	1.29
707	Nandi	281.4	0.49
708	Narok	1 799.1	3.12
709	Samburu	2 051.1	3.57
710	Trans Nzoia	246.7	0.43
711	Turkana	6 586.8	11.43
712	Uasin Gishu	382.6	0.66
713	West Pokot	535.7	0.93
	<b>Rift Valley Province</b>	<b>17 512.6</b>	<b>30.40</b>
801	Bungoma	319.3	0.56
802	Busia	191.4	0.33
803	Kakamega	361.5	0.63
	<b>Western Province</b>	<b>872.2</b>	<b>1.52</b>
	<b>KENYA</b>	<b>57 607.2</b>	<b>100.00</b>

The inventory of climatic resources allows:

- A differentiation of the country into reference thermal zones, reflecting the geographical and 'seasonal' distribution of the prevailing temperature regimes.
- A differentiation of the country into reference LGP and LGP-pattern zones, reflecting the prevailing moisture regimes and including the year-to-year variations.
- A quantification of potential yields (of crops, livestock and fuelwood) that can be attained under constraint-free conditions.
- An assessment of various agroclimatic constraints in order to take into account yield losses likely to occur.

### 3.1.1 Climatic Data Bank

In order to build up as detailed a picture as possible of the agroclimatic conditions it will almost certainly be necessary to draw on a number of sources. For the Kenya assessment, the climatic data bank was compiled from three data sets, all of which derived originally from data supplied by the Kenya Meteorological Department.

Data set 1 (Historical Data, from Jaetzhold and Kutsch 1980) consisted of the following information for 437 stations:

- Average decadal (10-day total) potential evapotranspiration (mm), and
- Historical decadal rainfall (mm) for individual years.

Data set 2 (Average Climatic Data, from FAO 1977) consisted of 45 stations with mean monthly values for the following 11 climatic parameters:

- Precipitation (mm)
- Mean daily temperature (°C)
- Maximum temperature (°C)
- Minimum temperature (°C)
- Day-time temperature (°C)
- Night-time temperature (°C)
- Mean water vapour pressure (mbar)
- Mean wind velocity (m/sec)
- Hours of bright sunshine as a percentage of maximum possible (%)
- Solar radiation (cal/cm/day)
- Potential evapotranspiration (mm).

Data set 3 (Average Data, from Kenya Soil Survey) provided average data on the following for 1489 stations:

- Annual daily temperature (°C)
- Annual potential evaporation (mm)
- Annual potential evapotranspiration (mm)
- Annual Rainfall (mm)
- Monthly rainfall (mm)
- Type of rainfall pattern — monomodal (M), bimodal (B) or trimodal (T).

Extracts of the three data sets are presented in Tables 2, 3 and 4 respectively.

TABLE 2  
Agroclimatic data bank - Extract data set 1 - Historical data

STATION: EMBU		NUMBER: 9037008	LAT: 0.32° S			LONG: 32.27° E			ALT: 1410 FT				40 YEARS' RECORDS			
			Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year	
AVERAGE PET	DECAD 1		40.8	43.2	44.8	40.0	37.6	34.4	32.8	32.8	37.6	40.8	36.8	36.8		
	DECAD 2		42.4	43.2	45.6	37.6	37.6	33.6	32.0	32.8	39.2	41.6	35.2	36.8		
	DECAD 3		42.4	44.0	44.0	37.6	36.8	33.6	32.0	34.4	40.0	40.0	36.0	38.4		
	MONTH		125.4	130.4	134.4	115.2	112.0	101.6	96.8	100.0	116.8	122.4	108.0	112.0	1375.0	
RAINFALL (1927)	DECAD 1		1.8	0.0	29.0	20.0	47.3	0.3	8.1	2.9	6.6	0.0	19.3	14.5		
	DECAD 2		0.0	2.0	167.8	64.5	19.1	52.2	2.1	7.0	0.0	58.3	68.1	16.8		
	DECAD 3		0.0	1.5	52.3	75.3	3.1	0.3	0.8	2.8	4.1	82.8	8.9	0.0		
	MONTH		1.8	3.5	249.1	159.8	69.5	52.8	11.0	12.7	10.7	141.1	96.3	31.3	839.6	
RAINFALL (1928)	DECAD 1		15.6	0.0	40.9	10.2	101.1	16.2	0.0	2.6	0.0	6.4	40.7	21.9		
	DECAD 2		39.1	0.0	0.0	140.2	103.0	1.1	6.7	0.0	0.0	0.0	108.2	0.0		
	DECAD 3		0.0	0.0	7.1	80.4	62.1	3.8	0.0	5.6	5.1	17.3	49.2	0.0		
	MONTH		54.7	0.0	48.0	230.8	266.2	21.1	6.7	8.2	5.1	23.7	198.1	21.9	884.5	
RAINFALL (1929)	DECAD 1		51.6	0.0	0.0	12.4	66.7	0.8	10.9	0.0	32.8	1.0	108.7	102.9		
	DECAD 2		6.6	0.0	66.5	12.4	7.9	7.9	14.3	0.0	27.2	34.0	104.5	38.0		
	DECAD 3		6.4	0.0	5.1	153.5	14.3	2.0	12.5	5.8	0.0	80.8	4.6	12.3		
	MONTH		64.6	0.0	71.6	178.3	88.9	10.7	37.7	5.8	60.0	115.8	217.8	153.2	1004.4	
RAINFALL (1930)	DECAD 1		0.0	28.7	76.5	57.8	66.9	12.5	0.0	10.7	2.6	26.7	122.8	42.9		
	DECAD 2		0.0	0.0	20.6	109.7	28.3	0.0	7.6	6.1	5.6	28.4	94.7	28.0		
	DECAD 3		43.0	0.0	80.7	107.3	5.4	6.6	0.8	33.0	2.5	66.1	53.9	1.0		
	MONTH		43.0	28.7	177.8	274.8	100.6	19.1	8.4	49.8	10.7	121.2	271.4	71.9	1177.4	

**TABLE 3**  
Agroclimatic data bank - Extract data set 2 - Average climatic data

COUNTRY: KENYA STATION: LOKITAUNG NUMBER: 63610 LAT: 4.15° LONG: 35.45°E ELEVATION: 730 m.a.s.

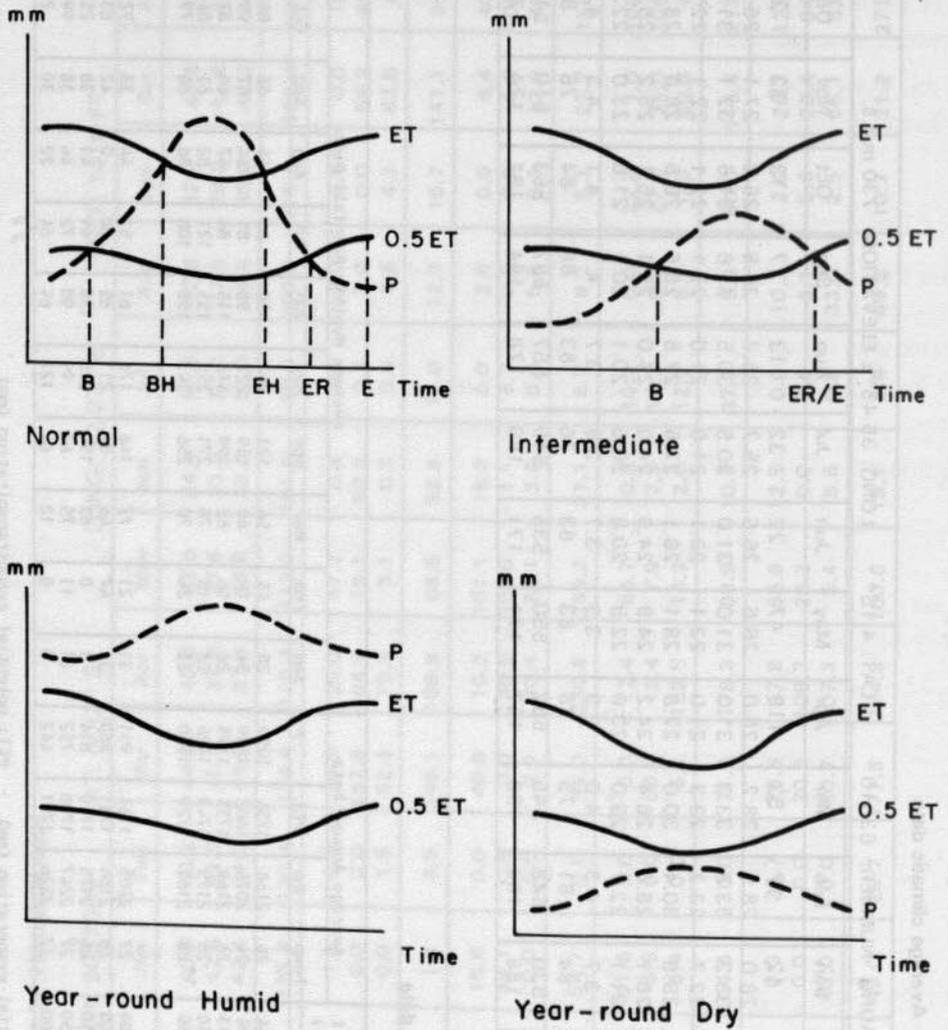
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
PRECIPITATION (mm)	12	17	53	119	47	22	32	13	7	13	32	28	395
TEMPERATURE (°C; AVERAGE)	28.0	28.5	28.2	26.0	26.6	26.6	25.7	25.7	26.8	26.8	27.1	26.8	26.9
TEMPERATURE (°C; MEAN MAX.)	33.2	33.8	33.2	31.0	31.0	31.0	30.5	30.5	31.6	31.6	32.1	31.6	31.8
TEMPERATURE (°C; MEAN MIN.)	22.7	23.2	23.3	21.0	22.1	22.1	21.0	21.0	22.1	22.1	22.1	22.1	22.1
TEMPERATURE (°C; MEAN DAY)	29.8	30.4	30.0	27.8	28.1	28.1	27.5	27.5	28.5	28.5	28.9	28.5	28.6
TEMPERATURE (°C; MEAN NIGHT)	26.1	26.6	26.4	24.2	24.9	24.9	24.0	24.0	25.1	25.1	25.2	25.1	25.1
VAPOUR PRESSURE	21.1	22.7	23.0	23.0	22.5	20.8	20.5	20.1	20.1	21.6	23.0	22.0	21.7
WIND SPEED (AT 2m ELEV.)	3.7	4.3	4.0	2.9	3.3	3.7	3.8	3.7	4.1	4.1	4.3	4.0	3.8
SUNSHINE (%)	84	81	75	78	83	83	76	83	88	84	76	81	81
TOTAL RADIATION	530	548	545	552	550	535	515	557	587	563	510	510	541
EVAPOTRANSPIRATION	188	184	198	157	171	171	169	178	194	191	174	173	2148

**TABLE 4**  
Agroclimatic data bank - Extract data set 3 - Average data

Station code	Station name	°Lat (N/S)	°Long (E)	Alt (ft)	Average Annual Data				Average Monthly Rainfall Data												Yrs	RP type		
					Temp	Eo	PET	P	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec				
94.39000	Kilindini	4.03	39.39	64	26	2168	1734	1059	28	13	56	171	262	106	68	64	66	88	83	54	50	B		
94.39001	Kwale Agr. Dept.	4.11	39.28	1294	24	2075	1662	1089	34	19	60	159	227	98	81	64	67	99	102	79	60	60	B	
94.39002	Nombasa Old.	4.04	39.41	53	26	2169	1735	1193	26	16	62	199	313	113	86	67	68	87	99	57	81	81	B	
94.39003	Ramisi Ass. Sug.	4.31	39.25	50	26	2175	1740	1426	23	18	78	271	359	155	121	82	61	84	103	71	39	39	B	
94.39004	Gazi Kenya Sug.	4.25	39.30	150	26	2161	1729	1350	23	24	70	256	347	150	100	86	68	79	89	58	50	50	B	
...																								
94.39046	Vangalunga	4.33	39.07	200	27	2205	1764	911	31	21	77	146	176	61	51	44	38	72	123	71	20	20	B	
94.39050	Changame	4.01	39.37	100	26	2164	1731	860	31	47	46	87	211	65	80	0	42	83	109	59	2	2	B	
94.39051	Tinwani	4.07	39.40	50	26	2175	1740	814	1	0	63	154	228	130	69	41	38	25	24	41	2	2	B	
94.39054	Mwena School	4.29	39.08	250	27	2247	1798	752	21	11	75	62	99	90	72	44	38	99	83	58	3	3	B	
94.39057	Puna Camp	4.06	39.14	600	27	2226	1781	442	0	0	12	64	127	64	64	22	30	2	2	55	2	2	B	

Temp: Mean daily temperature (celcius) - Eo: Potential evaporation (mm) - PET: potential evapotranspiration (mm)  
 P: Rainfall (mm) - RP type: Rainfall pattern type - M = Monomodal, B = Bimodal, T = Trimodal

**FIGURE 4**  
Schematic presentation of types of growing periods



- B - Beginning of growing period  
 BH - Beginning of humid period  
 EH - End of humid period  
 ER - End of rainy season  
 E - End of growing period  
 P - Precipitation  
 ET - Potential evapotranspiration

### 3.1.2 Growing Period Model

The definitions and model used to quantify the reference LGP are described more fully elsewhere (FAO/IIASA 1991: Tech. Annex 1), but, in essence, the LGP is that period when moisture supply exceeds half potential evapotranspiration; it includes the time required to evapotranspire up to 100 mm of stored soil moisture, with the model able to handle a storage value in the range 0-250 mm. The calculation of the reference growing period is based on a water balance model, comparing rainfall with potential evapotranspiration. The LGP (and the number of growing periods and dry periods per year) from a climatic viewpoint alone, and independent of crop, soil and landform, is therefore quantified in a reference manner (Kowal and Kassam 1978; Doorenbos and Kassam 1979; Kassam *et al.* 1982; Brammer *et al.* 1988).

Two types of growing periods are schematically shown in Figure 4. The distinction between 'normal' and 'intermediate' is useful because in the latter it is unlikely that full water requirements can be met during the growing season without moisture conservation or a supply from groundwater or irrigation.

In addition, two more growing period types have been identified (Figure 4). These are all-year-round humid with rainfall exceeding full potential evapotranspiration throughout the year, and all-year-round dry with rainfall not exceeding half potential evapotranspiration throughout the year.

#### i. Length of growing period (LGP).

The mean LGP and frequency distribution for each individual group of years have to be computed. Where there is more than one LGP per year, the total mean length as well as the individual mean lengths (e.g., two, three) and their frequency distribution are calculated (Figure 5).

For a group of years with one LGP, the length is coded L1, and the dry period is coded D1 (Figure 5a). For a group of years with two LGPs per year, the lengths are coded L2<sub>1</sub> and L2<sub>2</sub>, and the first length (L2<sub>1</sub>) is followed by the first dry period (D2<sub>1</sub>) and the second length (L2<sub>2</sub>) by the second dry period (D2<sub>2</sub>) (Figure 5b). The sum of lengths L2<sub>1</sub> and L2<sub>2</sub> is coded L2. For a group of years with three LGPs per year, the lengths are coded L3<sub>1</sub>, L3<sub>2</sub> and L3<sub>3</sub>, and there are dry periods in between, namely D3<sub>1</sub>, D3<sub>2</sub> and D3<sub>3</sub> (Figure 5c). The sum of lengths L3<sub>1</sub>, L3<sub>2</sub> and L3<sub>3</sub> is coded L3.

#### ii. Pattern of length of growing period (LGP-Pattern).

To inventory the year-to-year variation in the number of LGPs per year, a historical profile is compiled showing groups of years, each with a different number of growing periods per year. The proportional representation of each group in the total historical series is computed. This information represents the pattern of growing periods. Twenty-two such LGP-patterns were recognized in the climatic resources inventory of Kenya. The patterns of number of LGPs and their composition are presented in Table 5.

The LGP-pattern code represents the number of growing periods per year in order of frequency of occurrence, thus for Kenya, in '2-1-3', the numeral 2 is the number of LGPs per year that occur in the majority of the years (55%) — the dominant length number; the numeral 1 is the number of LGPs per year that has the next most commonly occurring frequency (25%) — the first associated length number; and the numeral 3 is the number of LGPs per year that has the smallest occurrence (20%) — the second associated length number.

**FIGURE 5**  
**Number of growing periods and dry periods per year**

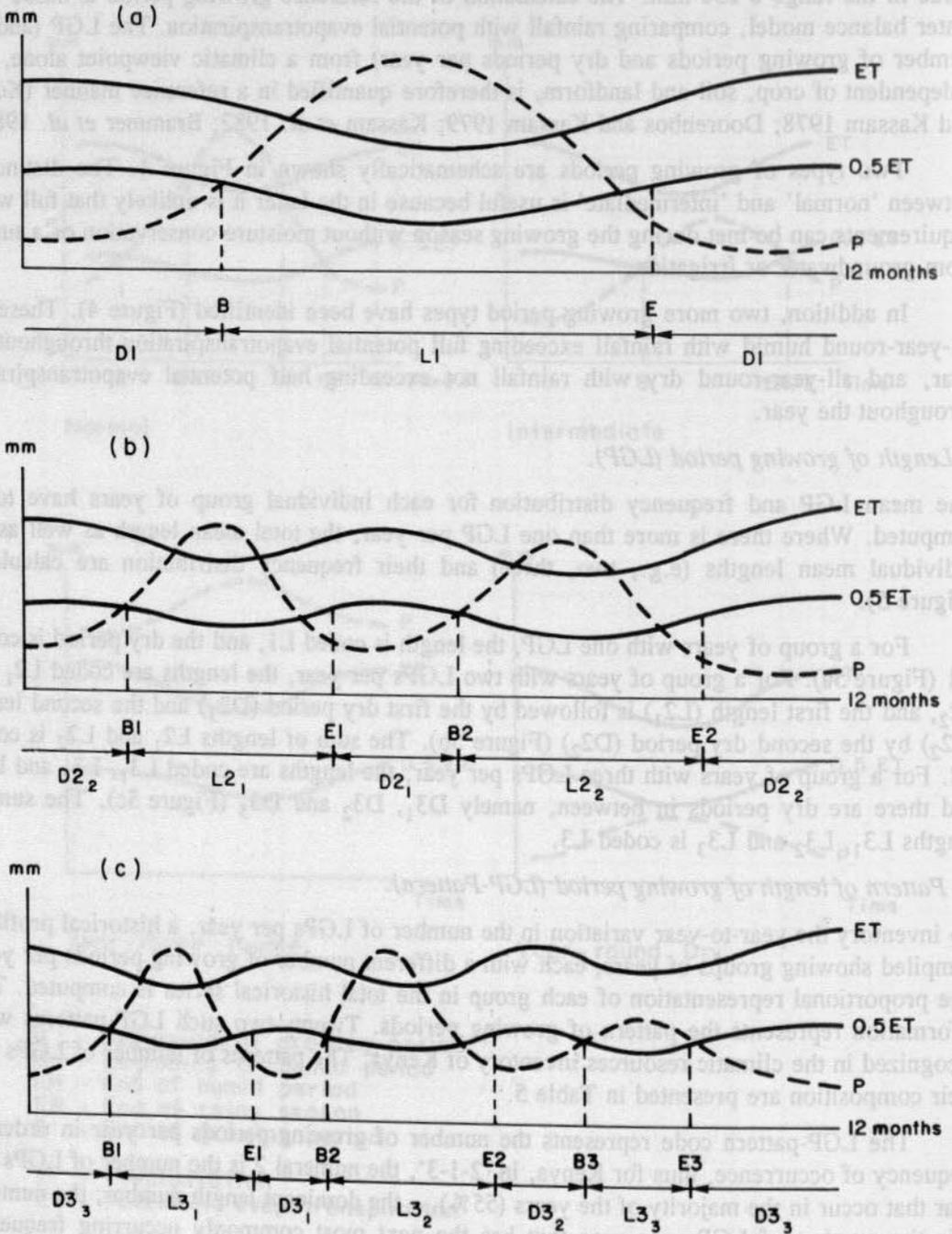


TABLE 5  
LGP-patterns in Kenya

Code	LGP-pattern	Proportion (%)
1	1	100
2	H - 1	60 : 40
3	1 - H	70 : 30
4	1 - H - 2	65 : 20 : 15
5	1 - 2 - H	65 : 20 : 15
6	1 - 2	65 : 35
7	1 - 2 - 3	50 : 35 : 15
8	1 - 3 - 2	40 : 35 : 20
9	1 - 2 - D	40 : 35 : 25
10	1 - D - 2	40 : 35 : 25
11	1 - D	60 : 40
12	2	100
13	2 - 1	70 : 30
14	2 - 1 - H	55 : 30 : 15
15	2 - 1 - 3	55 : 25 : 20
16	2 - 3	75 : 25
17	2 - 3 - 1	60 : 25 : 15
18	2 - 3 - 4	50 : 30 : 10
19	2 - 1 - D	70 : 15 : 15
20	3 - 2	60 : 40
21	3 - 2 - 1	50 : 35 : 15
22	D	100

TABLE 6  
Relationships between mean total dominant and mean total associated LGPs

LGP-Pattern	Relationship
1 - 2	$L2 = 80.40 + 0.75 L1$
1 - 2 - H	
1 - H - 2	
1 - 2 - 3	$L2 = 71.56 + 0.66 L1$
1 - 3 - 2	$L3 = 77.14 + 0.66 L1$
1 - 2 - D	
1 - 2 - D	
2 - 1	$L1 = -86.09 + 1.28 L2$
2 - 1 - H	$L3 = 25.29 + 0.82 L2$
2 - 1 - 3	
2 - 1 - D	
2 - 3	$L3 = 30.11 + 0.83 L2$
2 - 3 - 1	$L1 = -98.72 + 1.35 L2$
2 - 3 - 4	$L4 = 114.54 + 0.58 L2$
3 - 2	$L2 = 45.05 + 0.80 L3$
3 - 2 - 1	$L1 = -9.86 + 0.88 L3$

L1 = Total length of one growing period per year  
 L2 = Total length of two growing periods per year  
 L3 = Total length of three growing periods per year  
 L4 = Total length of four growing periods per year

For each LGP-pattern, the mean total length of the dominant number is correlated with the mean total length of the associated numbers. Also, when the mean total length is a summation of more than one mean length, the latter are again correlated with the former. These relationships, for Kenya, are presented in Tables 6 and 7.

In the climatic inventory map of Kenya, only the mean total dominant length has been inventoried on the map. The relationships in Table 6 and 7 are more fully explored in FAO/IIASA 1991: Tech. Annex 1, giving the mean total dominant (mapped) and the corresponding mean total associated (unmapped) LGPs, and also the relationships in terms of LGP-zones, giving the mean total LGP-zones and the corresponding individual component LGPs.

### iii. Variability of LGP.

In addition to the frequency distribution mentioned in (i) above, the coefficient of variation was calculated to allow a comparison of the variability in the mean LGP, and to take into account likely losses in production. An aggregate relationship is given in Table 8.

### iv. Intermediate LGPs.

From the frequency distribution information in (i) above, the occurrence of intermediate LGPs was quantified by relating the precipitation:evapotranspiration (P/ET) ratio and moisture excess values with LGP.

The P/ET ratio for the intermediate LGPs of less than 150 days corresponds to values in the range 0.70 - 0.75.

**TABLE 7**  
Relationship between individual component mean length and mean total LGP

LGP-Pattern	Relationship
2	$L2_1 = -1.11 + 0.55 L2$
1 - 2	$L2_1 = 4.94 + 0.62 L2$
1 - 2 - H	
1 - H - 2	
1 - 2 - 3	$L2_1 = 5.87 + 0.64 L2$
1 - 3 - 2	$L3_1 = 22.12 + 0.39 L3$
1 - 2 - D	$L3_2 = 1.58 + 0.32 L3$
1 - D - 2	
2 - 1	$L2_1 = -5.48 + 0.64 L2$
2 - 1 - H	$L3_1 = 0.14 + 0.46 L3$
2 - 1 - 3	$L3_2 = -0.98 + 0.33 L3$
2 - 1 - D	
2 - 3	$L2_1 = -3.05 + 0.61 L2$
2 - 3 - 1	$L3_1 = 1.68 + 0.43 L3$
2 - 3 - 4	$L3_2 = -3.00 + 0.34 L3$
	$L4_1 = 26.35 + 0.34 L4$
	$L4_2 = -20.88 + 0.38 L4$
	$L4_3 = -17.66 + 0.27 L4$
3 - 2	$L2_1 = -2.33 + 0.63 L2$
3 - 2 - 1	$L3_1 = 5.62 + 0.45 L3$
	$L3_2 = 1.25 + 0.31 L3$

L2<sub>1</sub> = First length of two growing periods per year

L3<sub>1</sub> = First length of three growing periods per year

L3<sub>2</sub> = Second length of three growing periods per year

L4<sub>1</sub> = First length of four growing periods per year

L4<sub>2</sub> = Second length of four growing periods per year

L4<sub>3</sub> = Third length of four growing periods per year

The relationship between the individual LGP and the occurrence of intermediate LGPs is shown in Table 9.

### 3.1.3 Thermal Zones

To identify thermal zones, temperature criteria corresponding to the requirements of crops (including pasture and fuelwood), have to be taken into account. Field crops, pasture and fodder grasses and legumes, and fuelwood tree species can be classified into temperature-photosynthesis adaptability groups. In the case of Kenya, it was sufficient to recognize four temperature adaptability groups for field crops, four for pasture and fodder grasses and legumes, and two for fuelwood species, with each group considered at three productivity levels.

To cater for differences in temperature requirements of crops in the compilation of the country inventory, commensurate with the scale of the assessment (1:1 million), thermal regimes were defined based on 2.5°C intervals. A thermal difference of 2.5°C corresponds to an altitudinal change of some 385 m, thus allowing a sufficiently fine matching of crop thermal

**TABLE 8**  
Relationship between mean LGP and coefficient of variation

Mean length of growing period (days)	Coefficient of variation (%)
< 30	> 50
30 - 59	50
60 - 89	45
90 - 119	40
120 - 149	35
150 - 179	30
180 - 209	25
210 - 239	20
240 - 269	15
270 - 299	10
> 299	< 10

**TABLE 9**  
Relationship between LGP and occurrence of intermediate LGPs

Mean length of growing period (days)	Occurrence of intermediate periods (%)
< 30	100
30 - 59	65
60 - 89	25
90 - 119	10
120 - 149	5
> 149	< 1

requirements to prevailing thermal conditions as inventoried. For Kenya, nine reference thermal zones were recognized, as shown in Table 10.

#### 3.1.4 Area Inventory of Climatic Resources

The area inventory for Kenya of thermal zones, LGP-patterns zones and LGP zones, by district, was prepared at 1:1 million scale.

The mapped inventory was compiled by:

- plotting the individual station data of temperature, LGP-pattern and mean total dominant LGP, derived as described above; and
- constructing boundaries of thermal zones, pattern of number of LGP-zones, growing period zones and isolines of mean total dominant LGPs, with the values of 0, 30, 60, 90, 120, 150, 180, 210, 240, 270, 300, 330, 365<sup>-</sup> and 365<sup>+</sup> days respectively, delineating the mean total dominant LGP zones of 0, 1-29, 30-59, 60-89, 90-119, 120-149, 150-179, 180-209, 210-239, 240-269, 270-299, 300-329, 330-364, 365<sup>-</sup> and 365<sup>+</sup> days.

In addition to normal extrapolation techniques, extensive use was made of Landsat images, climatic maps, vegetation maps, land-use maps, topographic maps and soil maps to guide the delineation of boundaries and isolines.

The three climatic inventories in map form were digitized, and the digitized information from the maps was converted to a grid cell data base.

A generalized map of the thermal zones for Kenya is presented in Plate 1, and their extents are presented in Table 11. A generalized map of mean total dominant LGP-zones is presented in Plate 2, and their extents are presented in Table 12. A generalized map of the LGP-pattern zones is presented in Plate 3, and their extents are presented in Table 13.

**TABLE 11**  
Extents of thermal zones in Kenya

Thermal zone code	Mean daily temperature range (°C)	Extent (000 ha)	Percentage of total area
1	> 25.0	38 121	66.17
2	22.5 - 25.0	5 784	10.04
3	20.0 - 22.5	4 070	7.07
4	17.5 - 20.0	4 484	7.78
5	15.0 - 17.5	3 448	5.99
6	12.5 - 15.0	1 268	2.20
7	10.0 - 12.5	307	0.53
8	5.0 - 10.0	107	0.19
9	< 5.0	18	0.03
1 - 9		57 607	100.00

**TABLE 10**  
Reference thermal zones

Thermal zone code	Mean daily temperature range (°C)	Altitude (m)
1	> 25.0	< 800
2	22.5 - 25.0	800 - 1200
3	20.0 - 22.5	1200 - 1550
4	17.5 - 20.0	1550 - 1950
5	15.0 - 17.5	1950 - 2350
6	12.5 - 15.0	2350 - 2700
7	10.0 - 12.5	2700 - 3100
8	5.0 - 10.0	3100 - 3900
9	< 5.0	> 3900

**TABLE 12**  
Extents of mean total dominant LGP zones in Kenya

LGP zone code	LGP zone (days)	Extent (000 ha)	Percentage of total area
1	0	6 838	11.87
2	1 - 29	14 941	25.94
3	30 - 59	9 544	16.57
4	60 - 89	6 027	10.46
5	90 - 119	5 019	8.71
6	120 - 149	4 437	7.70
7	150 - 179	2 378	4.13
8	180 - 209	1 381	2.40
9	210 - 239	1 205	2.09
10	240 - 269	1 193	2.07
11	270 - 299	1 712	2.97
12	300 - 329	1 627	2.82
13	330 - 364	1 223	2.12
14	365 <sup>-</sup>	57	0.10
15	365 <sup>+</sup>	25	0.04
1 - 15		57 607	100.00

**TABLE 13**  
Extents of LGP-pattern zones in Kenya

Pattern zone code	Pattern zone symbol	Extent (000 ha)	Percentage of total area
1	1	31	0.05
2	H - 1	25	0.04
3	1 - H	330	0.57
4	1 - H - 2	611	1.07
5	1 - 2 - H	52	0.09
6	1 - 2	3 687	6.40
7	1 - 2 - 3	615	1.07
8	1 - 3 - 2	18	0.03
9	1 - 2 - D	3 488	6.05
10	1 - D - 2	6 081	10.56
11	1 - D	6 219	10.80
12	2	534	0.93
13	2 - 1	20 333	35.30
14	2 - 1 - H	43	0.07
15	2 - 1 - 3	3 327	5.77
16	2 - 3	1 634	2.84
17	2 - 3 - 1	2 696	4.68
18	2 - 3 - 4	54	0.09
19	2 - 1 - D	699	1.21
20	3 - 2	76	0.13
21	3 - 2 - 1	219	0.38
22	D	6 835	11.87
1 - 22		57 607	100.00

## 3.2 SOIL RESOURCES

### 3.2.1 Exploratory Soil Map of Kenya

The Exploratory Soil Map of Kenya (Siderius and van der Pouw 1980; KSS 1982a) at 1:1 million scale was used to compile the soil resources inventory for the Kenya assessment, and a generalized version of this soil map is presented in Plate 4.

This soil map was published by the Kenya Soil Survey in 1980 and provided the most recent country-wide soil data base, including information on distribution and characteristics of soils, landform and geology/parent material.

### 3.2.2 Soil Mapping Units

Soil mapping units are soil associations or soil complexes composed of dominant soils, associated soils and inclusions, and registered on the map by a symbol reflecting the landform in which they occur. In Table 14, the occurrences of soil mapping units in Kenya are presented by landform.

The Exploratory Soil Map of Kenya consists of 390 different soil mapping units, which have been described in detail in FAO/IIASA (1991: Tech. Annex 1). For each soil mapping unit the following semi-quantified information in terms of description, classes and extents was transferred to the soil resources data base for this assessment:

- Landform
- Geology/Parent material
- Soil units (with implied characteristics)
- Slope-gradient classes
- Soil texture classes
- Soil phases

### 3.2.3 Landform

Landform is the first entry in the legend of the Exploratory Soil Map. It provides information on physiography, altitudinal position and slope patterns. A generalized map of landforms in Kenya is presented in Plate 5, and a description of landforms and their extents is presented in Table 14.

For the Exploratory Soil Map of Kenya six slope classes were employed in 12 combinations. The slope classes were: A, 0-2%; B, 2-5%; C, 5-8%; D, 8-16%; E, 16-30%; and F, >30%.

A generalized map of slope-gradient classes in Kenya is presented in Plate 6. The combinations of slope classes employed and their extents are presented in Table 15.

To each of the 12 combination slope classes inventoried in the Exploratory Soil Map, associated slope classes have been assigned. These associated slope classes, covering up to 10% of the land area of the 12 combination slope classes, are used for evaluation purposes and included in the land resources inventory. The inventoried slope classes and associated slope classes are presented in Table 16. For the same purposes, assumed mean slopes of quartiles of the land area of each of the slope classes have been assigned. These values are presented in Table 17.

TABLE 14  
Occurrence of soil mapping units by landform in Kenya

Landform symbol	Landform description	Soil Mapping units	Extent (000 ha)	Percentage of total area
A	Floodplain	1 - A18	3 179	5.52
B	Bottomland	A8 + A12		
D	Dunes or dune land	B1 - B16	973	1.69
F	Footslopes	D1 - D3	90	0.16
FY	Footslopes and piedmont plain (undifferentiated)	D1 + P13		
H	Hills and minor scarps	F1 - F19	2 111	3.66
Hs	Step-faulted scarp of the Rift Valley	FY1 - FY3	614	1.07
L	Plateau and high level structural plain	H1 - H22	3 204	5.56
La	Lava flow	Hs1	515	0.89
Lc	Coastal plateau	L1 - L31	4 052	7.03
Ls	Step-faulted floor of the Rift Valley	Lava	960	1.67
Lu	Plateau/upper-level upland transition	Lc1 - Lc31	213	0.37
M	Mountains and major scarps	Ls1 - Ls3	811	1.41
Pch	Higher-level coastal plain	Lu1 - Lu2	98	0.17
Pcl	Lower-level coastal plain	M1 - M12	2 375	4.12
Pcr	Reef coastal plain	Pc1 - Pc3	430	0.75
Pd	Dissected erosional plain	Pc4 - Pc7	599	1.04
Pf1	Sedimentary plain of large alluvial plains (older fans)	Pc8 - Pc10	83	0.14
Pf2	Sedimentary plain of large alluvial plains (younger fans)	Pd1 - Pd6	1 895	3.29
Pl	Lacustrine plain	Pf1 - Pf3	312	0.54
Pn	Non-dissected erosional plain	Pf4 - Pf5	377	0.65
Psh	Higher-level sedimentary plain	Pf1 - Pf13	863	1.50
Ps1	Lower-level sedimentary plain	Pn1 - Pn35	6 007	10.43
Psm	Middle sedimentary plain ('enclosed') plain and sealing loam plain)	Ps1 - Ps6	3 885	6.74
Psx	Sedimentary plain of undifferentiated level	Ps3 + Ps15		
Pt	Sedimentary plain of upper river terrace	Ps21 - Ps27	3 138	5.54
Pv	Volcanic plain	Ps7 - Ps20	5 618	9.75
R	Volcanic footridges	Ps11 + D1		
S	Swamp	Ps28 - Ps29	247	0.43
T	Mangrove swamp	Ps28 + D1		
Uc	Coastal upland	Pt1 - Pt4	323	0.56
Uh	Upper middle-level upland	Pv1 - Pv12	998	1.73
Ul	Lower-level upland	R1 - R14	3 121	5.42
Um	Lower middle-level upland	S1 - S3	95	0.16
Up	Upland/high-level plain transitional land	T	134	0.23
Uu	Upper-level upland	Uc1 - Uc11	533	0.93
Ux	Upland, undifferentiated land	Uh1 - Uh19	786	1.36
V	Minor valley	Ul1 - Ul21	1 400	2.43
W	Badland	Um1 - Um29 Up1 - Up8	2 090	3.63
Y	Piedmont plain	Uu1 - Uu3	132	0.23
Z1	Older coastal beach ridge	Ux1 - Ux10	1 744	3.03
Z2	Younger coastal beach ridge	V1 - V2	112	0.20
Z3	Lakeside beach ridge	W1 - W2	722	1.25
Lakes		Y1 - Y13	2 134	3.70
Towns		Z1	79	0.14
		Z2	39	0.07
		Z3	5	0.01
Total extent			57 607	100.00

**TABLE 15**  
Extents of slope classes

Slope class symbol	Slope class (%)	Extent (000 ha)	Percentage of total area
A	0 - 2	19 869	34.49
AB	0 - 5	14 541	25.24
B	2 - 5	3 098	5.38
BC	2 - 8	7 351	12.76
C	5 - 8	759	1.32
BCD	2 - 16	1 707	2.96
CD	5 - 16	1 557	2.70
D	8 - 16	1 616	2.81
DE	8 - 30	886	1.54
E, EF, F	> 16	6 093	10.58
Lakes		118	0.20
Towns		10	0.02
Total extent		57 607	100.00

**TABLE 16**  
Associated slope classes

Slope class symbol	%	Associated slope classes			
A	0 - 2	100%	A		
AB	0 - 5	100%	AB		
B	2 - 5	100%	B		
BC	2 - 8	90%	BC	5%	A 5% D
C	5 - 8	90%	C	5%	AB 5% D
BCD	2 - 16	90%	BCD	5%	A 5% E
CD	5 - 16	90%	CD	5%	AB 5% E
D	8 - 16	90%	D	5%	BC 5% E
DE	8 - 30	90%	DE	5%	BC 5% F
E	16 - 30	90%	E	5%	BCD 5% F
EF	16 - 56	95%	EF	5%	BCD
F	30 - 56	95%	F	5%	DE

**TABLE 17**  
Quartiles of slope classes

Slope class symbol	%	Gentlest	Lower	Upper	Steepest
		Q1	Q2	Q3	Q4
A	0 - 2	0	1	1	2
AB	0 - 5	0	2	4	5
B	2 - 5	2	3	4	5
BC	2 - 8	2	4	6	8
C	5 - 8	5	6	7	8
BCD	2 - 16	2	6	11	16
CD	5 - 16	5	9	12	16
D	8 - 16	8	11	13	16
DE	8 - 30	8	16	22	30
E	16 - 30	16	21	25	30
EF	16 - 56	16	30	42	56
F	30 - 56	30	39	47	56

**TABLE 18**  
Geology/parent material

Geology symbol	Geology description	Extent (000 ha)	Percentage of total area
A	(Alluvial) Sediments from various sources <sup>1</sup>	2 242	3.89
B	Basic and ultra-basic igneous rocks	6 787	11.78
B <sup>+</sup>	As in B, but with volcanic ash admixture	233	0.39
BP	As in B, but volcanic ash predominant	52	0.09
D	Mudstones, claystones	103	0.18
E	Aeolian sediments (cover sands)	235	0.41
F	Gneisses rich in ferromagnesian minerals, hornblende gneisses	1 681	2.92
G	Granites, granodiorites	478	0.83
G <sup>+</sup>	As in G, but with volcanic ash admixture	14	0.02
GF	Biotite-hornblende granites	38	0.07
GF <sup>+</sup>	As in GF, but with volcanic ash admixture	71	0.12
GP	As in G, but volcanic ash predominant	19	0.03
GR	Complex of G and R	51	0.09
I	Intermediate igneous rocks (syenites etc.)	500	0.87
I <sup>+</sup>	As in I, but with volcanic ash admixture	91	0.16
J	Lagoonal deposits	1 155	2.00
K	Siltstones	1 467	2.55
KT	Complex of K and T	94	0.16
L	Limestones, calcitic mudstones	2 056	3.57
N	Biotite gneisses	400	0.70
N <sup>+</sup>	As in N, but with volcanic ash admixture	160	0.28
O	Plio-pleistocene bay sediments	9 607	16.28
P	Pyroclastic rocks	1 897	3.29
Q	Quartzites	406	0.70
R	Quartz-feldspar gneisses	59	0.10
S	Feldspar, grits, arkoses	647	1.12
T	Shales	164	0.28
U	Undifferentiated basement system rocks	14 007	24.31
U <sup>+</sup>	As in U, but with volcanic ash admixture	1 172	2.04
UP	As in U, but volcanic ash predominant	37	0.06
V	Undifferentiated or various igneous rocks	8 536	14.28
W	Marls	168	0.29
X	Undifferentiated or various rocks	1 350	2.34
X <sup>+</sup>	As in X, but with volcanic ash admixture	12	0.02
Y	Acid igneous rocks (rhyolite, aplite)	156	0.27
Y <sup>+</sup>	As in Y, but with volcanic ash admixture	79	0.14
-	Not defined	1 263	2.19
Lakes		118	0.20
Towns		11	0.02
Total extent		56 607	100.00

<sup>1</sup> If the source of alluvial sediments and bottomland infills is known (e.g., basalts), then the code for this rock is used, otherwise the code A applies.

### 3.2.4 Geology

Geology is the second entry in the legend of the Exploratory Soil Map. The geological subdivisions reflect mainly resistance to weathering and richness of parent material in order to provide linkage with soil formation. The first level subdivision comprises three types of rocks: igneous, metamorphic and sedimentary.

Igneous rocks and metamorphic rocks are further subdivided by gradations from basic to acid, and the sedimentary rocks further subdivided by texture, from fine to coarse.

Each soil mapping unit is accordingly characterized by its geological setting/parent material. A generalized map of geology/parent material is presented in Plate 7 and the descriptions and extents of geological units are presented in Table 18.

### 3.2.5 Soil Units

The individual soil units of the soil associations or soil complexes (soil mapping units of the Exploratory Soil Map) have been defined in accordance with the FAO-Unesco legend of the Soil Map of the World (FAO 1974). The soil units adopted were selected on the basis of present knowledge of the formation, characteristics and distribution of the soils, their importance as resources for agricultural production and their significance as a factor of the environment.

In the legend of the Exploratory Soil Map, some adaptations of the FAO-Unesco legend have been introduced. At the first level (great group) the terminology for Lithosols and Nitisols has been modified. At the second level (unit level) new subgroups have been introduced (cambic and orthic Rendzinas) and others modified (vertic Gleysols, mollic Nitisols, chromic Acrisols, chromic Luvisols and chromic Cambisols). In order to reflect the greater amount of detail of the Exploratory Soil Map of Kenya, a third level of terminology (sub-unit level) has been introduced for the subdivision of soil units into sub-units. The prefixes used to distinguish sub-units are ando-, calcaro-, chromo-, ferralo-, luvo-, nito-, ortho- and verto-.

In the Exploratory Soil Map, 123 different soil units and five miscellaneous units occur, and these are listed in Table 19, together with their extents.

The soil units have been defined in terms of measurable and observable properties of the soil itself, and specific clusters of such properties are combined into 'diagnostic horizons' and 'diagnostic properties'.

The diagnostic horizons have been used as defined in the FAO-Unesco legend. Diagnostic horizons and properties of the soil units for Kenya are given in FAO/IIASA (1991: Tech. Annex 1), while the complete definitions of the soil units are given in Volume 1 (Legend) of FAO-Unesco Soil Map of the World (FAO 1974) and Exploratory Soil Survey Report (KSS 1982a).

### 3.2.6 Soil Textures

Soil textures may vary within the range of textures defined for a particular soil unit. Textural classes for individual soil units by soil mapping unit are presented in the legend of the Exploratory Soil Map of Kenya. There are three major textural divisions, subdivided into 17 classes. The classifications and their relative occurrences in Kenya are listed in Table 20.

**TABLE 19**  
Extents of soil units

Soil unit symbol	Soil unit name	Extent (000 ha)	Percentage of total area
A	Acrisols	45	0.08
Ac	Chromic Acrisols	83	0.14
Ag	Gleyic Acrisols	50	0.09
Ah	Humic Acrisols	151	0.26
Aic	Ferralsol-chromic Acrisols	773	1.34
Aif	Ferralsol-ferric Acrisols	128	0.22
Aio	Ferralsol-orthic Acrisols	325	0.56
Ao	Orthic Acrisols	168	0.29
Ap	Plinthic Acrisols	15	0.03
Ath	Ando-humic Acrisols	15	0.03
B	Cambisols	9	0.02
Bc	Chromic Cambisols	1 001	1.74
Bd	Dystric Cambisols	70	0.12
Be	Eutric Cambisols	630	1.09
Bf	Ferralsol Cambisols	54	0.09
...			
R	Regosols	13	0.02
Rc	Calcaric Regosols	1 256	2.18
Rd	Dystric Regosols	139	0.24
Re	Eutric Regosols	696	1.21
Rtc	Ando-calcaric Regosols	301	0.52
S	Solonetz	635	1.10
Sg	Gleyic Solonetz	434	0.75
Slo	Luvo-orthic Solonetz	4 664	8.10
Sm	Mollic Solonetz	44	0.08
So	Orthic Solonetz	2 537	4.40
Th	Humic Andosols	456	0.79
Tm	Mollic Andosols	529	0.92
Tv	Vitric Andosols	82	0.14
U	Rankers	155	0.27
V	Vertisols	150	0.26
Vc	Chromic Vertisols	764	1.33
Vp	Pellic Vertisols	1 514	2.63
W	Planosols	4	0.01
Wd	Dystric Planosols	114	0.20
Wh	Eutric Planosols	324	0.56
We	Humic Planosols	196	0.34
Ws	Solodic Planosols	2 472	4.29
Wve	Verto-eutric Planosols	251	0.44
X	Xerosols/Yermosols	103	0.18
Xh	Haplic Xerosols/Yermosols	651	1.13
Xk	Calcic Xerosols/Yermosols	3 621	6.29
Xy	Gypsic Xerosols/Yermosols	169	0.29
Z	Solonchaks	578	1.00
Zg	Gleyic Solonchaks	187	0.32
Zo	Orthic Solonchaks	1 601	2.78
Zt	Takyric Solonchaks	148	0.26
Lava		1 016	1.76
Lava flows		129	0.22
Lava fields		56	0.10
Rock outcrops		558	0.97
Ice cap		5	0.01
Lakes		118	0.20
Towns		11	0.02
Total extent		57 607	100.00

### 3.2.7 Soil Stoniness

The presence of coarse material (stoniness) in the soil profile is inventoried separately from soil textures. The presence of coarse material is subdivided into six types (with symbols), namely Gravely (G), Bouldery (SB), Very gravely (VG), Stony/bouldery (SB), Stony (S), and Bouldery/stony (BS).

### 3.2.8 Soil Phases

Soil phases indicate land characteristics which are not considered in the definition of the soil units but are significant to the use and management of land. The soil phases recognized on the Exploratory Soil Map of Kenya can be grouped into phases indicating a mechanical hindrance or limitation (rocky, bouldery, boulder-mantle, stony, stone-mantle or gravel-mantle); phases indicating an effective soil depth limitation (lithic, paralithic, petrocalcic, piso-calcic, petro-ferric or piso-ferric); and phases indicating a physico-chemical limitation (saline, sodic or saline-sodic). Soil phases can occur alone (one soil phase) or in combination (two or three phases). Some of these phases have been defined in the FAO-Unesco Legend, while others have been introduced in the Exploratory Soil Map of Kenya.

TABLE 20

Percentage occurrence of textural classes

Texture class	Texture symbol	Percentage <sup>1</sup>
Sand	S	0.2
Loamy coarse sand	LCS	0.5
Fine sand	FS	0.2
Loamy fine sand	LFS	0.8
Loamy sand	LS	3.8
$\Sigma$ Coarse textures		5.5
Fine sandy loam	FSL	1.3
Sandy loam	SL	3.1
Loam	L	6.4
Sandy clay loam	SCL	15.4
Silt loam	SL	0.6
Clay loam	CL	28.5
Silty clay loam	SICL	0.4
Silt	SI	<0.1
$\Sigma$ Medium textures		55.8
Sandy clay	SC	10.2
Silty clay	SIC	0.3
Peaty clay	PC	<0.1
Clay	C	28.2
$\Sigma$ Fine textures		38.7

<sup>1</sup> Total extent where texture is applicable is 55 714 270 ha (96.9% of total area).

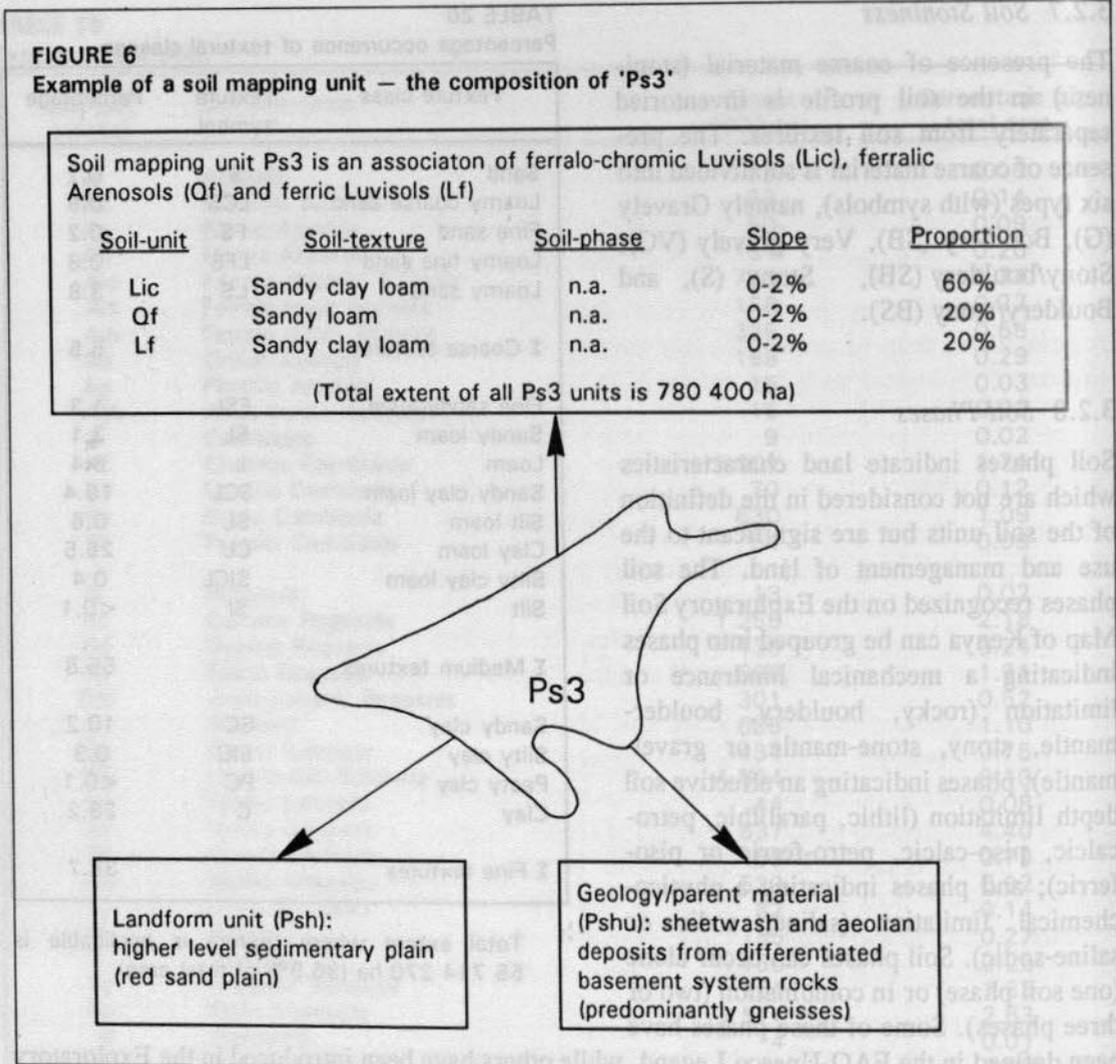
### 3.2.9 Soil Mapping Unit Composition

At the exploratory level, a soil mapping unit only rarely comprises a single soil; usually it consist of one main soil with minor associates. When the various soils of a soil mapping unit occur in a recognizable geographical pattern in defined proportions, they constitute a soil association; if such a pattern is absent, they form a soil complex.

The productivity potential of different soil units within a soil mapping unit consequently may vary widely. The suitability of a particular soil association or complex for a specific use cannot be assessed without taking into account each individual soil unit within the association.

The legend of the Exploratory Soil Map of Kenya does not provide explicit information in a quantified manner on the composition of the soil mapping units. This information for Kenya was provided to FAO by Stiboka in Wageningen, working in close cooperation with both the Kenya Soil Survey in Nairobi and the International Soil Reference and Information Centre (ISRIC) in Wageningen, The Netherlands (van der Pouw 1983).

**FIGURE 6**  
Example of a soil mapping unit – the composition of 'Ps3'



The complete mapping unit composition table as elaborated for Kenya is presented in FAO/IIASA 1991: Tech. Annex 1. This table consists of the percentage allocation of soil units by slope class, soil texture and soil phases for each soil mapping unit, and of information on landform and geology/parent material.

The composition of an example soil association (Ps3) is illustrated and explained in Figure 6.

### 3.3 LAND USE AND OTHER OVERLAYS

Land-use and other overlays, such as the tse-tse-infestation overlay for Kenya, are then integrated into the physical resources inventories. Subsequently, each agro-ecological cell is further characterized by the information contained in these various overlays.

Tables 21, 22, 23, 24, and 25 present descriptions, map symbols, computer coding and extents of map units respectively of cash crop zones, forest zones, parkland areas, irrigation schemes and tse-tse infestation areas, as prepared for Kenya. Plates 8, 9, 10, 11 and 12 present generalized maps of the same information.

**TABLE 21**  
Extents of cash crop zones in Kenya

Crop symbol	Crop code	Crop description	Extent (000 ha)	Percentage
01	2	Tea (secondary)	423	8.37
02	3	Coffee (secondary)	442	8.75
03	4	Sugarcane (secondary)	849	16.81
04	5	Cotton (secondary)	924	18.30
05	6	Pyrethrum	465	9.21
06	7	Sisal (secondary)	585	11.58
10	8	Tea (primary)	68	1.34
12	9	Tea/Coffee	144	2.85
13	10	Tea/Sugarcane	56	1.11
15	11	Tea/Pyrethrum	53	1.06
20	12	Coffee (primary)	51	1.01
23	13	Coffee/Sugarcane	104	2.05
30	14	Sugarcane (primary)	69	1.37
34	15	Sugarcane/Cotton	289	5.73
40	17	Cotton (primary)	341	6.76
60	18	Sisal (primary)	171	3.39
70	19	Pineapple (primary)	16	0.32
Total extent			5 048	100.00

**TABLE 22**  
Extents of forest zones in Kenya

Forest symbol	Forest code	Forest description	Extent (000 ha)	Percentage
F1	2	Registered Forest	1 522	77
F2	3	Unregistered Forest	60	3
F3	4	Proposed Forest	392	20
Total extent			1 974	100

**Table 23**  
Extents of parkland areas in Kenya

Parkland symbol	Parkland code	Parkland description	Extent (000 ha)	Percentage
P1	2	National park	2 820	67.18
P2	3	Game reserve	891	21.21
P3	4	National reserve	487	11.61
Total extent			4 198	100.00

**TABLE 24**  
Extents of irrigation schemes in Kenya

Irrigation area			Extent (ha)	Percentage
symbol	code	Name		
01	2	Turkwell	400	0.98
02	3	Katilu	700	1.72
03	4	Amolem	400	0.98
04	5	Kaputir	500	1.23
05	6	Bunyala	500	1.23
06	7	Ahero I	2 000	4.91
07	8	Ahero II	2 500	6.14
08	9	Marigat	1 200	2.95
09	10	Mwea	13 200	32.43
10	11	Malka daka	400	0.98
11	12	Merti	400	0.98
12	13	Mbalambala	500	1.23
13	14	Garisa	1 000	2.46
14	15	Hola	2 700	6.63
15	17	Garsen	2 400	5.90
16	18	Tavete	600	1.47
17	19	Mandera	100	0.25
19	20	Bura (proposed)	10 900	26.78
16	21	Wemba	300	0.74
Total extent			40 700	100.00

**TABLE 25**  
Extent of tse-tse infestation areas in Kenya

Tse-tse infestation areas		Extent (000 ha)	Percentage of total area
symbol	code		
T	2	7 561	13.15

### 3.4 COMPUTERIZED LAND RESOURCES INVENTORY

The computerized land resources inventory records total extents of agro-ecological cells. Each cell contains information on: Sequence number; Province; District; Thermal Zone; LGP Zone; LGP-Pattern; Soil Mapping Unit; Landform; Geology/Parent Material; Soil Unit; Soil Texture; Soil Phases (1<sup>st</sup>, 2<sup>nd</sup> and 3<sup>rd</sup>); Cash Crop Zone; Forest Zone; Irrigation Scheme; Tse-tse Infestation Area; Parkland Area; and Extent (in hectares).

Additional categories could be needed, and some of the above attributes, such as tse-tse areas, may not be relevant elsewhere. The land resources inventory as developed for Kenya consisted of some 91 000 unique agro-ecological cells.

## Chapter 4

## Soil erosion and productivity

This chapter describes the soil erosion and productivity model, which quantifies implications of alternative land uses in terms of topsoil loss due to erosion and the impact of that loss on the productivity of land under different assumed soil conservation measures. The model operates on the basis of values derived from the climatic and soil resources inventories described in Chapter 3. Details of the model, which is based substantially on the work of Mitchell (1986), are described in full in FAO/IIASA (1991: Tech. Annex 2).

The methodology for the estimation of topsoil loss is essentially based on a modified Universal Soil Loss Equation (USLE) (Wischmeier and Smith 1978). The topsoil loss is subsequently converted into productivity loss with or without specific soil conservation measures. The methodology is schematically shown in Figure 7 and consists of the following steps:

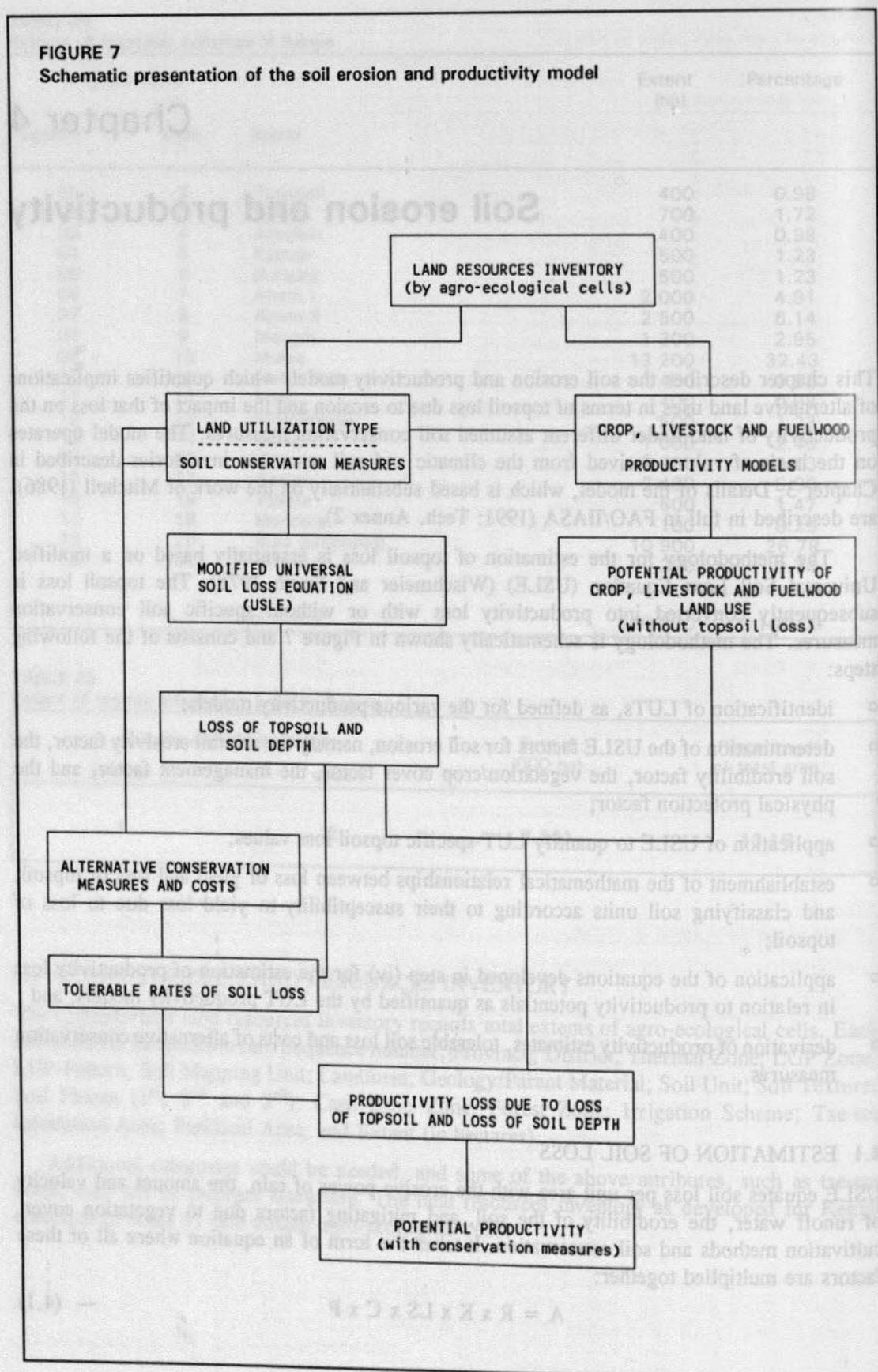
- identification of LUTs, as defined for the various productivity models;
- determination of the USLE factors for soil erosion, namely the rainfall erosivity factor, the soil erodibility factor, the vegetation/crop cover factor, the management factor, and the physical protection factor;
- application of USLE to quantify LUT-specific topsoil loss values;
- establishment of the mathematical relationships between loss of yield and loss of topsoil, and classifying soil units according to their susceptibility to yield loss due to loss of topsoil;
- application of the equations developed in step (iv) for the estimation of productivity loss in relation to productivity potentials as quantified by the LUT productivity models; and
- derivation of productivity estimates, tolerable soil loss and costs of alternative conservation measures.

## 4.1 ESTIMATION OF SOIL LOSS

USLE equates soil loss per unit area with the erosive power of rain, the amount and velocity of runoff water, the erodibility of the soil, and mitigating factors due to vegetation cover, cultivation methods and soil conservation. It takes the form of an equation where all of these factors are multiplied together:

$$A = R \times K \times LS \times C \times P \quad \text{--- (4.1)}$$

**FIGURE 7**  
Schematic presentation of the soil erosion and productivity model



where:

- A: Annual soil loss in t/ha
- R: Rainfall erosion factor, to account for the erosive power of rain, related to the amount and intensity of rainfall over the year. It is expressed in units described as erosion index units.
- K: Soil erodibility factor to account for the soil loss rate in t/ha per erosion index unit for a given soil as measured on a unit plot, defined as a plot 22.1 m long on a 9% slope under a continuous bare cultivated fallow. It ranges from less than 0.1 for the least erodible soils to approaching 1.0 in the worst possible case.
- LS: A combined factor to account for the length and steepness of the slope. The longer the slope, the greater the volume of runoff; the steeper the slope, the greater its velocity. LS = 1.0 on a 9% slope, 22.1 m long.
- C: A combined factor to account for the effects of vegetation cover and management techniques. These reduce the rate of soil loss, so in the worst case, where the soil is bare and no management is being applied, C = 1.0. In the ideal case, when there is no loss occurring, C would be zero.
- P: Physical protection factor, to account for the effects of soil conservation measures. In this context, 'conservation measures' are defined as structures or vegetation barriers spaced at intervals on a slope, as distinct from continuous mulches or improved cultural techniques, which come under the management techniques.

The USLE equation has been modified by separating the two elements of the cover and management factor C into:

- C\*: a vegetation cover factor, which accounts for only the effects of the natural vegetation or crop canopy, and includes leaf litter and residues accumulating during the life of the crop; and
- M: a management factor, to account for tillage methods, the effects of previous crop residues, previous grass or bush fallows, and applied mulches.

The soil loss equation therefore becomes:

$$A = R \times K \times LS \times (C^* \times M) \times P. \quad - (4.2)$$

Equation (4.2) is used in the model to estimate topsoil loss under specified vegetation/crop cover and management conditions for each LUT. These estimates in turn are related to productivity losses and conservation needs.

Each of the factors making up soil loss equation (4.2) is quantified, in turn, for a specified or alternative LUTs. Attributes of LUTs for crops, pasture and livestock, and fuelwood in the Kenya situation are given in Tables 34, 48 and 65 respectively. The soil loss quantification procedure is presented more fully in FAO/IIASA (1991: Tech. Annex 2). Plate 13 presents a generalized map of potential erosion hazard in Kenya. This map combines the erosivity factor (R), the erodibility factor (K) and the slope factor (LS).

#### 4.2 SOIL EROSION AND LOSS OF PRODUCTIVITY

The effect of soil erosion can be measured in different ways according to the kind of damage suffered. In the model (Figure 7), the estimate is based on short-term losses in crop production due to erosion of fertile topsoil, and long-term losses in land productivity due to truncation of the soil profile and consequent reduction of available water. No account is taken at this stage

**TABLE 26**  
Slope-land use association screen

Land utilization type	Level of inputs		
	Low	Intermediate	High
Dryland crops without soil conservation measures	< 30%	< 30%	< 16%
Dryland crops with soil conservation measures	< 30%	< 30%	< 30%
Wetland crops without soil conservation measures	< 5%	< 5%	< 2%
Wetland crops with soil conservation measures <sup>1</sup>	< 30%	< 30%	< 30%
Coffee, tea, fuelwood and pasture with and without soil conservation measures	< 45%	< 30%	< 45%

<sup>1</sup> For wetland crops, terracing is required.

**TABLE 27**  
Regeneration capacity (mm/yr) of topsoil in Kenya by LGP and thermal zone (derived from Hammer 1981)

LGP (days)	Thermal zone								
	T1	T2	T3	T4	T5	T6	T7	T8	T9
< 75	0.5	0.5	0.5	0.5	0.5	0.25	0.25	0.25	0.25
75 - 179	1.0	1.0	1.0	0.5	0.5	0.25	0.25	0.25	0.25
180 - 269	1.5	1.5	1.5	0.75	0.75	0.5	0.6	0.5	0.5
> 270	2.0	2.0	2.0	1.0	1.0	0.5	0.5	0.5	0.5

in the model development of possible damage to lowlands by flooding and silt deposition, or of the possible benefit from the deposition of fertile silt on alluvial plains, or change in workability constraints due to changes in terrain characteristics.

In the model, permissible slopes for various land uses under different levels of inputs have been defined as model variables, and these are given in Table 26. The critical slope values in the slope-land use association screen define the upper slope limits to cultivation, and they may be modified as appropriate.

Further, the model takes into account losses in crop production resulting from soil erosion through:

- the removal of topsoil which, in many soils, is the source of most or all the nutrient fertility; and
- reduction in the overall depth of the soil profile, leading to a reduction in both soil water-holding capacity and soil foothold capacity, to a point where yield becomes constrained.

An acceptable rate of soil erosion is considered to be one that over a specified number of years (e.g., 25, 50 or 100):

- does not result in a crop yield reduction of more than a specified amount due to loss of topsoil; and

- does not result in more than a specified proportion of land being downgraded to a lower class of agricultural suitability due to soil depth reduction.

These two criteria are not interdependent, so that the acceptable rate of soil loss is taken as the lesser of the two alternatives. The model therefore provides a framework for assessing tolerable soil loss, based on its likely impact on crop yields and the future availability of cultivable land.

The soil erosion and productivity model is linked to crop, livestock and fuelwood productivity models which provide the assessments of land suitabilities and the associated yield potentials for the estimation of tolerable soil loss.

#### 4.2.1 Effect of Topsoil Loss on Productivity

Soils differ in their susceptibility to loss of productivity as the topsoil is eroded. The differences are related to the depth of the topsoil and the amount of nutrient fertility or presence of unfavourable conditions in the subsoil.

Loss of productivity due to topsoil loss can be largely compensated for by the use of manure and fertilizer, and low rates of soil erosion are, to some extent, compensated for by the formation of new topsoil. The rate of topsoil formation can vary from <0.25 mm/year in dry and cold environments to >1.5 mm/year in humid and warm environments (Hammer 1981; Hudson 1981). Topsoil formation at the rate of 1 mm/year is equivalent to an annual addition of 12 t/ha. Therefore, the rate of topsoil formation has been considered as a factor in the model in assessing loss of productivity and tolerable soil losses. Regeneration capacities of soils used in the model in calculating net loss of topsoil are given by moisture and thermal regimes in Table 27.

Based on experimental evidence (Stallings 1957; Barr 1957; Lal 1976a, 1976b, 1976c; Higgins and Kassam 1981) and analytical data from Kenya Soil Survey (KSS 1975, 1976, 1982b), soil units of the Exploratory Soil Map of Kenya were classified according to their susceptibility to productivity loss with loss of topsoil, and by the presence of other unfavourable subsoil conditions (Table 28). These susceptibility rankings of the soils are related to actual yield losses, by input levels, through a set of linear equations, similar to those for Kenya given in Table 29. The reduced impact of topsoil loss under intermediate and high levels of inputs is due to the compensating effect of fertilizers at their normal rates of use. It is assumed that the benefit of fertilizers is less on the more susceptible soils because of their more unfavourable subsoil conditions.

The tolerable loss rate, for a given soil unit and specified amount and time scale of yield reduction, is calculated in the model by:

$$TL = \{(R_a/R_m \times 100 \times B \times D_t) + 3T\} / T \quad - (4.3)$$

where:

- TL = tolerable loss rate (t/ha/year)
- $R_a$  = acceptable yield reduction (%)
- $R_m$  = yield reduction (%) at the given input level when the effective topsoil is all lost
- B = bulk density of the soil ( $g/cm^3$ )
- $D_t$  = depth of effective topsoil (cm)
- T = time (years) over which yield reduction is acceptable.

**TABLE 28**  
Ranking of soils (Kenya Soil Survey) according to their susceptibility to productivity loss per unit of topsoil

Most susceptible	Intermediate susceptible	Least susceptible
Acrisols, except Humic Arenosols	Arenosols	Chernozems
Ferralic Cambisols	Cambisols, except Ferralic Cambisols	Fluvisols
Ferralsols, except Humic Ferralsols	Gleysols	Histosols
Ironstone soils	Greyzems	Humic Andosols
Lithosols	Humic Acrisols	Mollic Andosols
Planosols	Humic Ferralsols	Vertisols
Rendzinas	Kastanozems	
Solonchaks	Luvisols	
Solonetz	Nitisols	
	Phaeozems	
	Regosols	
	Vitric Andosols	
	Xerosols	
	Yermosols	

**TABLE 29**  
Relationships between topsoil loss and yield loss

Soil susceptibility ranking	Levels of inputs	Equation
Least susceptible	Low	$Y = 1.0 X$
	Intermediate	$Y = 0.6 X$
	High	$Y = 0.2 X$
Intermediate susceptible	Low	$Y = 2.0 X$
	Intermediate	$Y = 1.2 X$
	High	$Y = 0.4 X$
Most susceptible	Low	$Y = 7.0 X$
	Intermediate	$Y = 5.0 X$
	High	$Y = 3.0 X$

Y = productivity loss in %; X = topsoil loss in cm

#### 4.2.2 Effect of Soil Depth Reduction on Productivity

The rate of soil formation by rock weathering is extremely slow, up to 0.025 mm/year on volcanic rocks in humid areas, and <0.01 mm/year on basement complex rocks in semi-arid areas (Dunne, Dietrich and Brunego 1978), and at the highest rate quoted by them it would take 4000 years to produce 10 cm of soil. Therefore, the rate at which the soil profile is deepened by rock weathering can be ignored as a factor in the model in assessing tolerable soil losses.

The estimation of the effect of soil depth reduction is based on the assumption that there is no significant loss of productivity until the soil becomes so shallow that shortage of moisture becomes a limiting factor. The critical depth varies according to crop and the climate. Once this critical depth is reached, productivity loss is linear until the soil becomes too shallow to produce any crop at all (Wiggins and Palma 1980). The critical points can be equated with land suitability class limits as follows (where depth is the limiting factor):

- VS/S: Soil water becomes limiting and at least 20% decrease in yield potential
- S/MS: Soil water becomes limiting and at least 40% decrease in yield potential

MS/mS: Soil water becomes limiting and at least 60% decrease in yield potential  
 mS/N: Soil water becomes limiting and at least 80% decrease in yield potential.

Thus the suitability classes VS (very suitable), S (suitable), MS (moderately suitable), mS (marginally suitable) and N (not suitable) correspond to yield levels of >80%, 60-80%, 40-60%, 20-40% and <20% of maximum attainable yield respectively.

If erosion takes place uniformly on soils of varying depth, the end result will be that some soils that had been marginally deep enough will become non-productive while others will become marginal. If the range of soil depths is known, the tolerable amount of soil loss can be gauged in terms of the amount of land that can be permitted to be lost to production.

In order to calculate tolerable soil losses, soil depth reduction is measured in terms of the proportion of the soils in a specified area that have, as a result of erosion, become shallower than a given depth. The soils of the mapping units of the Exploratory Soil Map of Kenya were assigned to 5 depth classes: shallow, <50 cm; moderately deep, 50-80 cm; deep, 80-120 cm; very deep, 120-180 cm; and extremely deep, >180 cm.

The rate of soil loss is related to the proportion of land whose soil has become shallower than a specified depth, by the following equations:

- Proportion (P, percent) of land downgraded to at least the next depth class:

$$P = (SL \times T) / (B \times D_r) \quad \text{--- (4.4)}$$

where:

- SL = soil loss (t/ha/year)
- T = time (years)
- B = bulk density of the soil (g/cm<sup>3</sup>) and
- D<sub>r</sub> = depth range of the soil class (cm).

- Proportion (P, percent) of land downgraded by more than one depth class:

$$P = \{[(SL \times T)/100B] / D_r\} - D_2 \times 100 \quad \text{--- (4.5)}$$

where D<sub>2</sub> = difference (cm) between the lower limit of the depth class and the upper limit of the shallower class to which the land is downgraded.

Table 30 shows, for Kenya, the proportions of land that would be downgraded from given depth classes to shallower classes as a result of soil erosion at different rates over a 100-year period. The values in Table 30 are based on equations 4.4 and 4.5, and assume that soil depths are evenly distributed over the range in each depth class.

If a tolerable soil loss was set to allow 10% of each depth class to be downgraded by one class over 100 year period, this would give the following soil loss rates for each depth class (assuming 25 cm is the minimum soil depth that would allow crop production):

Shallow (≥25 cm)	— 3	t/ha/year
Moderately deep	— 3.6	
Deep	— 4.8	
Very deep	— 7.2	
Extremely deep	— 26.8	

TABLE 30

Proportion of land in Kenya that would be downgraded from a given depth class to a shallower class or to bedrock as a result of soil erosion at different rates over a 100-year period

Soil depth class and change (cm)	Extent of land downgraded (% of class) at erosion rate (t/ha) of:							
	5	10	25	50	75	100	200	400
From shallow (0-50) — to bedrock (0)	8	17	42	83	100			
From moderately deep (50-80) — to shallow (0-50) — to bedrock (0)	14 0	28 0	70 0	100 0		42 100		
From deep (80-120) — to moderately deep (50-80) — to shallow (0-50) — to bedrock (0)	10 0	21 0	52 0	100 25 0		81 0 100		
From very deep (120-180) — to deep (80-120) — to moderately deep (50-80) — to shallow (0-50) — to bedrock (0)	7 0	14 0	35 0	70 3 0	100 38 0		72 100 22 100 0	
From extremely deep (200-400) — to very deep (120-180) — to deep (80-120) — to moderately deep (50-80) — to shallow (0-50) — to bedrock (0)	2 0	4 0	9 0	19 0	28 1 0	38 11 0 0	76 48 30 17 0	100 100 100 92 70

#### 4.2.3 Assessment of Tolerable Soil Loss on a Combined Basis of Topsoil Loss and Soil Depth Reduction

Criteria for estimating soil loss tolerance are set according to the amount of yield loss that can be tolerated, or the proportion of the land that can be permitted to become shallower than a specified depth, over a specified time. The two bases for soil loss estimation do not interact, so when used in combination the tolerable soil loss would be the lesser of the estimates.

Table 31 gives an example of the soil losses that would give either a 50% yield reduction or soil depth reduction resulting in downgrading of 10% of each depth class, over a period of 100 years.

TABLE 31  
Tolerable rates of soil loss<sup>1</sup>

Soil depth class	Susceptibility to yield loss of topsoil		
	Low	Intermediate	High
Shallow <sup>2</sup>	3.0	3.0	3.0
Moderately deep	3.6	3.6	3.6
Deep	4.8	4.8	4.8
Very deep	7.2	7.2	7.2
Extremely deep	12.0	26.4	26.4

<sup>1</sup> In t/ha/year, to give not more than 10% land loss from a given depth class and not more than 50% crop yield reduction at low input level over a 100-year period.

<sup>2</sup> Assuming a minimum depth of 25 cm for crop production.

### 4.3 SOIL CONSERVATION MEASURES

Three kinds of benefits can be obtained from soil conservation on cultivated land.

- i. Long-term reduction or halting of decline in agricultural production or availability of good quality land.
- ii. Immediate or gradual increase in agricultural production.
- iii. Non-agricultural benefits such as improved dry season flow of rivers, reduced flooding and siltation of reservoirs, and reduced damage to infrastructure and farm land on lower slopes.

The soil erosion and productivity model essentially quantifies the long-term benefits (i.e., reduction in or prevention of further losses of agricultural land and decline in crop yields) of seven soil conservation measures for alternative uses of land. It is envisaged that the model can be extended in the future to include an estimation of other agricultural and non-agricultural benefits implied in (i) and (ii) above.

The seven types of conservation measures considered in the model for Kenya were cut-off drains, narrow-based terraces, bench terraces, converse terraces ('fanya juu' terraces), grass strips, trash-lines, and stone terraces. Of these, narrow-based terraces and grass strips are suitable for large farms, while all measures except narrow-based terraces are suitable for small farms. Bench terraces can be used on large farms, but the costs of making them wide enough for mechanical cultivation is high. Also, narrow-based terraces are applicable to slopes  $< 20\%$ , and the effectiveness of grass strips is reduced in low rainfall areas (LGP  $< 150$  days) because of poor establishment. Also, trash-lines are subject to availability of crop residues, while stone terraces are subject to availability of stones, and are feasible only on stony soils.

In the application of the soil erosion and productivity model, potential erosion losses for each desired land use (crop, livestock, fuelwood) is evaluated first on the assumption that no specific soil conservation measures are applied, i.e., protection factor  $P = 1$ . The results are compared with what is considered as acceptable rates of soil loss under the three levels of inputs, and then the required amount of conservation and associated costs are estimated.

#### 4.3.1 Estimation of Conservation Need

The need for soil conservation is estimated from the protection factor (P) required to reduce soil erosion from its average rate on unprotected land to the tolerable rate as estimated in Section 4.2.3. The average rate of erosion covers both the cultivated and the uncultivated parts of the crop and fallow period cycle, but the soil conservation measures described are only applied and maintained in the cultivated part of the cycle. If unacceptable rates of erosion are also occurring during the uncultivated part of the cycle, then additional protection will be needed.

The following example shows how the conservation need can be estimated in the model, for the cultivated part of the crop and fallow period cycle. The soil loss reduction needed is 66 t/ha (i.e., 146 - 80). The total soil loss over 6 years of the crop cycle is 130 t/ha, which has to be reduced by 66 t/ha to 64 t/ha. The P factor needed to achieve this is  $64/139 = 0.49$ .

The protective effect of conservation measures varies according to natural conditions — soil, topography, climate — and the intensity of the measure, e.g., the interval between terraces.

Year		Annual soil loss (t/ha)	Total soil loss (t/ha)
1-4	(Rest period)	4	16
5	(Crop 1 <sup>st</sup> year)	12	12
6	(Crop 2 <sup>nd</sup> year)	18	18
7-10	(Crop 3 <sup>rd</sup> - 6 <sup>th</sup> years)	25	100
Total soil loss over 10 years			146
Tolerable rate of soil loss over 10 years			80

The equations to calculate the required spacing for a given measure, when the relevant natural conditions and the required protection factor (P) are known, are given in Mitchell (1986). These equations form the basis of cost calculations in the model for the seven types of conservation measures listed above.

These conservation measures deal with cultivated land, and in the model their benefit is assumed to last only while the land is under cultivation. If excessive erosion is taking place during the uncultivated part of a crop-fallow period cycle, the most effective way to reduce it is by improving the grass cover. The first requirement for this is to reduce or eliminate the grazing pressure of livestock.

Other possible causes of excessive erosion on uncultivated land are poor established grass due to low rainfall, and unfavourable soil conditions. These have not been explicitly incorporated in the model at this stage in its development, but possible measures to overcome them are pasture improvement with fertilizers; planting or broadcasting seed of improved pasture species; use of lines of cut bushes to slow runoff to protect germinating grass seeds; and use of small earth banks to trap water to encourage germination of broadcast seed (Critchley 1984).

#### 4.3.2 Costs of Conservation Measures

The costs of conservation measures are given in terms of man-days of labour, and the proportion of land taken out of agricultural production by the measures. Where fertilizer is used, for example in establishing grass strips, the amount of fertilizer is specified. It is assumed that all materials used are locally available and therefore not explicitly costed.

Table 32 presents a generalized comparison of the characteristics, effectiveness and costs of the seven types of conservation measures considered in the model as applied in Kenya.

The appropriate conservation measure for a given set of circumstances is normally the cheapest that will achieve the required measure of protection. The costs presented in Table 32 are based on man-days of work for manual labour, and include both initial and maintenance costs. Initial costs are mainly based on the horizontal interval between measures, whereas annual maintenance costs are derived as fixed percentages of the initial costs. In order to compare costs directly, the annual maintenance costs over the cultivated part of the 10-year crop and fallow cycle are converted to net present value using an interest rate of 10%.

Most conservation measures involve taking some land out of production. They vary according to the type of measure, and whether the plants used to protect the terrace banks and other structures have any production value.

TABLE 32  
Economic aspects of soil conservation measures

Type of measure and physical protection factor (P)	Slope (%)	Horizontal interval (m)	Height of risers (m)	Initial cost			Annual maintenance cost (man-day/ha)	Proportion of land taken out of agriculture (%)
				Construction (man-day/ha)	Grass planting (man-day/ha)	Fertilizer (kg/ha) <sup>1</sup>		
Cut-off drains P = 0.25-0.75 <sup>2</sup>	>16	-	-	27	-	-	3	-
	<16	-	-	40	-	-	4	-
Narrow-based terraces P = 0.1-0.4 <sup>2</sup>	5	40	1.0	50	17	5	5	5
	8	20	1.0	100	36	10	10	10
	16	10	1.6	200	51	15	20	15
	32	5	1.6	400	102	30	40	30
Bench terraces P = 0.05-0.15 <sup>2</sup>	12	8	1	1000	44	12	104	6
	12	16	2	2000	44	12	204	6
	16	6	1	900	58	16	96	8
	16	12	2	1800	58	16	186	8
	24	4	1	750	88	24	84	10
	24	8	2	1500	88	24	159	10
	32	2.8	1	630	125	36	76	13
	32	5.5	2	1270	125	36	140	13
	56	1.4	1	400	250	72	65	22
	56	2.8	2	800	250	72	105	22
Converse terraces P = 0.05-0.15 <sup>2</sup>	5	20	1.0	100	17	5	18	5
	8	16	1.3	125	22	6	22	6
	16	8	1.3	250	44	12	44	13
	32	5	1.3	400	72	20	72	20
Grass strips P = 0.35-0.75 <sup>2</sup>	5	40	-	-	9	2	1	2.5
	8	20	-	-	18	6	3	5
	16	10	-	-	35	10	5	10
	32	5	-	-	70	20	10	20
Trash-lines P = 0.35-0.75 <sup>2</sup>	5	40	-	1	-	-	1	2.5
	8	20	-	2	-	-	2	5
	16	10	-	3	-	-	3	10
	32	5	-	5	-	-	5	20
Stone terraces P = 0.35-0.75 <sup>2</sup>	5	40	0.4	50	-	-	5	1.5
	8	20	0.4	71	-	-	7	3
	16	10	0.4	125	-	-	13	6
	32	5	0.4	235	-	-	24	12

<sup>1</sup> 50% sulphate of ammonia and 50% triple superphosphate.

<sup>2</sup> Guideline ranges for physical protection factor (P) under good management only.

Sources: Derived from Mitchell (1986); A.C. Vlaanderen, FAO, Rome, 1989, pers. comm.

### 5.1.1 Crops and Land Utilization Types

Twenty-five crop species were considered for the study. Coffee, cotton, pineapple, pyrethrum, and tea were the most important crops. The reported production and land use were as follows:



## Chapter 5

## Crop productivity

This chapter describes the crop productivity model. The model is schematically shown in Figure 8, and has five elements:

- i. Land suitability assessment and selection of crop options.
- ii. Formulation of cropping pattern options.
- iii. Formulation of crop rotation options.
- iv. Quantification of productivity potentials of crop rotation options.
- v. Linkage to livestock and fuelwood productivity models.

The model derives its inputs from the climate and soil resources inventories described in Chapter 3, and explicitly formulates options in respect of annual cropping patterns and crop rotations, and quantifies their production potentials at three levels of inputs. The model formulates optimum cropping patterns and quantifies their productivities to meet a given food demand, taking into account desired levels of production 'stability' at the micro-economic level. The crop productivity model, described below, is interlinked with the livestock and fuelwood productivity models described in Chapters 6 and 7, and the three models together constitute the land productivity model.

### 5.1 LAND SUITABILITY ASSESSMENT AND SELECTION OF CROP OPTIONS

Land suitability assessments of single crops are made using the methodologies developed for the FAO-AEZ project (FAO 1978-81), and involve:

- the selection and definition of LUTs (e.g., crop, cropping type, produce, production system, input level);
- the matching of the thermal zones of the climatic inventory with the temperature requirements of the crops, and, where these requirements are met, the computation of agronomically attainable crop yields by LGP and LGP-pattern zones; and
- the matching of the soil requirements of crops with the soil type, texture classes, stoniness, phases and slope classes of the soil inventory, by rating their limitations.

#### 5.1.1 Crops and Land Utilization Types

Twenty-five crop species were considered in the assessment for Kenya, as listed in Table 33. Coffee, cotton, pineapple, pyrethrum, sisal and tea were considered in the model to take account of the reported production and land area occupied by these crops as quantified by the land use

**FIGURE 8**  
**Schematic representation of the crop productivity model**

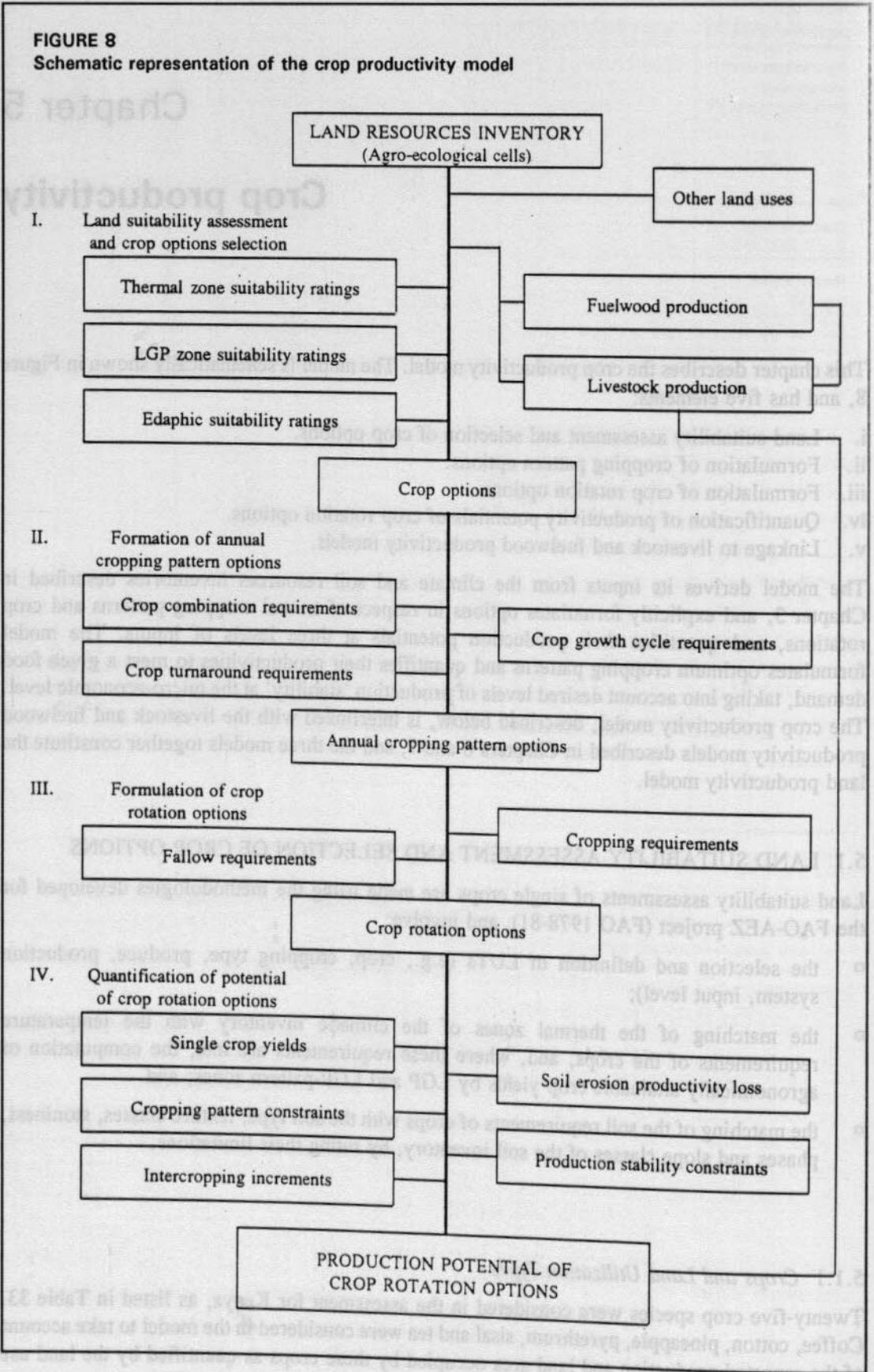


TABLE 33  
List of crops included in the assessment

Crop	Scientific name	Growth cycle (days)	Crop	Scientific name	Growth cycle (days)
Banana	<i>Musa</i> spp.	300-365	Pigeon pea	<i>Cajanus cajan</i>	130-150 150-170 170-190
Barley	<i>Hordeum vulgare</i>	90-120 120-150 150-180	Pineapple	<i>Ananas comosus</i>	330-365
Cassava	<i>Manihot esculenta</i>	150-300	Pyrethrum	<i>Chrysanthemum cinerariifolium</i>	210-330
Coffee, Arabica	<i>Coffea arabica</i>	240-330	Rice, dryland	<i>Oryza sativa</i>	90-110 110-130
Cotton	<i>Gossypium hirsutum</i>	160-180	Rice, wetland	<i>Oryza sativa</i>	80-100 100-120 120-140
Cowpea	<i>Vigna unguiculata</i>	80-100 100-140 160-190	Sisal	<i>Agave sisalana</i>	150-270
Green gram	<i>Vigna radiata</i>	60-80 80-100	Sorghum, lowland	<i>Sorghum bicolor</i>	70-90 90-110 110-130
Groundnut	<i>Arachis hypogea</i>	80-100 100-140	Sorghum, highland	<i>Sorghum bicolor</i>	120-140 140-180 180-200 200-220 220-280 280-300
Maize, lowland	<i>Zea mays</i>	70-90 90-110 110-130	Soybean	<i>Glycine max</i>	80-100 100-140
Maize, highland	<i>Zea mays</i>	120-140 140-180 180-200 200-220 220-280 280-300	Sugarcane	<i>Saccharum officinarum</i>	210-265
Oat	<i>Avena sativa</i>	90-120 120-150 150-180	Sweet potato	<i>Ipomoea batatas</i>	115-125 125-145 145-155
Oil palm	<i>Elaeis guineensis</i>	270-365	Tea	<i>Camelia sinensis</i>	240-365
Pearl millet	<i>Pennisetum americanum</i>	60-80 80-100	Wheat	<i>Triticum aestivum</i>	100-130 130-160 160-180
Phaseolus bean	<i>Phaseolus</i> spp. <sup>1</sup>	90-120 120-150 150-180	White potato	<i>Solanum tuberosum</i>	90-110 110-130 130-170

<sup>1</sup> Includes *Phaseolus vulgaris* (Common bean), *P. lunatus* (Lima bean), *P. coccineus* (Runner bean) and *P. acutifolius* (Tepary bean).

**TABLE 34**  
**Attributes of land utilization types**

Attribute	Low inputs	Intermediate inputs	High inputs
Produce and production	Rainfed cultivation of barley, maize, oat, pearl millet, dryland rice, wetland rice, sorghum, wheat, cowpea, green gram, groundnut, <i>Phaseolus</i> bean, pigeon pea, soybean, cassava, sweet potato, white potato, banana, oil palm and sugarcane. Sole and multiple cropping of crops 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 source	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.

inventory. The remaining 19 crops are differentiated into 58 crop types to accommodate differences in ecotype adaptation, crop phenology and growth cycles within each crop species.

Each of the 58 crop types are considered at three levels of inputs, low, intermediate and high. The attributes of the three input levels are listed in Table 34, and formed the basis for defining the LUTs in the Kenya assessment.

The following conditions apply to the crops considered:

- cereal and legume crops are grown for dry grain production;
- only sorghum varieties with white and yellow grain types are considered;
- only maize varieties with white or yellow endosperm types are considered;
- barley, oat and wheat cultivars are day-length neutral types;
- groundnut is grown for dry kernel production from either sequentially branched cultivars (the Spanish and Valencia types) or alternately branched cultivars (the Virginia and Castle Cary types);
- sugarcane is grown for sugar production using noble cane cultivars;
- banana is grown for fruit (pulp) production using cultivars from genome groups AAA and AAB; and
- oil palm is grown for oil production from fruit mesocarps using the African oil palm stock, and it is assumed that the rotation length is 30 years and time to reach first harvest is 6 years.

### 5.1.2 Climatic Suitability

To enable crops to be matched to climatic conditions, the climatic inventory of Kenya was compiled to permit the interpretation of the climatic resources in terms of their suitability for production of crops. The appropriate climatic adaptability attributes of the crop dictate what parameters need to be taken into account in the compilation of the climatic inventory. The climatic adaptability attributes of crops form the basis of defining the crop climatic requirements, and are outlined below.

#### i. Crop climatic adaptability and requirements.

Crops have climatic requirements for photosynthesis and phenological development, both of which bear a relationship to yield. The rate of crop photosynthesis and growth are related to the assimilation pathway and its response to temperature and radiation. However, the phenological climatic requirements, which must be met, are not specific to a photosynthetic pathway.

In the FAO-AEZ methodology (FAO 1978: Vol. 1), which was based extensively on the work of Kassam, Kowal and Sarraf (1977), crops are classified into climatic adaptability groups according to their fairly distinct photosynthetic characteristics. Each group comprises crops of 'similar ability' in relation to potential photosynthesis, and the differences between land within groups in the response of photosynthesis to temperature and radiation determine crop-specific biomass productivity when climatic phenological requirements are met.

Crop adaptability groups and their characteristic average photosynthetic response to temperature and radiation are presented in Table 35. Barley, oat, wheat, *Phaseolus* bean, and white potato have a C<sub>3</sub> photosynthetic pathway. They belong to group I and are adapted to grow under cool conditions (< 20°C mean daily temperature). Cowpea, green gram, pigeon pea, rice,

**TABLE 35**  
Average photosynthetic response of individual leaves of four groups of crops to radiation and temperature

Characteristics	Crop adaptability group <sup>1</sup>			
	I	II	III	IV
Photosynthetic pathway	C <sub>3</sub>	C <sub>3</sub>	C <sub>4</sub>	C <sub>4</sub>
Rate of photosynthesis at light saturation at optimum temperature (mg CO <sub>2</sub> dm <sup>-2</sup> h <sup>-1</sup> )	20-30	40-50	> 70	> 70
Optimum temperature (°C)	15-20	25-30	30-35	20-30
Radiation intensity of maximum photosynthesis (cal cm <sup>-2</sup> min <sup>-1</sup> )	0.2-0.6	0.3-0.8	> 1.0	> 1.0
Crops included in the Kenya assessment	Barley Oat Wheat <i>Phaseolus</i> bean White potato	Cowpea Green gram Pigeon pea <i>Phaseolus</i> bean Rice Soybean Groundnut Sweet potato Cassava Banana Oil palm	Pearl millet Sorghum Maize Sugarcane	Sorghum Maize

<sup>1</sup> For further information on crop adaptability groups see Tables 3.1 to 3.5 in FAO (1978).

soybean, groundnut, sweet potato, cassava, banana and oil palm also have a C<sub>3</sub> photosynthetic pathway, but belong to group II as they are adapted to grow under warm conditions (>20°C) with a potential rate of photosynthesis that is greater than in group I crops. Crops in group III (pearl millet, lowland sorghum, lowland maize and sugarcane) have a C<sub>4</sub> photosynthetic pathway, and are adapted to grow under warm conditions (>20°C), but with a potential photosynthetic rate that is greater than in group II crops. Crops in group IV (highland sorghum and highland maize) have a C<sub>4</sub> photosynthetic pathway, but are adapted to growth under cool conditions (<20°C) with a potential rate of photosynthesis similar to group III crops.

The time required to form yield has an important influence, and depends on the phenological constraints on the use of time available in the growing period, and the location of yield in the plant (e.g., seed, leaf, stem or root). Temperature has a rate controlling/limiting effect on growth, and it may influence the growth of a specific part and the accumulation of yield if located therein. For example, in wheat, barley and oats, cool night temperatures are required for tillering but the optimum temperatures at the time of flowering and subsequent yield formation are higher. Similarly, optimum temperatures for growth in sugarcane are greater than 20°C, but during the ripening period, and because the yield is located in the stem, a lower temperature, in the range 10-20°C, is required for concentration in the cane of sugar of the right kind. On the other hand, optimum temperatures for growth, development and yield formation in cowpea, green gram and pigeon pea are greater than 20°C and most of the specific temperature requirements are also met when temperatures are optimal for photosynthesis and growth.

**TABLE 36**  
Climatic adaptability attributes of crops

Attributes	Barley	Oat	Cowpea	Green gram	Pigeon pea
Species	<i>Hordeum vulgare</i>	<i>Avena sativa</i>	<i>Vigna unguiculata</i>	<i>Vigna radiata</i>	<i>Cajanus cajan</i>
Photosynthetic pathway	C <sub>3</sub>	C <sub>3</sub>	C <sub>3</sub>	C <sub>3</sub>	C <sub>3</sub>
Crop adaptability group	I	I	II	II	II
Days to maturity	90-120 <sup>1</sup> 120-150 <sup>2</sup> 150-180 <sup>3</sup>	90-120 <sup>1</sup> 120-150 <sup>2</sup> 150-180 <sup>3</sup>	80-100 <sup>4</sup> 100-140 <sup>4</sup>	60-80 <sup>4</sup> 80-100 <sup>4</sup>	130-150 <sup>4</sup> 150-170 <sup>4</sup> 170-190 <sup>4</sup>
Harvested part	Seed	Seed	Seed	Seed	Seed
Main product	Grain (C)	Grain (C)	Grain (L)	Grain (L)	Grain (L)
Growth habit	Determinate	Determinate	Indeterminate	Indeterminate	Indeterminate
Life-span					
— Natural	Annual	Annual	Annual	Annual	Short-term perennial
— Cultivated	Annual	Annual	Annual	Annual	Annual/Biennial
Yield: Cultivated	TI	TI	LI	LI	LI
Formation period	LT	LT	ME	ME	ME
Thermal zone for consideration	3,4,5,6,7	3,4,5,6,7	1,2,3	1,2,3	1,2,3

C - Cereal  
L - Legume  
TI - Terminal inflorescence  
LI - Lateral inflorescence  
LT - Last one third of growth cycle  
ME - Middle to end period of growth cycle

Thermal zones:  
1 - >25.0 °C  
2 - 22.5-25.0  
3 - 20.0-22.5  
4 - 17.5-20.0  
5 - 15.0-17.5  
6 - 12.5-15.0  
7 - 10.0-12.5

<sup>1</sup> thermal zones 3 & 4  
<sup>2</sup> thermal zone 5  
<sup>3</sup> thermal zones 6 & 7  
<sup>4</sup> thermal zones 1, 2 & 3

The attributes that are helpful in assessing the climatic adaptability of the crops in the matching exercise are given in Table 36, for five example crops for adaptability groups I and II. Similar information regarding other crops is given in FAO (1978) and Kassam (1980).

Barley and oat (C<sub>3</sub>-species, group I) are annuals with a botanically determinate growth habit. Their yield is located in terminal inflorescences in seeds, and the crop yield formation period is the last one-third of their growth cycle. Their climatic adaptability attributes qualify them to be considered for matching in areas with mean daily temperatures less than 22.5°C and more than 10°C (i.e., thermal zones 3, 4, 5, 6 and 7).

Cowpea (C<sub>3</sub>-species, group II) is an annual with botanically indeterminate growth habit, with cultivars that may be morphologically determinate (bunch types) or indeterminate (spreading types). Its yield is located in the lateral inflorescences in seeds, and the crop yield formation period is from the middle to the end of its growth cycle. Its climatic adaptability attributes qualify it to be considered for matching in areas with mean daily temperatures greater than 20°C (i.e., thermal zones 1, 2 and 3).

**TABLE 37**  
**Crop growth cycle and thermal regime associations**

Crop	Growth cycle (days)	Thermal regime	
		Range (°C) <sup>1</sup>	Thermal zone
Barley	90-120	17.5-22.5	3,4
	120-150	15.0-17.5	5
	150-180	10.0-15.0	6,7
Maize (lowland)	70-90	> 20.0	1, 2, 3
	90-110	> 20.0	1, 2, 3
	110-130	> 20.0	1, 2, 3
Maize (highland)	120-140	17.5-20.0	4
	140-180	17.5-20.0	4
	180-200	17.5-20.0	4
	200-220	15.0-17.5	5
	220-280	15.0-17.5	5
	280-300	15.0-17.5	5
Oat	90-120	17.5-22.5	3, 4
	120-150	15.0-17.5	5
	150-180	10.0-15.0	6, 7
Pearl millet	60-80	> 20.0	1, 2, 3
	80-100	> 20.0	1, 2, 3
Rice (dryland)	90-110	> 20.0	1, 2, 3
	110-130	> 20.0	1, 2, 3
Rice (wetland)	80-100	> 20.0	1, 2, 3
	100-120	> 20.0	1, 2, 3
	120-140	> 20.0	1, 2, 3
Sorghum (highland)	120-140	17.5-20.0	4
	140-180	17.5-20.0	4
	180-200	17.5-20.0	4
	200-220	15.0-17.5	5
	220-280	15.0-17.5	5
	280-300	15.0-17.5	5
Sorghum (lowland)	70-90	> 20.0	1, 2, 3
	90-110	> 20.0	1, 2, 3
	110-130	> 20.0	1, 2, 3
Wheat	100-130	17.5-22.5	3, 4
	130-160	15.0-17.5	5
	160-190	10.0-15.0	6, 7
Cowpea	80-100	> 20.0	1, 2, 3
	100-140	> 20.0	1, 2, 3
Green gram	60-80	> 20.0	1, 2, 3
	80-100	> 20.0	1, 2, 3
Groundnut	80-100	> 20.0	1, 2, 3
	100-140	> 20.0	1, 2, 3
Phaseolus bean	90-120	17.5-25.0	2, 3, 4
	120-150	15.0-17.5	5
	150-180	12.5-15.0	6

Crop	Growth cycle (days)	Thermal regime	
		Range (°C) <sup>1</sup>	Thermal zone
Pigeon pea	130-150	> 20.0	1, 2, 3
	150-170	> 20.0	1, 2, 3
	170-190	> 20.0	1, 2, 3
Soybean	80-100	> 17.5	1, 2, 3, 4
	100-140	> 17.5	1, 2, 3, 4
Cassava	150-330	> 17.5	1, 2, 3, 4
Sweet potato	115-125	> 20.0	1, 2, 3
	125-145	> 20.0	1, 2, 3
	145-155	> 20.0	1, 2, 3
White potato	90-110	15.0-22.5	3, 4, 5
	110-130	12.5-22.5	3, 4, 5, 6
	130-170	10.0-22.5	3, 4, 5, 6, 7
Banana	300-365	> 17.5	1, 2, 3, 4
Oil palm	270-365	> 22.5	1, 2
Sugarcane	210-365	> 17.5	1, 2, 3, 4
Coffee (Arabica)	240-330	15.0-22.5	3, 4, 5
Cotton	160-180	> 20.0	1, 2, 3
Pineapple	330-365	> 17.5	1, 2, 3, 4
Pyrethrum	210-330	10.0-20.0	4, 5, 6, 7
Sisal	150-270	> 17.5	1, 2, 3, 4
Tea	240-365	12.5-22.5	3, 4, 5, 6

<sup>1</sup> 24-hour mean temperature.

Green gram ( $C_3$ -species, group II) is an annual with botanically an indeterminate growth habit, but with cultivars that may be morphologically determinate in growth and stature. Its yield is located in the lateral inflorescences in seeds, and the crop yield formation period is from the middle to the end of its growth cycle. Its climatic adaptability attributes qualify it to be considered for matching in areas with mean daily temperatures greater than 20°C (i.e., thermal zones 1, 2 and 3).

Pigeon pea ( $C_3$ -species, group II) is a short-term perennial with botanically an indeterminate but morphologically a determinate growth habit. Its yield is located in the lateral inflorescences in seeds, and the crop yield formation period is from the middle to the end of its annual cultivated life-span. Its climatic adaptability attributes qualify it to be considered for matching in areas with mean daily temperatures greater than 20°C (i.e., thermal zones 1, 2 and 3).

#### ii. Thermal Zone Suitability

The association between crop growth cycles and thermal zones in Kenya for the 64 crop types is presented in Table 37. In general, growth cycle length (number of days to maturity) of wheat, barley, oat, *Phaseolus* bean and white potato increases by some 5 to 6 days for each 100 m increase in altitude above 1500 m, or for each 0.5°C decrease in mean temperature

from 20.0°C. In maize and sorghum there is generally about 20 days extension in the time to maturity for each 100 m increase in altitude above 1500 m or for each 0.5°C decrease in mean temperature from 20°C. The 20 days extension in the time to maturity is made up of some 5 to 6 days delay in flowering (silking/anthesis) and some 14 to 15 days extension in the grain filling phase or time taken to reach black layer physiological maturity. For example, 110 and 130 days to maturity correspond respectively to 63 and 69 days to tasselling or heading, 73 and 79 days to silking or anthesis, and 110 and 130 days to physiological maturity.

For wheat, barley, oat, *Phaseolus* bean and white potato, mean temperatures of 10°C to 12.5°C or below have been taken to correspond to a risk of frost damage too great for successful cultivation of these crops. A mean temperature range of 10°C to 12.5°C corresponds to the 2700 - 3100 m altitude range in Kenya.

For maize and sorghum, mean temperatures below 15°C have been considered too low for normal production because of the very severe problems with seed set and maturation. Mean temperatures below 15°C are reached at altitudes of 2350 m and above in Kenya.

The crop thermal zone suitability ratings for each crop type in Kenya are presented in Table 38. Five suitability classes are employed — S1, S2, S3, S4 and N — and the ratings apply to all three levels of inputs: where requirements are fully met, the zone is adjudged S1; where requirements are sub-optimal the zone is adjudged S2, S3 or S4; where requirements are not met, the zone is categorized N (not suitable).

A rating of S1 indicates that the temperature conditions for growth and yield physiology and phenological development are optimal, and that it is possible to achieve the maximum attainable agronomic yield potential if there are no additional climatic and/or edaphic (including landform) limitations. Ratings of S2, S3 and S4 indicate that temperature conditions for growth and development are sub-optimal and that there would be a reduction in yield potential of the order of 25%, 50% and 75% respectively. A rating of N indicates that temperatures are not suitable for production of the crop.

### iii. LGP Zone Suitability

*Individual component LGP suitability.* Potential yields with constraints for individual LGPs were derived according to the method developed by the FAO-AEZ project (Kassam 1977; FAO 1978-81) for all crops except coffee, cotton, pineapple, pyrethrum, sisal and tea. The background details for maize, pearl millet, wetland rice, sorghum, *Phaseolus* bean, soybean, cassava, sweet potato and white potato are given in FAO (1978-81); the details for groundnut, dryland rice, sugarcane, banana and oil palm are given in (FAO 1980); the details for barley, oat, cowpea, green gram and pigeon pea are given in FAO/IIASA (1991: Tech. Annex 3).

Agronomically attainable yield potentials from the agro-climatic viewpoint (i.e., on suitable soils and terrain) for suitable thermal zones (i.e., thermal zones with an S1 rating) are presented in Appendix Table A5.1 for high levels of inputs, Table A5.2 for intermediate inputs and Table A5.3 for low levels of inputs.

Yields in Tables A5.1, A5.2 and A5.3 refer to single crops which act as building blocks in the formulation of annual cropping patterns and crop rotations, taking into account LGP-Patterns and soil and landform constraints. Single crop yields attainable with low inputs are set at 25% of those attainable with high inputs. Single crop yields at the intermediate level of inputs are set half-way between the high and low input yields.

Yields in Table A5.1, A5.2 and A5.3 apply to normal lengths of growing periods, i.e. growing period with a humid period during which precipitation is greater than full potential evapotranspiration. For intermediate growing periods, i.e. growing period with no humid

TABLE 38  
Thermal zones suitability ratings

Crop code	Crop	Growth cycle (days)	Thermal zone								
			T1	T2	T3	T4	T5	T6	T7	T8	T9
011	Barley	90-120	N	N	S3	S1	na	na	na	N	N
012		120-150	N	N	na	na	S1	na	na	N	N
013		150-180	N	N	na	na	na	S2	S4	N	N
021	Maize (lowland)	70-90	S1	S1	S1	N	N	N	N	N	N
022		90-110	S1	S1	S1	N	N	N	N	N	N
023		110-130	S1	S1	S1	N	N	N	N	N	N
031	Maize (highland)	120-140	N	N	N	S1	na	na	N	N	N
032		140-180	N	N	N	S1	na	na	N	N	N
033		180-200	N	N	N	S1	na	na	N	N	N
034		200-220	N	N	N	na	na	na	N	N	N
035		220-280	N	N	N	na	S2	na	N	N	N
036		280-300	N	N	N	na	S2	S4	N	N	N
041	Oat	90-120	N	N	S4	S2	na	na	na	N	N
042		120-150	N	N	na	na	S1	na	na	N	N
043		150-180	N	N	na	na	na	na	na	N	N
051	Pearl millet	60-80	S1	S1	S3	N	N	N	N	N	N
052		80-100	S1	S1	S3	N	N	N	N	N	N
061	Rice (dryland)	90-110	S1	S1	S3	N	N	N	N	N	N
062		110-130	S1	S1	S3	N	N	N	N	N	N
071	Rice (wetland)	80-100	S1	S1	S3	N	N	N	N	N	N
072		100-120	S1	S1	S3	N	N	N	N	N	N
073		120-140	S1	S1	S3	N	N	N	N	N	N
081	Sorghum (lowland)	70-90	S1	S1	S1	N	N	N	N	N	N
082		90-110	S1	S1	S1	N	N	N	N	N	N
083		110-130	S1	S1	S1	N	N	N	N	N	N
091	Sorghum (highland)	120-140	N	N	N	S1	na	N	N	N	N
092		140-180	N	N	N	S1	na	N	N	N	N
093		180-200	N	N	N	S1	na	N	N	N	N
094		200-220	N	N	N	na	S3	N	N	N	N
095		220-280	N	N	N	na	S3	N	N	N	N
096		280-300	N	N	N	na	S3	N	N	N	N
111	Wheat	100-130	N	N	S4	S1	na	na	na	N	N
112		130-160	N	N	na	na	S1	na	na	N	N
113		160-190	N	N	na	na	na	S2	S4	N	N
211	Cowpea	80-100	S1	S1	S3	N	N	N	N	N	N
212		100-140	S1	S1	S3	N	N	N	N	N	N
221	Green gram	60-80	S1	S2	S4	N	N	N	N	N	N
222		80-100	S1	S2	S4	N	N	N	N	N	N
231	Groundnut	80-100	S1	S1	S3	N	N	N	N	N	N
232		100-140	S1	S1	S3	N	N	N	N	N	N
241	Phaseolus bean	90-120	N	S4	S1	S1	na	na	N	N	N
242		120-150	N	na	na	na	S1	na	N	N	N
243		150-180	N	na	na	na	na	S3	S4	N	N

texture of a soil is determined by both its physical and its chemical properties, the

Crop code	Crop	Growth cycle (days)	Thermal zone								
			T1	T2	T3	T4	T5	T6	T7	T8	T9
251	Pigeon pea	130-150	S1	S1	S3	N	N	N	N	N	N
252		150-170	S1	S1	S3	N	N	N	N	N	N
253		170-190	S1	S1	S3	N	N	N	N	N	N
261	Soybean	80-100	S2	S1	S1	S3	N	N	N	N	N
262		100-140	S2	S1	S1	S3	N	N	N	N	N
311	Cassava	150-130	S1	S1	S2	S4	N	N	N	N	N
321	Sweet potato	115-125	S1	S1	S2	S4	N	N	N	N	N
322		125-145	S1	S1	S2	S4	N	N	N	N	N
323		145-155	S1	S1	S2	S4	N	N	N	N	N
331	White potato	90-110	N	N	S4	S1	S1	na	na	N	N
332		110-130	N	N	S4	S1	S1	S2	na	N	N
333		130-170	N	N	S4	S1	S1	S2	S4	N	N
411	Banana	300-365	S1	S1	S1	S3	N	N	N	N	N
421	Oil palm	270-365	S1	S2	N	N	N	N	N	N	N
431	Sugarcane	210-365	S1	S1	S2	S4	N	N	N	N	N
511	Coffee (Arabica)	240-365	N	N	S3	S1	S4	N	N	N	N
521	Cotton	160-180	S1	S1	S3	N	N	N	N	N	N
531	Pineapple	330-365	S1	S1	S1	S3	N	N	N	N	N
541	Pyrethrum	210-330	N	N	N	S3	S1	S2	S4	N	N
551	Sisal	150-270	S1	S1	S2	S4	N	N	N	N	N
561	Tea	240-265	N	N	S3	S1	S2	S4	N	N	N

TABLE 39

Reduction ratings for perennial crops matched to total LGP in days for L2, L3 and L4

Crop	LGP								
	150-179	180-209	210-239	240-269	270-299	300-329	330-364	365-	365+
Cassava	S2	S2	S1	S1	S1	S1	S1	S1	S1
Banana	N	N	N	N	S1	S1	S1	S1	S1
Oil palm	N	N	N	S1	S1	S1	S1	S1	S1
Sugarcane	N	N	S3	S2	S1	S1	S1	S1	S1

period, full crop water requirements cannot be met and yield reductions are assumed to be of the order of 50% on all soils except Fluvisols and Gleysols. The percentage of occurrence of intermediate lengths of growing periods in all LGP-Pattern zones is 100% in LGP zone 1-29 days, 65% in LGP zone 30-59 days, 25% in LGP zone 60-89 days, 10% in LGP zone 90-119 days and 5% in LGP zone 120-149 days (Chapter 3).

*LGP-Pattern suitability.* All annual crops are matched to individual component LGPs, i.e., L1, L2<sub>1</sub>, L2<sub>2</sub>, L3<sub>1</sub>, L3<sub>2</sub>, L3<sub>3</sub>, L4<sub>1</sub>, L4<sub>2</sub>, L4<sub>3</sub> and L4<sub>4</sub>. The LGP-Pattern evaluation for each annual crop is achieved by taking into account all the constituent component lengths in each LGP-Pattern, thus providing a profile of variability in potential yields over time (e.g., average yield, maximum yield, minimum yield). From such information, it is then possible to set the desired level of yield stability (e.g., in terms of percentage difference between maximum yield and minimum yield, or in terms of percentage difference between average yield and minimum yield) in the selection of optimum crops and crop rotations.

Perennial crops (cassava, banana, oil palm, sugarcane) are matched to total lengths of LGPs L1, L2, L3 and L4, with yield potential downgraded as shown in Table 39 for LGP-Patterns L2, L3 and L4. Reduction ratings S1, S2 and S3 in Table 39 correspond to zero, 25% and 50% yield reduction respectively, due to moisture stress. A rating of N represents unsuitable moisture conditions for crop production.

*Cash crops LGP and LGP-Pattern allocation ratings.* For coffee, cotton, pineapple, pyrethrum, sisal and tea in Kenya, allocation ratings by LGP and LGP-Patterns were formulated based on the rules given in FAO/IIASA (1991: Tech. Annex 4) to enable these crops to be allocated to their suitable climatic zones on suitable soils.

*Fluvisols suitability.* Cultivation of Fluvisols is governed by the depth, intensity and duration of flooding which occurs in the low-lying areas of these soils. These flooding attributes are generally controlled, not by the amount of 'on site' rainfall but by external factors, such as the river flood regime, hydrological features of the catchment area and catchment-site relationship. Additionally, cultivation of these soils is normally confined to post-flood periods, the crops being grown on moisture remaining in the soil profile.

Because of these factors, Fluvisols were rated separately for all crops at high, intermediate and low levels of inputs, as presented in FAO/IIASA (1991: Tech. Annex 4).

### 5.1.3 Edaphic Suitability

The edaphic suitability assessment is input-specific and based on:

- matching the soil requirements of crop with the soil conditions of the soil units described in the soil inventory (soil unit evaluation); and
- modification of the soil unit evaluation in respect of limitations imposed by texture, stoniness and phase.

As a medium in which roots grow and as a reservoir for water and nutrients on which plants continuously draw during their life cycle, soils are a primary natural resource and valuable economic asset, requiring protection, conservation and improvement through good husbandry.

The adequate agricultural exploitation of the climatic potential and sustained maintenance of productivity largely depends on soil fertility and management of soil on an ecologically sound basis. Soil fertility is concerned with the ability of the soil to supply nutrients and water to enable crops to maximize their benefits from the climatic resources at a given location. The fertility of a soil is determined by both its physical and its chemical properties, the

understanding of which is essential to the effective utilization of climate and crop resources for optimum production.

In order to assess the suitability of soils for crop production, the soil requirements of crops must be known. Furthermore, these requirements must be understood within the context of limitations imposed by landform and other features which are not part of the soil proper, but may have a significant influence on the use to which that soil could be put.

### i. *Crop Edaphic Requirements and Adaptability*

There are a number of basic soil properties, both internal and external, which affect plant growth. These include:

Internal parameters:

- the soil temperature regime, as a function of the net heat balance of soils resulting from annual, seasonal and daily temperature fluctuations;
- the soil moisture regime, as a function of the water balance of soils as related to the soil's capacity to store, retain, transport and release moisture for crop growth, and/or to the soil's permeability and drainage characteristics;
- the soil aeration regime, as a function of the soil air balance as related to its capacity to supply and transport oxygen to the root zone and to remove carbon dioxide;
- the natural soil fertility regime, as related to the soil's capacity to store, retain and release plant nutrients in such kinds and proportions as required by crops during growth;
- the effective soil depth available for root development and foothold of the crop;
- soil texture, both at the surface and within the whole depth of soil required for normal crop development;
- the absence of soil salinity and of specific toxic substances or ions deleterious to crop growth;
- other specific properties, such as soil tilth as required for germination and early growth;

External parameters:

- soil slope, topography and characteristics determined by the micro- and macro-relief of the soil surface;
- occurrence of flooding in relation to crop susceptibility to flooding during the growing period; and
- soil accessibility and trafficability under certain management systems.

From the basic soil requirements of crops, a number of crop-response-related soil characteristics can be derived. One of these characteristics is, for instance, soil pH. For most crops and cultivars, optimal soil pH is known and can be quantified by a range within which it is not limiting to growth. Outside the optimal range, there is a critical range within which the crop can be grown successfully but with diminished yield. Beyond the critical range, the crop cannot be expected to yield satisfactorily unless special precautionary management measures are taken.

The same holds for other plant soil requirements related to soil characteristics. Many soil characteristics can be defined by a range that is optimal for a given crop, a range that is critical or marginal, and a range that is unsuitable under present technology. As an illustration, Table 40 presents, for five crops, optimal and critical ranges of the following soil characteristics: soil slope, soil depth, soil drainage, flooding, texture and clay type, natural fertility (including cation exchange capacity, percent base saturation and organic matter), salinity, pH, free calcium carbonate content and gypsum content. Such information for a number of other crops is given in FAO (1978-81, 1980).

TABLE 40  
Crop edaphic adaptability inventory

CROP	SLOPE (PERCENT)				DRAINAGE	
	High inputs		Low & Int. inputs		All inputs	
	Optimum	Marginal	Optimum	Marginal	Optimum	Range
Barley	0-8	8-16	0-8	8-24	MW-W	I-SE
Oat	0-8	8-16	0-8	8-24	MW-W	I-SE
Cowpea	0-8	8-16	0-8	8-20	MW-W	I-SE
Green gram	0-8	8-16	0-8	8-20	MW-W	I-SE
Pigeon pea	0-8	8-16	0-8	8-20	MW-W	I-SE

Drainage classes — I = imperfectly drained; MW = moderately well drained; W = well drained; SE = somewhat excessively drained; E = excessively drained.

CROP	FLOODING			TEXTURE		
	All inputs		High inputs	Low & Int. inputs		
	Optimum	Marginal	Optimum	Range	Optimum	Range
Barley	F <sub>0</sub>	F <sub>1</sub>	L-MCs	SL-MCs	L-SC	SL-KC
Oat	F <sub>0</sub>	F <sub>1</sub>	L-C	SL-MCs	L-SC	SL-KC
Cowpea	F <sub>0</sub>	F <sub>1</sub>	SL-SCL	LS-KC	SL-SCL	LS-KC
Green gram	F <sub>0</sub>	F <sub>1</sub>	L-CL	SL-KC	L-CL	LS-KC
Pigeon pea	F <sub>0</sub>	F <sub>1</sub>	SL-SCL	LS-KC	SL-SCL	LS-KC

Flooding classes — F<sub>0</sub> = no floods; F<sub>1</sub> = occasional flooding.

Texture classes — MCs = montmorillonitic clay, structured; C = clay (mixed unspecified); KC = kaolinitic clay; SC = sandy clay; SiCL = silty clay loam; CL = clay loam; SCL = sandy clay loam; L = loam; SL = sandy loam; LS = loamy sand.

CROP	DEPTH (cm)		CaCO <sub>3</sub> (%)		GYPSUM (%)	
	All inputs		All inputs		All inputs	
	Optimum	Marginal	Optimum	Marginal	Optimum	Marginal
Barley	> 50	25-50	0-30	30-60	0-5	5-20
Oat	> 50	25-50	0-30	30-60	0-5	5-20
Cowpea	> 75	50-75	0-20	20-35	0-3	3-15
Green gram	> 75	50-75	0-25	20-35	0-3	3-15
Pigeon pea	> 100	50-100	0-25	20-50	0-3	3-15

CROP	pH		FERTILITY REQUIREMENTS		SALINITY (mmhos/cm)	
	All inputs		All inputs		All inputs	
	Optimum	Range	Range		Optimum	Range
Barley	6.0-7.5	5.2-8.5	moderate		0-8	8-12
Oat	6.0-7.5	5.2-8.2	low/moderate		0-5	5-10
Cowpea	5.2-7.5	5.0-8.2	low/moderate		0-3	3-6
Green gram	5.5-7.5	5.2-8.2	moderate		0-3	3-6
Pigeon pea	5.2-7.5	5.0-8.2	low/moderate		0-3	3-6

TABLE 40 (continued)

CROP	ALKALINITY (ESP)	
	All inputs	
	Optimum	Marginal
Barley	0-35	35-50
Oat	0-30	30-45
Cowpea	0-5	8-12
Green gram	0-5	8-12
Pigeon pea	0-5	8-12

TABLE 41

Relations between basic soil requirements for crops and soil characteristics

Basic soil requirements	Soil characteristics (soil factors)
Moisture availability <sup>1</sup>	- Effective soil depth - Available soil moisture holding capacity - Drainage
Nutrient availability	- Nutrient availability - Soil reaction
Oxygen availability <sup>2</sup>	- Soil permeability - Drainage
Foothold for roots	- Effective soil depth
Salinity	- Soil salinity
Toxicity	- Soil reaction <sup>3</sup>
Accessibility and Trafficability (workability)	- Topsoil consistency and bearing capacity
Soil tilth for species establishment	- Topsoil consistency and bearing capacity

<sup>1</sup> Moisture availability is influenced by climatic factors.

<sup>2</sup> Oxygen availability is influenced by inundation and flooding characteristics.

<sup>3</sup> Chemical properties of soil parent material may also be involved in some cases.

Many of the soil characteristics listed above and in Table 41 are, at least in part, intrinsically related to the soil. This relationship guides the definition of optimal and marginal ranges of the various soil characteristics and so simplifies the subsequent matching of the different soil units with the inventoried soil requirements of crops.

From the basic soil requirements of crops, a number of responses related to soil characteristics have been derived. The correlation between the basic soil requirements listed above and soil characteristics that can be used as soil factors to rate crop performance is given in Table 41.

As explained earlier (Section 3.2.5), the soil units (Table 19) have been defined in terms of measurable and observable properties of the soil itself, and specific clusters of such properties are combined into diagnostic horizons and diagnostic properties. They are also used to rate soil suitability.

## ii. Soil Unit Evaluation

The soil unit evaluation is expressed in terms of suitability ratings based on how far the soil conditions of a soil unit meet the crop requirements under a specified level of inputs. The result is five basic classes for each crop and level of inputs, i.e., very suitable (S1), suitable (S2), moderately suitable (S3), marginally suitable (S4), and not suitable (N).

A rating of S1 indicates that the soil conditions are optimal, and that suppression of potential yields (if any) are assumed to be slight. Ratings of S2, S3 and S4 indicate that soil conditions are sub-optimal for crop production and that potential yields would be suppressed by 25%, 50% and 75% respectively. A rating of N indicates that soil conditions are so limiting that the soil unit is not suitable for crop production.

The ratings for all 25 crops used in the Kenya assessment are presented in FAO/IIASA (1991: Tech. Annex 4).

## iii. Texture Evaluation

The soil unit ratings as given in FAO/IIASA (1991: Tech. Annex 4) apply unmodified if there are no additional limitations imposed by texture.

Soil unit ratings remain unchanged for Arenosols (Q), albic Arenosols (Qa), cambic Arenosols (Qc), ferralic Arenosols (Qf), calcareo-cambic Arenosols (Qkc), luvisol Arenosols (Ql) and vitric Andosols (Tv), since coarse texture limitations are taken into consideration in the soil unit ratings.

Soil unit ratings remain unchanged where textures are medium (fine sandy loam, FSL; sandy loam, SL; loam, L; sandy clay loam, SCL; silt loam, SiL; clay loam, CL; silty clay loam, SiCL; and silt, Si), or fine (sandy clay, SC; silty clay, SiC; peaty clay, PC; and clay, C).

In all other cases, for soil units with coarse textures (sand, S; loamy coarse sand, LCS; fine sand, FS; loamy fine sand, LFS; and loamy sand, LS) the soil unit rating is reduced by 25% for all crops except groundnuts and white potatoes.

## iv. Stoniness and Phase Evaluation

The five basic soil unit ratings noted above apply unless there are additional limitations imposed by stoniness or phase, in which case the ratings are modified in the manner set out in FAO/IIASA (1991: Tech. Annex 4) to reflect effect on yield.

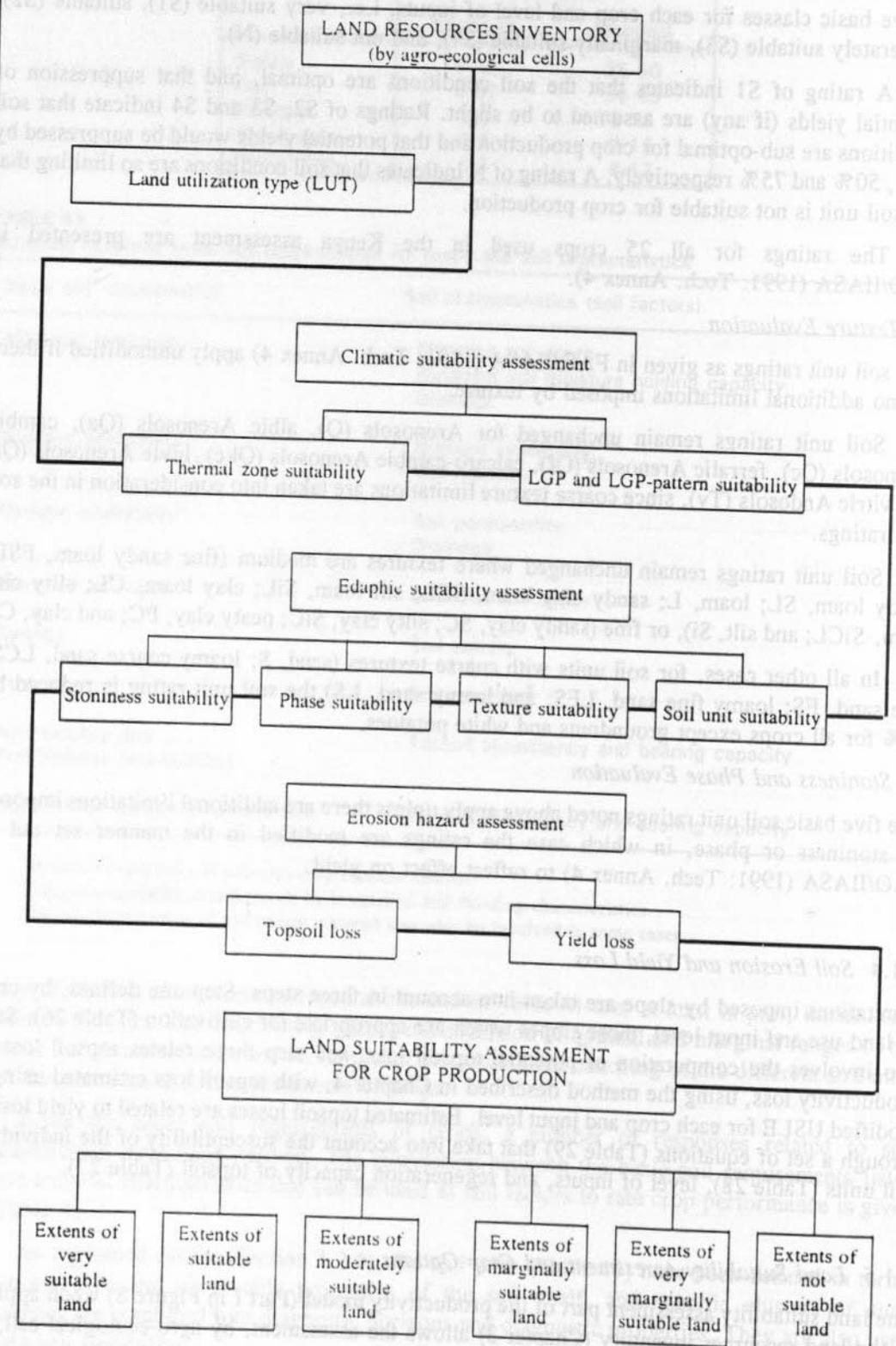
### 5.1.4 Soil Erosion and Yield Loss

Limitations imposed by slope are taken into account in three steps. Step one defines, by crop or land use and input level, those slopes which are appropriate for cultivation (Table 26). Step two involves the computation of potential topsoil loss, and step three relates topsoil loss to productivity loss, using the method described in Chapter 4, with topsoil loss estimated using a modified USLE for each crop and input level. Estimated topsoil losses are related to yield losses through a set of equations (Table 29) that take into account the susceptibility of the individual soil units (Table 28), level of inputs, and regeneration capacity of topsoil (Table 27).

### 5.1.5 Land Suitability Assessment and Crop Options

The land suitability assessment part of the productivity model (Part I in Figure 8) when applied to the land resources inventory (Chapter 3) allows the assessment, by agro-ecological cell, of potential crop performance and consequently crop options to be selected for further processing

**FIGURE 9**  
Schematic presentation of the land suitability assessment model for rainfed crop production



in Part II of the model. At the same time, land that is reserved for other uses, such as cash crops zones, irrigation schemes, forest zones, reservation and conservation areas, is taken into account as appropriate.

All three assessments — climatic suitability, edaphic suitability, soil erosion hazard — are required to determine the ecological land suitability for crop production of each climate-soil unit of the land resources inventory. In essence, the land suitability assessment takes account of all the inventoried attributes of land and compares them with the requirements of the crops, to give a picture that is easy to understand of the suitability of land for crop production.

Land suitability assessment is achieved by working through the steps shown schematically in Figure 9. The assessment is carried out separately for each crop and level of inputs.

First, the photosynthetic and phenological temperature requirements of the crop are compared with the prevailing temperature conditions of each thermal zone. If they do not match, all the LGP zones in that thermal zone are classified as not suitable. If the temperature conditions of a thermal zone partially or fully match the crop thermal requirements, all LGP zones in that thermal zone are considered for further suitability assessment according to the thermal zone rating.

This further assessment comprises application of LGP suitability to the computed areas of the various LGP zones by LGP-Pattern zone. Thus if the thermal zone rating of a particular growing period zone is S1, then potential yield biomass value for the growing period zone is not modified. If the thermal zone rating of the growing period zone is S3, then the potential yield biomass value for the computed extents of the period zone is decreased by 50%. The thermal and moisture suitability assessments are described in Section 5.1.2.

The LGP suitability is applied according to the LGP-Pattern make-up. All annual crops are matched to the individual component LGP, i.e., L1, L2<sub>1</sub>, L2<sub>2</sub>, L3<sub>1</sub>, L3<sub>2</sub>, L3<sub>3</sub>, L4<sub>1</sub>, L4<sub>2</sub>, L4<sub>3</sub> and L4<sub>4</sub>. The LGP-Pattern evaluation for each crop is achieved by taking into account the constituent component lengths of each LGP-Pattern, thus providing a profile of variability in potential yields over time (e.g., average yield, maximum yield, minimum yield). Perennial crops are matched in a similar manner but to total length of growing period, i.e., L1, L2, L3 and L4, and as explained in Section 5.1.2.iii.

The next step is an appraisal of the soil units present in each LGP zone. The rating of soil units, for the crops and levels of inputs under consideration, is applied to the computed area of the growing period zone occupied by each soil unit. The appraisal, undertaken on the basis of the soil ratings as described in Section 5.1.3, leads to appropriate modifications of the climatic suitability assessment and the attainable yield. Subsequently, the ratings for the different soil textures, phases and stoniness are applied consecutively.

Finally, limitations imposed by slope are taken into account to arrive at the final land suitability appraisal for the crops, for the levels of inputs under consideration.

The results of the land suitability assessment are presented as six basic suitability classes, each linked to attainable yields for the three levels of inputs considered. For each level of input, the land suitability classes are: very suitable (VS) —  $\geq 80\%$  of maximum attainable yield; suitable (S) —  $< 80\%$  to  $\geq 60\%$ ; moderately suitable (MS) —  $< 60\%$  to  $\geq 40\%$ ; marginally suitable (mS) —  $< 40\%$  to  $\geq 20\%$ ; very marginally suitable (VmS) —  $< 20\%$  to  $\geq 5\%$ ; and not suitable (NS) —  $< 5\%$ .

The six classes of land suitability are related to attainable yield as a percentage of the maximum attainable under the optimum climatic, edaphic and landform conditions. Thus, for

each land unit, an assessment of crop production potential results, which can be aggregated for any given area.

For Kenya, the generalized results of land suitability assessment at the intermediate level of inputs for cowpea are presented in Plate 14.

For a crop to qualify for selection to the list of crop options for a particular agro-ecological cell, its attainable yield in that cell must be more than the 'threshold' or critical minimum percentage of the maximum attainable potential yield, after taking into account limitations due to climate, soil and erosion hazards.

The threshold minimum yield percentage parameter is a model variable, and was set at 20% for the Kenya study to include the suitability classes VmS and NS. Thus land whose yield potential for any crop was less than 20% of its maximum attainable yield was regarded as not suitable for production of that crop. Instead, the land would be set aside for subsequent consideration, in Part V of the model, for livestock and fuelwood production (Chapters 6 and 7).

The introduction of a threshold minimum yield potential allows the identification of a 'gross' list of crop options from which a further selection of crops can be made based on additional selection criteria or constraints. In the model, these additional criteria (a model variable) can be set as required, depending on the objective function driving the productivity model.

## 5.2 FORMULATION OF CROPPING PATTERN OPTIONS

The land suitability assessment part of the crop productivity model (Part I of Figure 8) allows the selection of single crops to be made, for each agro-ecological cell, according to their yield potentials in the cell. The overall objective of the crop productivity model is to quantify productivity potential of each agro-ecological cell from the whole growing period, or all growing periods per year, and not just single crops from a part of the growing period.

The next step in the model (Part II) is therefore the formulation of cropping pattern options. This is achieved by incorporating the features of multiple cropping using the input-specific information on land suitabilities and crop options generated through Part I of the model. Once annual cropping pattern options have been formulated, it is then possible to specify cropping pattern constraints and fallow requirements for each cropping pattern.

### 5.2.1 Multiple Cropping

Multiple cropping is the intensification of cropping in the space and time dimensions, i.e., growing two or more crops on the same land in a year (Table 42). The various patterns of multiple cropping reflect essentially two underlying principles: that of growing individual crops in sequence — sequential cropping — or of growing crops simultaneously in mixtures — intercropping. Double (and triple, etc.), relay and ratoon cropping all work on the former principle, while mixed, row, strip and alley cropping use the latter. There are several other forms of multiple cropping patterns, but these originate through synthesis of the sequential and simultaneous cropping practices. Some of the related terminology used to describe multiple cropping systems is given in Table 43.

Crops are grown sequentially one after another so that time is used to obtain more production, or crops can be mixed and grown together simultaneously intercropped. With the latter, since the participating crops have different growth requirements, a mixture of crops of similar length to maturity can have higher productivity than a single crop. However, crops

TABLE 42

Definitions of the principle multiple cropping patterns (Andrews and Kassam 1976)

Multiple cropping	The intensification of cropping in time and space dimensions. Growing two or more crops on the same field in a year.
1. Sequential cropping	Growing two or more crops in sequence on the same field per year. The succeeding crop is planted after the preceding crop has been harvested. Crop intensification is only in the time dimension. There is no intercrop competition. Farmers manage only one crop at a time in the field.
2. Intercropping	Growing two or more crops simultaneously on the same field. Crop intensification is in both time and space dimensions. There is intercrop competition during all or part of crop growth. Farmers manage more than one crop at a time in the field.

TABLE 43

Related terminology used in multiple cropping systems (Andrews and Kassam 1976)

1. Sole Cropping	One crop variety grown alone in pure stands at normal density. Synonymous with solid planting; opposite of intercropping.
2. Sequential Monoculture	The repetitive growing of the same sole crop on the same land in a year.
3. Sequential Multiculture	The repetitive growing of different sole crops on the same land in a year.
4. Cropping Pattern	The yearly sequence and spatial arrangement of crops or of crops and fallow on a given area.
5. Cropping System	The cropping patterns used on a farm and their interaction with farm resources, other farm enterprises, and available technology which determine their make-up.
6. Land Equivalent Ratio (LER)	The ratio of the area needed under sole cropping to one of intercropping at the same management level to give an equal amount of yield. LER is the sum of the fractions of the yields of the inter-crops relative to their sole crop yields.

commonly used in mixtures usually differ in maturity, so their growth requirements are further separated in time, and competition between them is lower.

The principle of yield increases resulting from a better use of time with crops in sequence is complementary to increases arising from a more efficient use of space with crops in mixture. Theoretically, therefore, maximum cropping should be obtained with sequences of high-yielding cultivars of crops in compatible mixtures. In practice, this pattern has evolved in relation to traditional resources at low and intermediate inputs, where several crops are planted and harvested in mixtures at different times.

The practice of multiple cropping has been reviewed (Andrews and Kassam 1976; Kowal and Kassam 1978; Kassam 1980), and the important rainfed cropping patterns, generalized according to thermal zones and LGPs, are given in Table 44. Advantages from intercropping

TABLE 44

Important rainfed cropping patterns generalized according to thermal zones and LGP zones

LGP (days)	Thermal zone		
	T1, T2, T3	T4, T5	T6, T7
< 120	SC <sub>as</sub> (I <sub>a</sub> )	SC <sub>as</sub> (I <sub>a</sub> )	SC <sub>as</sub>
120-210	SC <sub>as</sub> I <sub>a</sub> + I <sub>d</sub> (S <sub>mo</sub> + S <sub>mu</sub> )	SC <sub>as</sub> I <sub>a</sub> + I <sub>d</sub>	SC <sub>as</sub> I <sub>a</sub>
210-270	SC <sub>a1</sub> I <sub>a</sub> + I <sub>d</sub> S <sub>mo</sub> + S <sub>mu</sub>	SC <sub>a1</sub> I <sub>a</sub> + I <sub>d</sub> (S <sub>mo</sub> + S <sub>mu</sub> )	SC <sub>a1</sub> I <sub>a</sub> + (I <sub>d</sub> )
270-365	SC <sub>a1</sub> + SC <sub>p</sub> I <sub>d</sub> + I <sub>a</sub> S <sub>mo</sub> + S <sub>mu</sub>	SC <sub>a1</sub> + SC <sub>p</sub> I <sub>d</sub> + I <sub>a</sub> (S <sub>mo</sub> + S <sub>mu</sub> )	SC <sub>a1</sub> + SC <sub>p</sub> I <sub>a</sub> + I <sub>d</sub> (S <sub>mo</sub> + S <sub>mu</sub> )

Note: Brackets indicate minor status.

Key: SC<sub>as</sub> — Sole cropping of annual short-duration crops; SC<sub>a1</sub> — Sole cropping of annual long-duration crops; SC<sub>p</sub> — Sole cropping of perennial crops; I<sub>a</sub> — Intercropping with crops of similar lengths of maturity; I<sub>d</sub> — Intercropping with crops of different lengths of maturity; S<sub>mo</sub> — Sequential monoculture; S<sub>mu</sub> — Sequential multiculture.

are numerous. These include better or fuller use of production resources of water, nutrients, heat, radiation, space and time; better distribution pattern of labour demands; better security of production; better control of pests, diseases and weeds in the absence of or sub-optimal use of biocides; better control of soil erosion; and extra yield advantages (i.e., LER > 1.0). Any of these attributes, either singly or in combination, may make intercropping attractive to farmers; and even where there may be no extra yield advantages, intercropping may still be normally practised because security of production is often a good enough reason for intercropping.

#### i. Sequential Cropping.

Sequential cropping is possible in areas where conditions for crop growth exist beyond the duration of one crop, either due to a longer growing period or due to more than one growing period.

In the frost-free areas in Kenya, the restriction to sequential cropping is one of availability of soil moisture. In the areas with a longer growing period, as in the moist sub-humid (growing period 210-270 days) and humid (> 270 days) areas, crop growth is possible throughout much of the year. It is in such areas that a strong association with sequential cropping emerges, and sequential crops in both monoculture and multiculture are involved (Table 44). However, because of the cool temperatures in thermal zones T6 and T7, sequential cropping is of minor importance because the annual crops that are adapted to the prevailing conditions are generally slow to reach maturity.

#### ii. Intercropping.

In areas with LGP < 120 days, sole cropping of short duration annual crops is dominant in all thermal zones. Some simultaneous cropping is practised with crops with similar maturation periods, but its status in thermal zones T1, T2, T3, T4 and T5 is a minor one. In thermal zones T6 and T7, growing conditions only permit a moderate to marginal production from sole cropping of single crops.

In areas with LGPs between 120 and 210 days, crop mixtures, including those involving crops of different maturation periods, are common in thermal zones T1, T2, T3, T4 and T5. Because of the cool temperatures in T6 and T7, crop mixtures involving crops of similar maturation periods are common.

In areas with LGPs >270 days, crop mixtures, especially those involving crops with different maturation periods, are common. In such areas, the slow growing and later maturing components generally tend to mature under better end-of-season moisture conditions. In these areas, multiple cropping, both simultaneous and sequential, is practised.

### 5.2.2 *Cropping Pattern Options*

The cropping pattern options in Part II of the productivity model (Figure 8) are formulated in three steps:

- i. Fitting crop growth cycles into prevailing component LGPs for each agro-ecological cell. For all annual crops except wetland rice, cropping patterns are made up by fitting growth cycle lengths (full or partial) to total component LGP. Where crop growth cycle is curtailed due to inadequate LGP, it may still be considered acceptable provided the crop is able to offer a yield.

For wetland rice, growth cycle lengths are matched to the humid period of each component length. For areas with year-round humid LGPs, the humid period is also year-round. For normal LGPs, the humid period is approximately 45 days shorter than the total length. For intermediate LGPs, there is no humid period.

For cassava and the perennial crops of banana, sugarcane and oil palm, the length of crop growth cycle is taken to be equal to the LGP, provided the minimum acceptable growth cycle length can be fitted.

The above matching process is applied, in each agro-ecological cell of the land resources inventory, to all component LGPs of each LGP-Pattern. This procedure allows the identification of cropping patterns for the complete range of annual cropping periods, including the worst and the best expected, in a given area; and within each year for the different expected LGPs, including the shortest and the longest.

- ii. The 'turn-around' time between crops, within sequential cropping patterns, needed to harvest the first crop, prepare the land and sow the subsequent crop, is then incorporated. The turn-around parameter is a model variable and can be modified as required. For annuals, a turn-around period of 10 days has been assumed. For banana and sugarcane a turn-around time of 15 days has been assumed in the year-round LGP zones.
- iii. The third step is to decide for which levels of inputs and for which crops intercropping is acceptable.

In the model as applied to Kenya, intercropping was considered only at the low and intermediate input levels for all crops except wetland rice, sugarcane, banana and oil palm.

### 5.3 FORMULATION OF CROP ROTATION OPTIONS

Once annual cropping patterns or crop combinations for each agro-ecological cell in each LGP-Pattern have been formulated, Part III of the crop productivity model (Figure 8) formulates crop rotation options. This is done by taking into account crop combination restrictions in space

and time of cropping patterns, and fallow requirements of crop combinations that have been selected to participate in the annual cropping patterns.

These two model variables provide for sustainability of production in the longer term. Additionally, they contribute (together with yield limits imposed in the selection of single crops in Part I of the model, and the production stability parameter imposed on the selection of rotations in Part IV) to the overall stability of production system.

### 5.3.1 Crop Combination Requirements

It is necessary to impose certain crop combination restrictions (as a model variable) for dryland cropping patterns to avoid continuous monocropping. It is also advisable to make a provision for biological nitrogen fixation in the cropping patterns at the low input level.

At this stage of the model development, the reference crop combination restrictions are that no crop combination should occupy more than a two-thirds share of the total cropping area during any year (i.e., total cropping hectare-days available in the agro-ecological cell). The remaining one-third of the annual cropping share of the total hectare-days will be occupied by another crop combination determined on the basis of where the crop combination (i.e., cropping pattern) occupying the two-thirds area is made up of non-leguminous crops, the remaining one-third of the cropping area should be occupied by a crop combination comprising legume crops under the low input situations, while under intermediate and high inputs, it should consist of non-cereal crops if the major crop is a cereal; non-leguminous crops if the major crop is a legume; and non-tuber crops if the major crop is a tuber.

For wetland rice, the above restriction is not imposed and all of the annual cropping time of an area could be considered for monocultural cropping, if required. Similarly, the restrictions are not applied to cassava and the perennial crops of banana, sugarcane and oil palm.

The restrictions for annual and perennial crops may be modified if it is desired that a certain proportion of the area of an agro-ecological cell or a group of agro-ecological cells be set aside for specific crops, or where the demand parameter in the objective function imposes a restriction on the types of products that are required.

### 5.3.2 Fallow Requirements

In their natural state, many soils cannot be continuously cultivated without undergoing degradation. Such degradation is marked by a decrease in crop yields and a deterioration in soil structure, nutrient status and other physical, chemical and biological attributes.

Under traditional farming systems, this deterioration is kept in check by alternating some years of cultivation with periods of fallow. The length of the necessary fallow is dependent on levels of inputs, soil and climatic conditions, and cropping history. However the prime reason for incorporating fallows into crop rotations is to enhance sustainability of production through maintenance of soil nutrient fertility.

Nutrient fertility of soils (i.e., the ability of soils to supply nutrients to crops) under traditional subsistence farming (corresponding to LUTs with low inputs) depends mainly on the soil organic matter present as humus.

The amount of humic organic matter in soils depends on the relative rates of addition of organic residues and their subsequent breakdown. The relative rates are related to the type,

extent and duration of growth of vegetation (natural or crop) and activity of soil organisms, all of which are influenced by soil and climatic conditions.

Maintenance and regeneration of nutrient fertility of land under subsistence low input cultivation is achieved through natural bush or grass fallow. With intermediate inputs LUTs, providing higher inputs to soils, soil fertility is maintained through a fallow which may include, for a portion of the time, a grass or grass-legume ley or a green manure crop.

Factors affecting changes in soil organic matter are reviewed in Nye and Greenland (1960) and in Kowal and Kassam (1978). They include temperature, rainfall, soil moisture and drainage, soil parent material, and cultivation practices.

In the Kenya work, the fallow requirements were derived for the inventoried environmental conditions for four main groups of crops: cereals, legume seed crops, roots and tubers, and banana and sugarcane (FAO/IIASA 1991). The environmental frame used consists of individual soil units, thermal regimes, represented by thermal zone T1 ( $T_{\text{mean}} > 25^{\circ}\text{C}$ ), T2 and T3 ( $T_{\text{mean}} 20^{\circ}\text{-}25^{\circ}\text{C}$ ), T4 and T5 ( $T_{\text{mean}} 15^{\circ}\text{-}20^{\circ}\text{C}$ ) and T6, T7 and T8 ( $T_{\text{mean}} 5^{\circ}\text{-}15^{\circ}\text{C}$ ), and moisture regime, represented by LGP zones 60-89, 90-119, 120-179, 180-269 and 270-365 days.

Basic values of fallow requirements (F), expressed as the percentage of the time of one cropping-fallow cycle (i.e.,  $(t_f/(t_c + t_f)) \times 100$ ) during which the land must be put under fallow, for the low input LUTs were first calculated. These reference values were then modified depending on the particular crop, and the Fertility Capability Classification (Fcc) of the soil (Sanchez, Couto and Buol 1982).

The basic length of fallow period was taken as that needed for LGPs between 120 and 269 days. For LGPs  $> 270$  days the reference fallow period is 50% greater than the basic, due to additional problems with weeds, pests and diseases, and leaching and erosion. Similarly, for LGP 90-119 days, fallow requirements are greater than the basic by 25% due to additional problems with fallow establishment from dry conditions, and degradation hazards, and for LGP 60-89 days, 50% greater due to problems with fallow establishment, degradation hazards and the need to conserve moisture.

For moderately warm and moderately cool temperature regimes (T2, T3, T4, T4 and T5 zones) all reference values are reduced by 25% due to lower pest and disease problems and better fallow establishment conditions. For cool temperature regimes (T6, T7, and T8 zones), reference values remain unchanged because temperature constraints on the rate of fallow establishment are considered to outweigh any advantages from less pest and disease problems.

Fallow requirements for Fluvisols and Gleysols are less because of their special moisture and fertility conditions.

Fallow requirements (F) for all suitable soil units are presented in FAO/IIASA (1991: Tech. Annex 4) for the low input levels of cereals, grain legumes, roots and tubers, and banana and sugarcane. Fallow requirements at the intermediate input levels are taken as one-third of those at the low level, while at the high level of inputs, fallow requirements are set at 10%.

For wetland rice on Fluvisols, fallow requirements are assumed to be 10% for all the three levels of input. For Gleysols, fallow requirements are 40% at the low and intermediate levels, and 10% at the high level.

For long-term perennial crops (i.e., oil palm, coffee, tea and sisal in Kenya), fallow requirements are assumed to be nil. For short-term perennials (i.e., pineapple, pyrethrum) and cotton, fallow requirements are similar to those for cereal crops.

The fallow factors have been verified against available published data and similar work done earlier by Young and Wright (1980) in the context of FAO's regional assessments.

### 5.3.3 *Crop Rotation Options*

In Part III of the productivity model (Figure 8), crop rotation options are formulated for each agro-ecological cell for each cropping pattern option generated in Part III of the productivity model. This is accomplished in two steps. Firstly the appropriate crop combination restrictions are applied to rule out risky or undesired crop combinations on space or time grounds, and secondly to incorporate the appropriate fallow requirements for each suitable cropping pattern.

With cropping patterns comprising more than one crop, average fallow requirements for the crops concerned are applied to define the rotations.

At the same time, Part III of the productivity model defines the extent of fallow land and therefore the portion of biomass that can be used for livestock production in Part V of the model (Chapter 6).

## 5.4 QUANTIFICATION OF PRODUCTIVITY POTENTIALS OF CROP ROTATIONS

In Part IV of the crop productivity model (Figure 8), productivity potentials for each agro-ecological cell for each crop rotation option are quantified in three steps.

Step one quantifies the sequential crop yields of each of the crop rotation options. Step two incorporates the intercropping yield increments, and step three applies the production stability constraints (and any other constraints) as criteria for selecting optimum crop rotations and productivities. Part IV also provides an estimate of potential crop residues, crop by-products and crop primary products that can be made available for livestock production.

### 5.4.1 *Sequential Crop Yields*

Sequential cropping is possible in areas where there is either a long continuous growing period or where there are more than one growing period separated in time due to a marked bimodal (or trimodal) pattern of rainfall distribution.

A sequential cropping pattern could be either monoculture or multiculture. In the former case (e.g., two crops of rice, or white potato), participating crops are of the same adaptability group. In the latter case, the second crop may be different but may belong to the same thermal adaptability group with a similar photosynthetic adaptability response to temperature and radiation (e.g., groundnut followed by cowpea, or pearl millet followed by lowland maize, or wheat followed by white potato), or a different thermal adaptability group (e.g., groundnut followed by lowland maize).

It is therefore an overriding condition that all crops participating in ecologically suitable and desired cropping patterns must first themselves be ecologically suitable. Accordingly, in Part I of the model, a crop type is only permitted to participate in the formulation of a reference crop rotation if its minimum yield (with climate, soil and landform constraints) for the chosen inputs level is more than 20% of its potential maximum attainable yield. Reference yields, including maximum yields, for situations with no thermal or soil constraints for all crops are given in Appendix Tables A5.1, A5.2 and A5.3 for high, intermediate and low levels of inputs respectively.

**TABLE 45**  
Yield reductions (%) of a crop when grown as second or third crop in the annual cropping pattern relative to its yield as a first crop

Crop position	Crop yield as first crop (% of maximum)			
	20 - 40	40 - 60	60 - 80	80 - 100
2 <sup>nd</sup>	50	25	25	25
3 <sup>rd</sup>	75	50	25	25

The reference crop yields in Tables A5.1, A5.2 and A5.3 apply (after taking into account climate, soil and erosion constraints) when the crops are considered as single, sole crops in the component growing period (i.e., no sequential cropping), or occupy the first position as sole crop in the annual sequential cropping patterns.

Two additional parameters are incorporated in the model (before single crop yields can be applied to quantify sequential crop yields) to take into account:

- i. the increased agroclimatic constraints (e.g., increased pest and diseases, increased workability constraints) on crops when they are positioned second or third in the cropping sequence instead of being first; and
- ii. those situations when the yield formation period of the crop in the cropping sequence cannot be fully accommodated within the time available for cropping, resulting in a partial yield loss (as opposed to total crop loss).

To allow for the increased agroclimatic constraints for crops in cropping patterns with two or three crops, single sole crop yields of the second and the third crop are downgraded, as shown in Table 45, relative to their yield as the first crop. Of the 58 crop types considered in the model as applied in Kenya, cassava, sugarcane, banana and oil palm do not have the possibility of taking up a second crop position in an annual cropping pattern.

Where crops cannot complete their yield formation within the time available, yield reductions are made proportionate to the decreases in the yield formation periods. The yield formation periods for cereal, grain legumes and roots and tuber crops are assumed as one-third, one-half and two-thirds respectively of their corresponding total length of normal growth cycle. This assumption is also made in defining the climatic adaptability of crops and in the calculation of net biomass and yields of crops (FAO/IIASA 1991).

#### 5.4.2 Intercropping Increments

The extent of the extra contribution to production per unit area from intercropping has been described by Kassam (1980). In practice, farmers select compatible mixtures with LER values of greater than 1.0 except in situations where intercropping is still advantageous for reasons other than extra yields.

Reference LER values which have been applied in the model are given in Table 46. Based on evidence from surveys and experiments, it is assumed that intensifying crop production through intercropping would have its limits. At the high input level, the primary disadvantage of intercropping is the difficulty of applying mechanization, and in effectively conducting some of the cultural operations. This generally restricts the widespread use of intercropping in large farm systems, particularly when under such systems most of the advantages of intercropping no longer apply. It is, therefore, suggested that at high input levels, there should be no extra yield

TABLE 46

Suggested LERs at different levels of inputs by LGP and crop yield relative to maximum attainable yield

LGP (days)	Inputs/Relative crop yield									
	Low					Intermediate				
	< 0.2	0.2- 0.4	0.4- 0.6	0.6- 0.8	0.8- 1.0	< 0.2	0.2- 0.4	0.4- 0.6	0.6- 0.8	0.8- 1.0
< 120	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
120-270	1.0	1.1	1.2	1.2	1.3	1.0	1.05	1.1	1.1	1.15
> 270	1.0	1.2	1.3	1.3	1.4	1.0	1.1	1.15	1.15	1.2

advantages (LER=1.0) in production over and above that which is already reflected by sole crop yields.

At the low input level, the most complex patterns, that are also potentially the more productive, would eventually require so much labour and other resources that even the small farmer may only use them occasionally on a small part of his land. Furthermore, it is most likely that the extra yield advantages claimed under experimental conditions (e.g., LER=1.3-1.5 in LGPs 120-270 days, LER=1.85 in LGPs > 270 days) with their accompanying 'high' inputs would decrease by about 50% under field conditions at the low input level. However, it is postulated that the extra yield advantages from intercropping would increase with increasing LGP; and that the maximum advantages should be with mixtures where the individual component crops are very suitably adapted to the prevailing climate and soil environment.

It is therefore suggested (as model variables in Table 46) that for LGP zones with less than 120 days, there would be no significant extra yield advantages (LER=1.0) from intercropping. The single sole crop yields are considered to adequately reflect the production potential.

For LGP zones with more than 120 days, the model has been modified for all crops except wetland rice, sugarcane, banana and oil palm, such that for LGP zones 120 to 270 days under low input levels there is a 30% extra yield advantage (LER=1.3) from intercropping when attainable yields (from Part I of the model) of the individual participating crops are 80% or more of the potential maximum attainable yields. This yield advantage is reduced to nil (LER=1.0) for participating crops with attainable yields that are less than 20% of the maximum attainable.

For LGP zones with more than 270 days, there is 40% extra yield advantage (LER=1.4) from intercropping when the attainable yields of the individual participating crops are 80% or more of the potential maximum attainable yields. This yield advantage is reduced to nil (LER=1.0) for participating crops with attainable yields that are less than 20% of the maximum attainable.

For intermediate input levels, yield advantages from intercropping are taken as half of those at the low inputs level, while for wetland rice, sugarcane, banana and oil palm, an LER of 1.0 has been applied.

#### 5.4.3 Production Stability Constraints

It is necessary to state the level of production stability, e.g., the tolerable difference between minimum (worst year) and maximum (best year) production, or the tolerable soil erosion rate

for the cropping patterns and rotations that are selected to meet food and other demands specified by the objective function. These constraints are introduced as model variables in the selection of cropping patterns and crop rotations and the quantification of production therefrom.

In the model, the desired level of production stability between minimum and maximum production is set at 75%. This means that the production variations from year-to-year from the selected cropping patterns would not exceed 25%.

#### 5.4.4 Crop Productivity Potential

When the crop productivity model is applied to the land resources inventory, crop productivity potentials of each agro-ecological cell are quantified taking into account the requirements and constraints imposed at the various stages in the model. Results of the crop productivity assessment at district level for Kenya are presented in FAO/IIASA (1991: Tech. Annex 8).

To be able to use the crop productivity potentials for planning, it is necessary to take into account the waste factor and the amount of production which is required as seed and therefore not available to enter the animal and human food chain. The waste factor, covering post harvest losses during food processing and in the food delivery system, has been taken as 10% and can be varied as required. The seed factors for crops are given in FAO/IIASA (1991: Tech. Annex 4), and are part of the input technology matrix (Bruinsma *et al.* 1983). They are applied after applying the waste factor, to arrive at the net production available.

The demand for food is expressed in terms of calorie and protein. The calorie and protein conversion factors for food products are given in FAO/IIASA (1991; Tech. Annex 4).

Once crop productivity potentials are quantified, it is possible to quantify crop residues, crop by-products, or crop primary products which may be, or need to be made, available for livestock production, as considered in Section 6.1.6.

### 5.5 LINKAGE WITH FUELWOOD AND LIVESTOCK PRODUCTIVITY MODELS

Part V of the crop productivity model (Figure 8) deals with the linkage with fuelwood and livestock productivity models. The linkage, in essence, allows the possibility of considering:

- fuelwood production on land assessed as not suitable for crops in Part I of the model;
- fodder from fuelwood trees for livestock production;
- fallow land, defined in Part III of the model, for livestock production because of the fodder potential of fallows; and
- crop residues, crop by-products and crop primary products, quantified in Part IV of the model, for livestock production.

#### 5.5.1 Fuelwood Productivity Model

The fuelwood productivity model, described in Chapter 7, is basically a land suitability assessment model, similar to Part I of the crop productivity model, which quantifies land potentials for individual fuelwood tree species at three levels of inputs.

Additionally, any portion of crop land may be considered for fuelwood production depending on how much land is required for crops, livestock and other land uses.

### 5.5.2 Fodder from Fuelwood Land

Any land which is allocated to fuelwood production using species that offer palatable fodder would have the potential for contributing a portion of the fodder for livestock production.

Fuelwood species suitable for Kenya and which offer palatable fodder to livestock are listed in Chapter 7. The amount of fodder which can be utilized by stock without affecting fuelwood yields would depend on the species and the ecological situation. However, at this stage of the model interlinkage development, it is assumed that about 10% of the foliage may be utilized by stock without affecting fuelwood yields. This nominal value may be modified as appropriate according to species and environment.

### 5.5.3 Fodder Potential of Fallow Land

It is assumed that low input level fallow land would be under bush or natural grass vegetation, whereas with intermediate and high input levels, fallow land would be under sown pasture. Biomass production potentials of sown or natural permanent pasture are assessed in the livestock productivity model described in Chapter 6.

At this stage of the model development, it is assumed, as a model variable, that the biomass production potential of natural grass fallow under low inputs and the sown grass fallow under intermediate and high inputs, is one-third of that quantified for normal permanent or sown pastures. Also, it is assumed that only 50% of the biomass may be consumed by stock.

## Chapter 6

# Livestock productivity

This chapter describes the livestock productivity model shown schematically in Figure 10. It has been conceptualized and applied within the framework of land evaluation guidelines (FAO 1976, 1991), and follows the FAO Agro-ecological Zones (FAO-AEZ) approach to quantifying land resources and assessing land use potentials (FAO 1978-81; Blair Rains and Kassam 1980).

The livestock productivity model has five parts, and operates on the land resources inventory described in Chapter 3:

- i. Estimation of feed supply potential (primary productivity).
- ii. Characterization of livestock systems.
- iii. Determination of herd performance.
- iv. Estimation of feed requirements.
- v. Quantification of livestock productivity potential (secondary productivity).

### 6.1 ESTIMATION OF FEED SUPPLY

Animals require an uninterrupted and adequate supply of nutritively satisfactory feed. Part I of the livestock productivity model (Figure 10) deals with the estimation of feed supply from different sources. A wide variety of plant biomass can be eaten by domestic herbivores, but the important sources of feed are the grasses, a small number of herbaceous legumes, leaves and fruits of many shrubs and trees, fodder crops, crop residues, crop by-products and primary products (e.g., grain).

#### 6.1.1 Sources of Feed

At any given location, the ecological potential of one or more of the following sources of feed needs to be quantified for each agro-ecological cell of the land resources inventory (Figure 10).

- (1) Grassland or pastures (permanent, long- or short-term grass-legume mixtures, natural or sown).
- (2) Browse (natural woody vegetation of shrubs and trees).
- (3) Fodder from bush and managed fallows within crop rotations (natural or sown grass-legume mixtures).
- (4) Sown fodder crops, including grasses, legumes and cereals.

FIGURE 10

Schematic presentation of the combined sources of feed supply and livestock productivity models

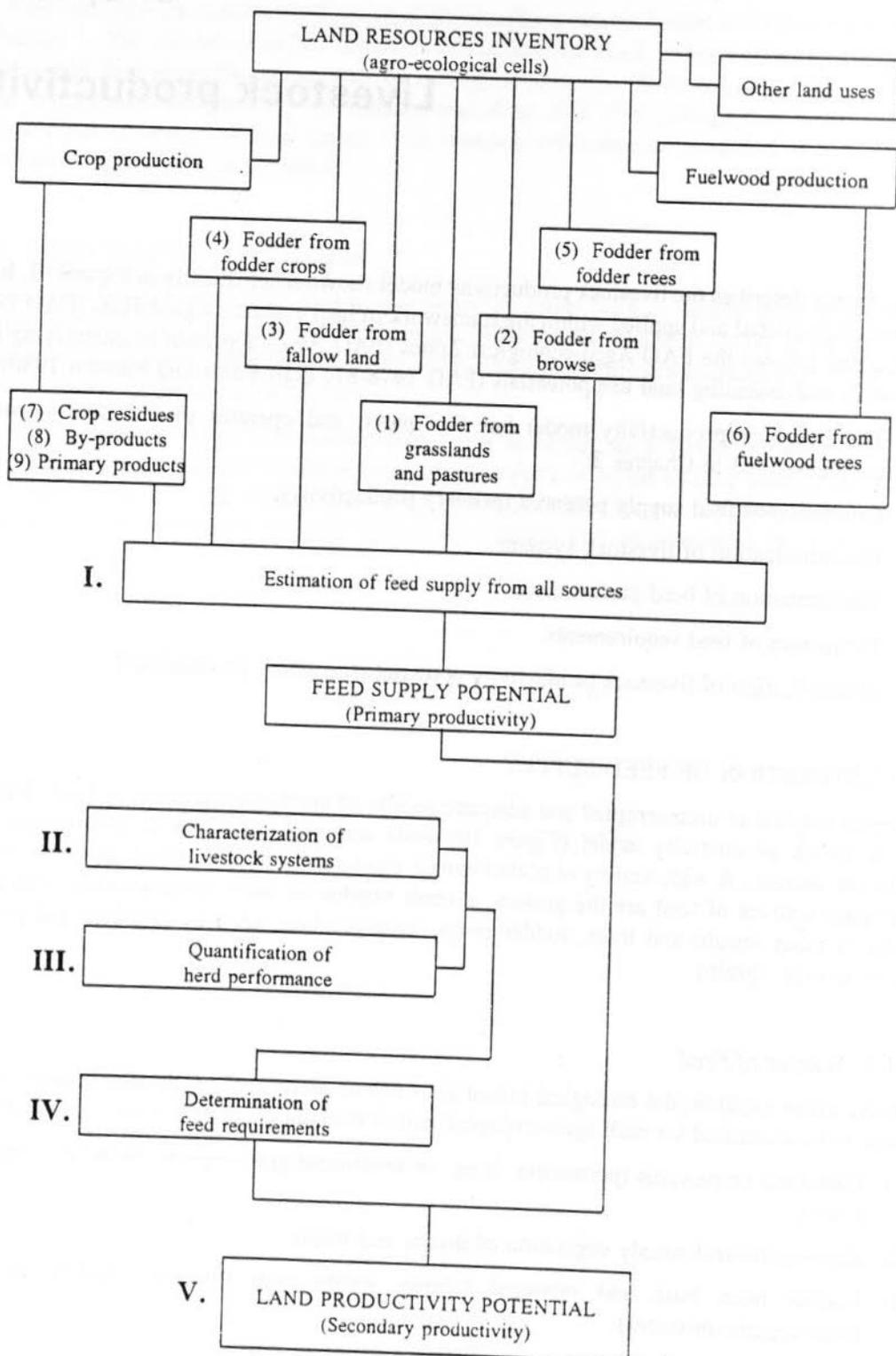
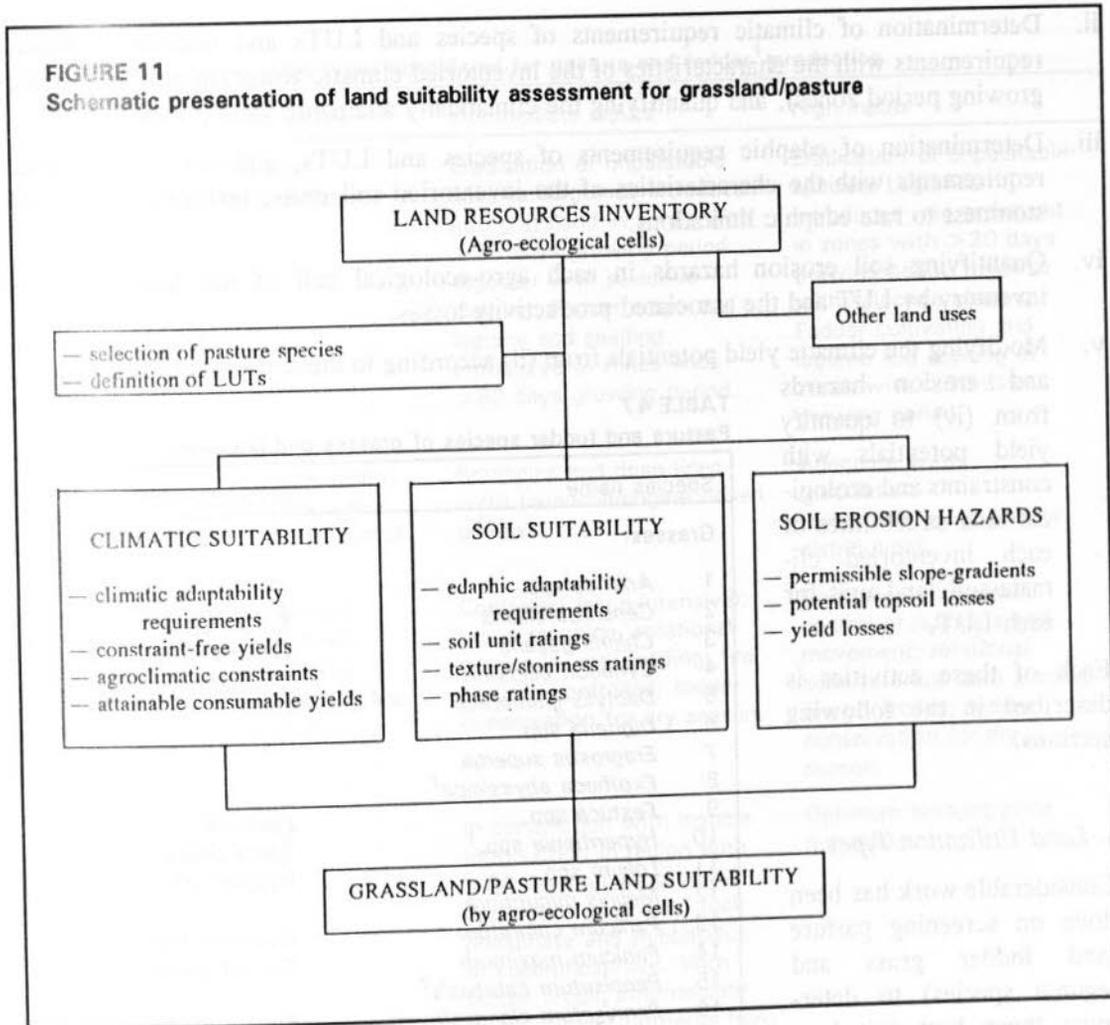


FIGURE 11  
Schematic presentation of land suitability assessment for grassland/pasture



- (5) Sown fodder trees.
- (6) Fodder from sown fuelwood trees.
- (7) Crop residues.
- (8) Crop by-products.
- (9) Crop primary products.

The characteristics of feed supplies from each of these sources are described below.

### 6.1.2 Grasslands and Pastures

Biomass production potential from grasslands or pastures in the model is estimated using the FAO-AEZ method (FAO 1978-81), and involves the activities depicted schematically in Figure 11, namely:

- i. Selection of the plant species and definition of LUTs (e.g., species; produce; technology and input level; labour; capital; markets).

- ii. Determination of climatic requirements of species and LUTs and matching climatic requirements with the characteristics of the inventoried climatic zones (thermal zones and growing period zones), and quantifying the climatically attainable yield potentials.
- iii. Determination of edaphic requirements of species and LUTs, and matching edaphic requirements with the characteristics of the inventoried soil units, textures, phases and stoniness to rate edaphic limitations.
- iv. Quantifying soil erosion hazards in each agro-ecological cell of the land resources inventory by LUT and the associated productivity losses.
- v. Modifying the climatic yield potentials from (ii) according to the soil limitations from (iii) and erosion hazards from (iv) to quantify yield potentials with constraints and ecological land suitabilities of each inventoried climate-soil land unit for each LUT.

Each of these activities is described in the following sections.

#### i. Land Utilization Types

Considerable work has been done on screening pasture (and fodder grass and legume species) to determine those best suited to particular environments in Kenya (Edwards and Bogdan 1951; Rattray 1960; Pratt and Gwynne 1977; Boonman 1979; Jaetzhold and Schmidt 1982). Table 47 sets out a list of some of these pasture (and fodder species) that are considered suitable in Kenya.

Pasture production is considered at three levels of input. The attributes of the three input levels are listed in Table 48, and they form the basis of the definition of LUTs considered in the model.

**TABLE 47**  
Pasture and fodder species of grasses and legumes

Species name	Common name
<b>Grasses:</b>	
1 <i>Aristida</i> spp.	
2 <i>Cenchrus ciliaris</i>	Buffel grass
3 <i>Chloris gayana</i>	Rhodes grass
4 <i>Cynodon dactylon</i>	Star grass
5 <i>Dactylis glomerata</i>	Cocksfoot
6 <i>Digitaria</i> spp.	
7 <i>Eragrostis superba</i>	
8 <i>Exothea abyssinica</i> <sup>1</sup>	
9 <i>Festuca</i> spp.	Fescues
10 <i>Hyperrhenia</i> spp. <sup>1</sup>	Zebra grass
11 <i>Lolium</i> spp.	Ryegrasses
12 <i>Melinis minutiflora</i>	
13 <i>Panicum coloratum</i>	Coloured Guinea grass
14 <i>Panicum maximum</i>	Guinea grass
15 <i>Pennisetum catabasis</i> <sup>1</sup>	
16 <i>Pennisetum clandestinum</i>	Kikuyu grass
17 <i>Pennisetum purpureum</i> <sup>2</sup>	Napier grass
18 <i>Pennisetum schimperi</i>	
19 <i>Setaria sphacelata</i>	
20 <i>Setaria splendida</i> <sup>2</sup>	Giant setaria
21 <i>Sorghum sudanense</i> <sup>2</sup>	Sudan grass
22 <i>Sporobolus helvolus</i> <sup>1</sup>	
23 <i>Themeda triandra</i>	Red oat grass
24 <i>Tripsacum laxacum</i> <sup>2</sup>	Guatemala grass
<b>Legumes:</b>	
25 <i>Centrosema pubescens</i> <sup>2</sup>	
26 <i>Desmodium</i> spp. <sup>3</sup>	Tick clover
27 <i>Lablab purpureus</i> <sup>2</sup>	Hyacinth bean
28 <i>Medicago sativa</i> <sup>2</sup>	Lucerne or alfalfa
29 <i>Macroptilium atropurpureum</i> <sup>3</sup>	Siratro
30 <i>Stylosanthes</i> spp.	Stylo
31 <i>Trifolium</i> spp.	Clover
32 <i>Vigna</i> spp. <sup>2</sup>	

<sup>1</sup> Common in areas of impeded drainage or in seasonally waterlogged areas.

<sup>2</sup> Fodder species.

<sup>3</sup> Includes both pasture and fodder types.

**TABLE 48**  
**Attributes of land utilization types considered for pasture and fodder<sup>1</sup> production**

Attributes	Low inputs	Intermediate inputs	High inputs
Primary resource	Natural vegetation	Eradication of unpalatable species. Legumes introduced into grassland in zones with > 30 days growing period together with selective clearing. Fodder crops and legume sod seeding introduced in zones with > 90 days growing period.	Eradication of unpalatable species. Legumes introduced into grassland in zones with > 30 days growing period together with selective clearing. Fodder cultivation and legume sod seeding in zones with > 90 days growing period.
Water	Surface water, shallow well (lifted by hand)	Boreholes and deep lined wells (windmill/engine driven pumps).	Adequate water reticulation (windmill/engine: gravity distribution).
Land use and feeding system	Traditional (extensive): permanent grazing; no fire control	Controlled (semi-intensive): group ranching; rotational grazing + stall feeding; fire partially controlled; fodder conservation for dry season.	Controlled (intensive): control of numbers and movement; rotational semi-zero and zero grazing; fire controlled; fodder conservation for dry season.
Fertilization	None	In conjunction with legume introduction in region with > 90 days growing period application of ground rock phosphate and thiobacillus or superphosphate. With fodder crops, intermediate levels of plant nutrients from fertilizer and manure.	Optimum amount plant nutrients.
Herding	Traditional	Organized	Use of hedges and fences.

<sup>1</sup> Fodder grasses and legumes.

ii. *Climatic Adaptability and Suitability*

Climatic suitability assessment of grass and legume pasture species is based on the climatic adaptability principles described in FAO (1978-81), and includes:

- an understanding of the climatic adaptability of pasture species in terms of their ecophysiological characteristics;
- matching the climatic requirements to thermal and moisture regimes, including the estimation of constraint-free biomass potentials;
- rating of agroclimatic constraints of water stress/excess; pests, diseases and weeds; and workability; and
- estimating attainable biomass production potentials with constraints, and the consumable biomass fractions.

The list of grass and legume species given in Table 47 includes both C<sub>4</sub> species (grasses) and C<sub>3</sub> species (legumes). Both groups of species include ecotypes adapted to warmer (mean daily

**TABLE 49**  
Thermal zone screen for pasture and fodder species

Species name	Adaptability group	Thermal zone							
		T1	T2	T3	T4	T5	T6	T7	T8
<b>Grasses:</b>									
1	<i>Aristida</i> spp.								
2	<i>Cenchrus ciliaris</i>	•	•	•					
3	<i>Chloris gayana</i>	•	•	•	•				
4	<i>Cynodon dactylon</i>	•	•	•	•	•			
5	<i>Dactylis glomerata</i>					•	•		
6	<i>Digitaria</i> spp.	•	•	•	•			•	•
7	<i>Eragrostis superba</i>	•	•	•	•				
8	<i>Exothea abyssinica</i>			•	•	•	•		
9	<i>Festuca</i> spp.								
10	<i>Hyperrhenia</i> spp.					•	•	•	•
11	<i>Lolium</i> spp.	•	•	•	•	•	•	•	•
12	<i>Melinis minutiflora</i>					•	•	•	•
13	<i>Panicum coloratum</i>	•		•	•		•		
14	<i>Panicum maximum</i>	•	•	•	•	•			
15	<i>Pennisetum catabasis</i>		•	•	•	•			
16	<i>Pennisetum clandestinum</i>			•	•	•	•	•	
17	<i>Pennisetum purpureum</i>		•	•	•	•	•	•	
18	<i>Pennisetum schimperii</i>			•	•	•	•	•	
19	<i>Setaria sphacelata</i>			•	•	•	•	•	•
20	<i>Setaria splendida</i>	•	•	•	•	•	•	•	
21	<i>Sorghum sudanense</i>	•	•	•	•	•			
22	<i>Sporobolus helvolus</i>	•	•	•	•	•			
23	<i>Themeda triandra</i>	•	•	•					
24	<i>Tripsacum laxacum</i>	•	•	•	•	•	•	•	•
<b>Legumes:</b>									
25	<i>Centrosema pubescens</i>	•	•	•					
26	<i>Desmodium</i> spp.	•	•	•					
27	<i>Lablab purpureus</i>	•	•	•					
28	<i>Medicago sativa</i>			•					
29	<i>Macroptilium atropurpureum</i>	•	•	•	•	•	•	•	
30	<i>Stylosanthes</i> spp.	•	•	•	•				
31	<i>Trifolium</i> spp.				•				
32	<i>Vigna</i> spp.	•	•	•	•	•	•	•	

**TABLE 50**  
Relationships between temperature and rate of leaf photosynthesis (kg CH<sub>2</sub>O/ha/hr) for legume species in adaptability groups I & II, and grass species in adaptability groups III & IV

Adaptability group	Temperature (°C)							
	5	10	15	20	25	30	35	40
Legume I	2.5	10.0	20.0	25.0	25.0	20.0	10.0	5.0
Legume II	-	2.5	15.0	35.0	37.5	37.5	30.0	20.0
Grass III	-	2.5	30.0	40.0	50.0	50.0	47.5	40.0
Grass IV	2.5	15.0	37.5	50.0	37.5	37.5	25.0	10.0

temperature  $>20^{\circ}\text{C}$ ) as well as cooler (mean daily temperature  $<20^{\circ}\text{C}$ ) conditions. Table 49 presents the thermal zone screen for pasture and fodder species, showing which species can be considered in which thermal zones.

Legume species adapted to cool temperatures belong to adaptability group I, and those adapted to warm temperatures belong to adaptability group II. Grass species adapted to warm temperatures belong to adaptability group III, and those adapted to cool temperatures belong to adaptability group IV. The relationships between photosynthesis and temperature for the four adaptability groups are presented in Table 50.

Consequently, the suggested thermal zone combination ratings for the grasses and legumes at this stage of the model development are: S1 (very suitable) for the thermal zones T1, T2, T3, T4 and T5, S2 (suitable) for T6, S3 (moderately suitable) for T7, S4 (marginally suitable) for T8 and N (not suitable) for T9. A rating of S1 indicates that there are no thermal constraints during the growing period and the requirements are fully met. S2 indicates slight to moderate thermal constraints, leading to a yield depression of some 25%. S3 indicates moderate to severe thermal constraints, leading to a yield depression of some 50%, and S4 indicates severe thermal constraints leading to yield depression of some 75%. A rating of N indicates that the thermal requirements are not met and the zone is not suitable for further consideration. These ratings correspond closely with the correlation between pasture dry matter production and temperature in Kenya (Booneman 1979).

Potential biomass estimates were derived according to the method developed by the FAO-AEZ project (Kassam 1977; FAO 1978-81). In computing 'constraint-free' biomass potential, it is assumed that both  $C_3$  and  $C_4$  pasture and fodder species of grasses and legumes will be represented, so that a maximum photosynthesis rate ( $P_{\max}$ ) of 37.5 kg  $\text{CH}_2\text{O}/\text{ha}/\text{hr}$  has been applied.

Estimates of potential constraint-free total biomass production (Bn) at the high input level are presented in Table 51, together with maximum leaf area index (LAI) values used, the agro-climatic constraint ratings, total biomass with constraints (Bnc), consumable coefficients (Cc) and consumable biomass with constraints (Bcc).

For a variety of reasons only a portion of the plant biomass is eaten by animals. About 20% of the total net biomass (Bn) is in roots; a portion of the biomass is not eaten (particularly under low inputs) due to low palatability; some biomass is lost due to trampling, fire and wind; and part is consumed by invertebrate animals. It is generally assumed that between a third and two-thirds of the total biomass yield of an area will be utilized or consumed by stock, depending on the environment.

Agroclimatic constraints applied to the constraint-free yield relate to water stress in LGPs  $<210$  days, and workability in LGP zone  $365^+$  days. Total biomass yield with constraint at high inputs ranges from 0.5 t/ha in LGP zone 1-29 days to 30.6 t/ha in LGP zone 330-364 days.

Consumable coefficients (Cc) range from 0.35 at low inputs in LGP zones with  $<120$  days to 0.6 at high inputs in LGP zones with  $>180$  days. Consequently, consumable biomass with constraints (Bcc) ranges from 0.23 t/ha to 18.9 t/ha for high inputs, from 0.16 t/ha to 10.83 t/ha for intermediate inputs, and from 0.09 t/ha to 3.94 t/ha for low inputs.

Bn at low inputs is assumed to be 25% and 50% of that at the high input level in LGP zones  $>90$  days and  $<90$  days respectively. Bn at the intermediate level is assumed to be between the high and the low input levels. For areas with no growing period, Bc is estimated at 70 kg/ha at the high, 35 kg/ha at the low, and 52.5 kg/ha at the intermediate input levels.

TABLE 51  
Potential biomass from pasture and fodder grasses and legumes (t/ha dry weight) at three input levels<sup>1</sup>

LGP (days)	1-29	30-59	60-89	90-119	120-149	150-179	180-209	210-239	240-269	270-299	300-329	330-364	365	365+
LAI	1-2	2-3	3-4	4	4	4	4	4	4	4	4	4	4	4
Bn	0.0-1.8	1.8-5.3	5.3-10.0	10.0-14.3	14.3-17.2	17.2-19.7	19.7-22.1	22.1-24.3	24.3-26.3	26.3-28.2	28.2-29.7	29.7-31.5	31.5	31.5
'a' <sup>1</sup>	2	2	2	1	1	1	1	0	0	0	0	0	0	0
'b'	0	0	0	0	0	0	0	0	0	0	0	0	0	0
'c'	0	0	0	0	0	0	0	0	0	0	0	0	0	0
'd'	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Bnc	0.5	1.8	3.8	9.1	11.8	13.8	15.7	23.2	25.3	27.3	29.0	30.6	31.5	23.6
Cc - H <sup>2</sup>	0.45	0.45	0.45	0.45	0.50	0.50	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60
- I	0.40	0.40	0.40	0.40	0.45	0.45	0.55	0.55	0.55	0.55	0.55	0.55	0.55	0.55
- L	0.35	0.35	0.35	0.35	0.40	0.40	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Bcc - H	0.23	0.81	1.71	4.10	5.90	6.80	9.42	13.92	15.18	16.38	17.40	18.36	18.90	14.16
- I	0.16	0.54	1.14	2.28	3.32	3.88	5.40	7.98	8.70	9.38	9.97	10.52	10.83	8.07
- L	0.09	0.32	0.67	0.80	1.18	1.38	1.96	2.90	3.16	3.41	3.63	3.82	3.94	2.96

<sup>1</sup> Agroclimatic constraints: a = water stress or excess; b = pests, diseases or weeds affecting vegetative growth; c = pests, diseases or weeds affecting reproductive growth; d = workability limitations.

<sup>2</sup> H = high inputs; I = intermediate inputs; L = low inputs.

Pasture species and biomass potentials are matched to individual component LGPs. The LGP-Pattern evaluation for pasture is achieved by taking into account all the constituent component lengths in each LGP-Pattern, thus taking into account the year-to-year variability in the number of LGPs per year.

Yields in Table 51 apply to normal LGPs. For intermediate growing periods, yield reductions are of the order of 50% on all soils except Fluvisols and Gleysols. The percentage of occurrence of intermediate LGPs in all LGP-Pattern zones combined is 100% in LGP zone 1-29 days; 65% in zone 30-59 days; 25% in zone 60-89 days; 10% in zone 90-119 days and 5% in zone 120-149 days.

An exception to the general methodology for climatic suitability assessment applies to areas occupied by Fluvisols because the inventoried LGP does not fully reflect their particular circumstances with regard to moisture regime, and they are modified as described earlier in Section 5.1.2.iii, with the full ratings given in FAO/IIASA (1991: Tech. Annex 5).

### iii. *Edaphic Suitability*

In order to assess soil suitability for pasture production, the soil requirements of pasture species must be determined. Furthermore, these requirements must be considered within the context of limitations imposed by landform and other features (e.g., soil phases, stoniness) which do not form part of soil composition but have a significant influence on the use that can be made of the soil.

Basic soil requirements for pasture species relate to internal soil properties in the same manner as for crops, as described in Section 5.1.3.ii. From the basic soil requirements for pasture species, a number of response-related soil characteristics have been derived. The correlation between the basic soil requirements and soil characteristics given in Table 41 is used to rate pasture and fodder crop performance, and, in a similar way, the diagnostic horizons and properties are also used to rate soil suitability (cf. Section 3.2.5).

The edaphic suitability classification is input-specific and based on:

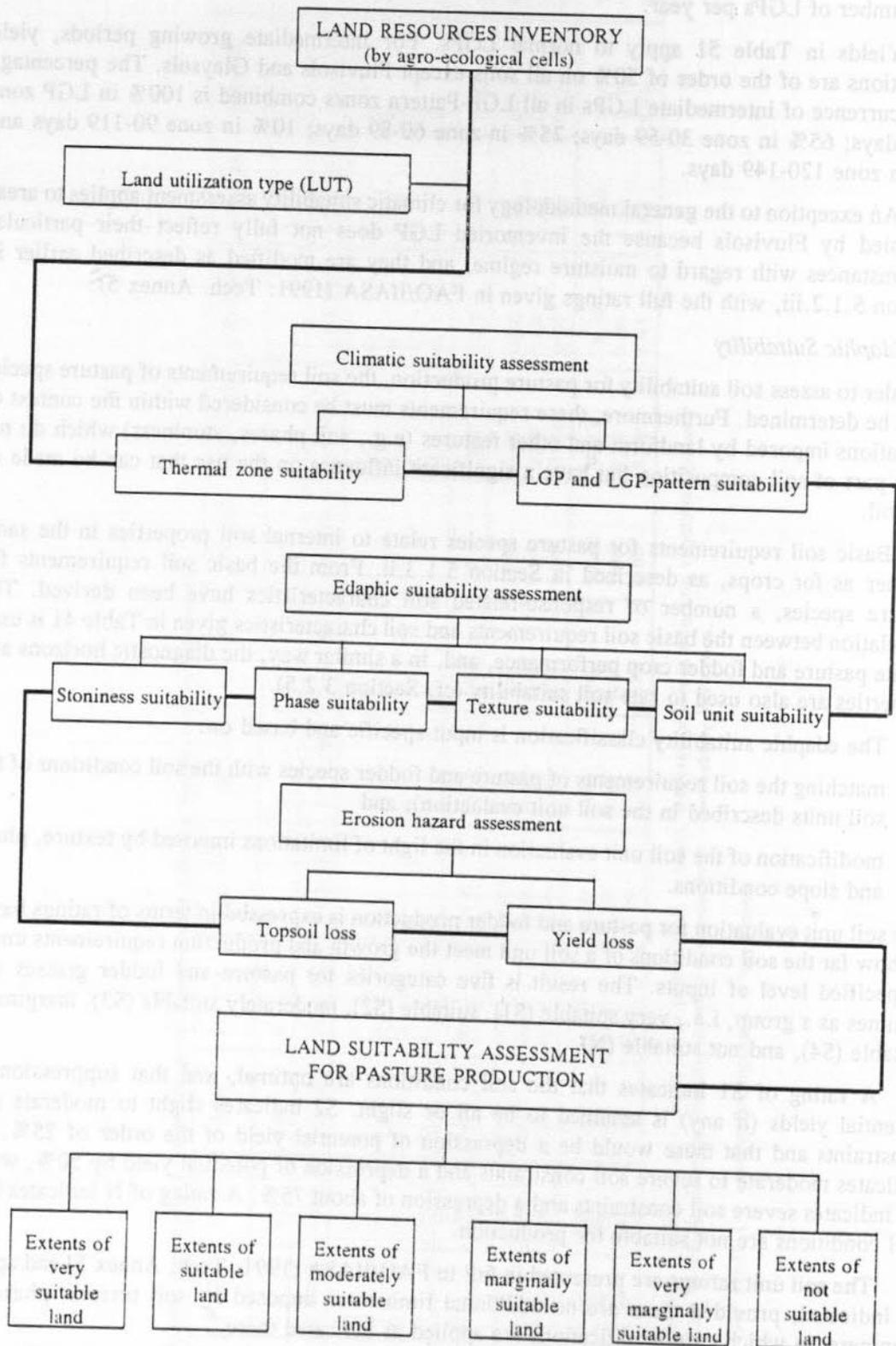
- matching the soil requirements of pasture and fodder species with the soil conditions of the soil units described in the soil unit evaluation); and
- modification of the soil unit evaluation in the light of limitations imposed by texture, phase and slope conditions.

The soil unit evaluation for pasture and fodder production is expressed in terms of ratings based on how far the soil conditions of a soil unit meet the growth and production requirements under a specified level of inputs. The result is five categories for pasture and fodder grasses and legumes as a group, i.e., very suitable (S1), suitable (S2), moderately suitable (S3), marginally suitable (S4), and not suitable (N).

A rating of S1 indicates that the soil conditions are optimal, and that suppression of potential yields (if any) is assumed to be nil or slight. S2 indicates slight to moderate soil constraints and that there would be a depression of potential yield of the order of 25%. S3 indicates moderate to severe soil constraints and a depression of potential yield by 50%, while S4 indicates severe soil constraints and a depression of about 75%. A rating of N indicates that soil conditions are not suitable for production.

The soil unit ratings are presented in full in FAO/IIASA (1991: Tech. Annex 5) and apply as indicated, provided there are no additional limitations imposed by soil texture, phase or stoniness, in which case modifications are applied as indicated there.

**FIGURE 12**  
Schematic presentation of the land suitability assessment model for pasture production



In the case of soil texture, soil unit ratings remain unchanged if the soil is an albic, cambic, ferralic, calcareo-cambic or luvic Arenosol (Q, Qa, Qc, Qf, Qkc, Ql) or a vitric Andosol (Tv), or where textures are medium (fine sandy loam, sandy loam, loam, sandy clay loam, clay loam, silty clay loam, silt), or fine (sandy clay, silty clay, peaty clay, clay). In all other cases (i.e., with coarse textures: sand, loamy coarse sand, fine sand, loamy fine sand, loamy sand) the soil unit rating is one class (25%) lower.

#### iv. Slope Limitations and Soil Erosion

Limitations imposed by slope are taken into account in three steps, as described earlier, in Chapter 4. Step one defines the slopes which are permissible for pasture production, and as a model variable this is defined as slopes less than 45% (Table 26).

Step two involves the computation of potential topsoil loss, estimated for each input level through a modified USLE (Wischmeier and Smith 1978).

Step three relates the estimated topsoil losses to yield losses through a set of equations (Table 29) taking into account soil susceptibility (Table 28), level of inputs and regeneration capacity of topsoil (Table 27).

#### v. Land Suitability Assessment

All three assessments — the climatic suitability, the edaphic suitability and the soil erosion hazard — are required to determine the ecological land suitability for grassland/pasture production of each climate-soil unit of the land resources inventory. In essence, the land suitability assessment takes account of all the inventoried attributes of land and compares them with the requirements of pasture species, to give an easy to understand picture of the suitability of land for grassland/pasture production.

The results of the land suitability assessment are presented in five basic suitability classes, each linked to attainable yields for the three levels of inputs considered. For each level of input, the land suitability classes are: very suitable (VS) —  $\geq 80\%$  of the maximum attainable yield; suitable (S) —  $< 80\%$  to  $\geq 60\%$ ; moderately suitable (MS) —  $< 60\%$  to  $\geq 40\%$ ; marginally suitable (mS) —  $< 40\%$  to  $\geq 20\%$ ; and not suitable (NS) —  $< 20\%$ .

Land suitability assessment is carried out through the steps of the process shown schematically in Figure 12, in a manner analogous to that described in Section 5.1.5.

The five classes of land suitabilities are related to attainable yield as a percentage of the maximum attainable under the optimum climatic, edaphic and landform conditions.

Consequently the results provide an assessment of pasture production potentials of each land unit, which in turn can be aggregated for any given area. Generalized results of land suitability assessment for pasture production at intermediate level of inputs in Kenya are presented in Plate 15, and in FAO/IASA (1991: Tech. Annex 8).

#### 6.1.3 Fodder from Browse, Fodder Trees and Fuelwood Trees

In the low rainfall areas (LGP  $< 120$  days), natural woody vegetation including leguminous shrubs and trees, can be important in the nutrition of domestic stock. However, relatively little is known about the digestibility of biomass materials from browse. By comparison with the large amount of herbage from grasslands or natural pastures, the quantity of fodder biomass from natural woody vegetation is limited. Contribution of browse biomass is assumed to be included in the estimates of biomass from grasslands and pastures given in Table 51, and no separate account is taken at this stage of the model development and application.

Trees are planted for fodder in Kenya, and the main species are *Acacia*, *Calliandra*, *Gliricidia*, *Grevillea*, *Leucaena* and *Sesbania*. Again the potential contribution from sown fodder trees is assumed to be included in the estimates of biomass from pastures given in Table 51, and no separate account is taken at this stage of model development and application. However, the land suitability procedure for separately quantifying fodder biomass from fodder trees is identical to the procedure of quantifying wood biomass from fuelwood trees in Chapter 7. Consequently, it is now possible, if required, to provide for a separate assessment of fodder from fodder trees.

Where trees are considered for fuelwood production and carry palatable foliage, it is assumed that about 10% (i.e., 3.3% of mean annual wood biomass increments given in Chapter 7) of the foliage may be utilized by stock without affecting fuelwood yields. Fuelwood species that can contribute fodder are: *Acacia gerrardii*, *A. nilotica*, *A. senegal*, *Calliandra calothyrsus*, *Casuarina equisetifolia*, *Conocarpus lancifolius*, *Eucalyptus camaldulensis*, *E. citriformis*, *E. tereticornis*, *Parkinsonia aculeata* and *Sesbania sesban*.

#### 6.1.4 Fodder from Fallow Land

In the crop productivity model (Chapter 5), fallow requirements for crop rotation options are formulated. At low input levels, fallow land is assumed to carry natural bush vegetation; at intermediate and high levels of input, fallow land is assumed to carry sown grass-legume pasture.

Biomass production from natural fallow under low input and from sown pasture under intermediate and high inputs is taken as one-third of that from normal sown or permanent pastures given in Table 51. It is further assumed that only 50% of the biomass may be utilized by stock.

#### 6.1.5 Fodder from Fodder Crops

Fodder grasses, legumes and cereals are grown for fodder production in Kenya. The main fodder grasses are Napier or bana grass (*Pennisetum purpureum*), giant setaria (*Setaria splendida*), Sudan grass (*Sorghum sudanense*) and Guatemala grass (*Tripsacum laxacum*). The main fodder legume species are *Centrosema pubescens*, *Dolichos (Lablab purpureus)*, Hyacinth bean (*Lablab niger*), Siratro (*Macroptilium atropurpureum*), *Vigna* spp. and *Stylosanthes* spp. The main fodder cereals are maize, oats, pearl millet and sorghum.

A separate assessment of potential biomass production from fodder grasses, legumes and cereals is possible according to the land suitability methodology described in Chapter 5. However, at this stage of model development and application, the range of biomass production potentials from pastures given in Table 51 were found to adequately cover the biological potentials of fodder crops in the Kenya situation.

#### 6.1.6 Crop Residues, By-products and Primary Products

In areas with more than a 120-day growing period, crop residues are an important source of fodder, particularly for the low and intermediate technology livestock systems. Important residues are the haulms of groundnut, cowpea and other grain legumes; the staves (stalks) of sorghum, maize and millet; and straw from rice, wheat, barley and oats. Quantities of residues

that may be available are estimated by applying the residue factor and the corresponding utilization coefficients to crop yields (FAO/IIASA 1991: Tech. Annex 5).

By-products, defined as edible materials remaining after a crop has been processed, are bran, pollard and germ meal from cereal milling; molasses and bagasse from sugar milling; and cotton, soybean and groundnut seedcakes. Quantities of crop by-products that may be available have been estimated by applying the by-product factor and the corresponding utilization coefficients to crop yields FAO/IIASA (1991: Tech. Annex 5).

The term primary product applies to grain used for the purpose of feeding to animals either directly in an unprocessed form or in a processed form. Main cereals used in Kenya are maize, sorghum wheat and barley. Direct grain feeding is used mainly at the high level of technology in the dairy and meat production systems with cattle and goat. The intensive livestock industries of poultry and pig production tend to rely on processed feeds.

#### 6.1.7 Feed Supply Potential (Primary Productivity)

When Part I of the livestock productivity model (Figure 10) is applied to the land resources inventory, the feed supply potential of each agro-ecological cell is quantified by feed source, as described earlier.

Once feed supply potential or primary productivity has been quantified, it is possible to quantify the livestock productivity potential of livestock systems at specified performance levels and feed requirements. These aspects are taken into account in Parts II, III, IV and V of the model.

## 6.2 CHARACTERIZATION OF LIVESTOCK SYSTEMS

Part II of the livestock productivity model (Figure 10) characterizes the livestock systems that are to be considered in assessing secondary productivity potentials. It defines, for three input or technology levels, the livestock types, production systems and herd structures.

Of the six types of livestock production system included in the model as applied to Kenya, four were considered under pastoral as well as non-pastoral systems. The other two, poultry and pig, were considered only under intensive systems, without explicitly defining the production systems at this stage in the model development. Cattle, goat, sheep and camel systems were considered at three input levels, as defined in Table 52.

For the pastoral systems, three types of cattle herds were considered, namely nomadic distant, nomadic with market access, and semi-nomadic, representing respectively low, intermediate and high input levels. For sheep and goats, two herding types were considered, nomadic distant and semi-nomadic, representing low and high input levels respectively. For camels, only one herd type was considered, representing the typical local low input level production.

Herd structures have been defined in terms of numbers of animals as well as in terms of Tropical Livestock Units (TLUs), where 1 TLU is the equivalent of a mature animal weighing 250 kg (Houerou and Hoste 1977; Stotz 1983).

Livestock conversion factors for non-pastoral systems in areas with LGP > 120 days are taken from Stotz (1983). Livestock conversion factors for pastoral systems in areas with LGP < 120 days are taken from Houerou and Hoste (1977), and are:

**TABLE 52**  
Attributes of the non-pastoral land utilization types considered for livestock production

Attributes	Low inputs	Intermediate inputs	High inputs
Nutrition	Traditional	Mineral supplements, improved calf care, better use of residues and products	As intermediate, plus feeding for optimum economic and biological production; use of primary products
Disease control	None	Current veterinary prophylaxis, plus control or eradication of diseases or their vectors, e.g., dipping against ticks	As intermediate, plus control of diseases of high performance, e.g., dipping and drenching for mastitis, foot-and-mouth, etc.
Breeding	Selection of unrelated bulls of good conformation, minimum size of heifer at mating	Introduction of adapted exotic breeds and cross-breeds	Introduction of graded and exotic breeds of high genetic potential for growth and milk production
Marketing	Low off-take, poor transport facilities, poor processing, including hides and skins	Better off-take, transport and processing, organized markets	Stratified livestock industries, producers receive fair price, organized dairying

Cattle in Herd	=	0.70 TLU	Goat	=	0.08 TLU
Cow	=	1.00 TLU	Donkey	=	0.50 TLU
Sheep	=	0.10 TLU	Camel	=	1.25 TLU

### 6.2.1 Cattle Systems: Dairy and Meat

At the low technology level, the systems are characterized by pure Zebu cattle (Stotz 1983).

The feed supply is generally native Kikuyu/star grass pastures, and crop residue (maize stover). Cattle are grazed, herded or tethered during the day and kraaled during the night. Cattle are not supplied with concentrates or mineral supplements.

Calves join their dams during milking and for a short while afterwards, during which time they consume the remaining milk in the udder, amounting to about 3 to 5 l/day (400 l total during the rearing period). Calves are weaned at 5 to 7 months old.

The animals are driven to water at rivers or reservoirs twice a day if nearby, otherwise once a day. Disease control measures are rarely practised, but cattle are compulsorily vaccinated against rinderpest and in some areas against foot and mouth disease.

At the intermediate technology level the cattle would be first generation crossbreeds with exotic or high performing grade cattle, bred using artificial insemination. Crossbred cattle are generally acquired through upgrading local Zebu cows by Ayrshire, Friesian, Guernsey or Jersey bulls.

Cattle graze natural ley pastures (Kikuyu/star grass) and fields are usually fenced. With regard to feeding, young stock rearing and watering, the same husbandry practices are

employed as for Zebu cattle. Crossbred cattle occasionally receive cattle salt, and cattle are regularly dipped or sprayed. Sick animals are treated.

Under high inputs, the systems are based on exotic cattle — Friesian, Ayrshire, Guernsey or Jersey — which have been upgraded from the original crosses with indigenous cattle by breeding back to the exotic type.

Stotz (1983) describes these systems as characterized by grade cows in a combined grazing/stall feeding system (semi-zero grazing) or complete stall feeding (zero grazing). In the case of semi-zero grazing, cattle usually graze Kikuyu or star grass during the daytime. At night cattle are kraaled or stabled, where they are fed with napier or bana grass. Sometimes they are also fed during the day with crop residues and napier grass, particularly during the dry season when pasture productivity is low. Where cattle are permanently housed in a shed, the feed is cut and carried to them. Cattle kept in a zero grazing unit are predominantly fed with napier or bana grass, which is first chopped. Dairy cows also receive 20-25 kg/cow/year of mineral supplement, and 500 to 1000 kg/cow/year manufactured compound concentrates when lactating.

Male and female calves are bucket fed and hand reared. Calves usually receive 270 to 400 l of milk before they are weaned at 10 to 18 weeks. When the weaning period is shorter, in the case of the zero grazing system, calves also receive about 165 kg of concentrates during the rearing period. After this time they depend entirely on forage and join the rest of the herd when about 6 months old at a weight of about 160 kg, or at 2 weeks at a weight of about 35 kg in the zero-grazing system.

Animals are watered twice a day and are regularly dipped or sprayed, drenched against internal parasites and receive other health treatment as needed.

Herd structure parameters are presented for the three cattle herd types in Table 53. Base herd structures are defined on the basis of a notional herd of 100 cows.

### 6.2.2 Goat Systems: Dairy and Meat

The low input technology system is characterized by the local small East African goats which are herded or tethered during the day and kept in store, stable or some kind of shelter at night. Goats feed mainly on natural pastures, which supply about 70% of all feed consumed. The remainder is obtained from crop residues and through browsing on farm hedges. There is no definite mating season, hence kids are born the whole year round. Kids suckle the mother for about 5 to 7 months and consume the whole amount of milk produced by the dam.

Intermediate technology level systems are characterized by dual-purpose goats, usually  $F_1$  or  $F_2$  crossbreeds. Generally, an exotic dairy goat buck, such as Toggenburg, Saanen or Anglo-Nubian, is used for upgrading local goats. Animals are kept under semi-zero grazing management systems. They are tethered during the day, graze mainly natural pasture, and frequently browse shrubs and farm hedges. Goats are penned during the night, when they are fed with crop residues and fodder crops like napier grass and maize. Under these feeding conditions, goats obtain approximately 40% of their dry matter requirements from grazing natural pastures. Another 40% is drawn from fodder crops and 20% supplied through feeding crop residues. Animals are sprayed with acaricides regularly and drenched against internal parasites at regular intervals. Lactating females are partially milked before kids are allowed to suckle, with an off-take of 1 to 2 kg of milk daily.

**TABLE 53**  
Cattle herd structures

Parameter	Input levels					
	Low		Intermediate		High	
Body weight (kg)	Weight	TLU	Weight	TLU	Weight	TLU
Cows	250	1.00	300	1.25	400	1.75
Replacement heifers (ave. of 1 & 2 yr old)	190	0.76	235	0.94	315	1.26
Calf birth weight	22	0.09	25	0.14	35	0.14
Weaning weight (6 months)	80	0.32	100	0.40	140	0.56
Bulls	300	1.20	-	-	-	-
Number in herds	Head	TLU	Head	TLU	Head	TLU
Cows						
- in milk	67	67	72	95	85	149
- dry	33	33	28	30	15	26
- total	100	100	100	100	100	175
Calves						
- heifers	33	-	36	-	42	-
- bulls	34	-	36	-	(43)	-
- total	67	23.5	72	30.4	(85)42	25.8
Replacement						
- heifers	29	22.0	37	32.0	51	63.8
- bulls	2	1.5	-	-	-	-
- total	31 <sup>1</sup>	23.5	37	32.0	-	-
Bulls	4	4.8	-	-	-	-
Total	202	151.8	209	187.4	194	264.6

<sup>1</sup> Contribution to meat output accounted for in FAO/IIASA (1991:Tech. Annex 5, Table A6.2).

**TABLE 54**  
Goat herd structures

Numbers in herd	Input levels		
	Low	Intermediate	High
Breeding does	100	100	100
Kids (under 6 months)	127	156	187
Replacement yearlings			
- female	19	25	19
- male	2	2	2
Bucks	4	4	4
Total head	252	287	312
Total adult animals	125	131	125
TLU/adult head	0.10	0.11	0.12
Total TLU	12.5	14.4	15.0

The high technology level situation is characterized by the intensive goat production system. The main aim of keeping exotic or grade dairy goats like Toggenburg, Saanen or Anglo-Nubian is to produce milk. Other by-products are sales of breeding stock and goat meat. Goats are usually kept in a zero grazing system, where they are fed with napier grass and other fodder crops together with up to 1.5 kg of concentrate per day. Water is provided in containers which are placed inside the stable. Kids are bucket fed with milk, receive 165 litres over a period of 4 months and are fed 50 kg of concentrate supplement. All animals are sprayed with acaricide regularly.

Herd structure parameters are presented for the three goat herd types in Table 54. Base herd structures are defined on the basis of a notional herd of 100 does.

### 6.2.3 Sheep Systems: Meat and Wool

The dominant local breed kept at the low technology level is the Red Maasai or Red Kikuyu. It is a fat-tailed hair sheep weighing 25 to 30 kg. The animals feed mainly on natural pasture both on the farm and adjacent common land, and use crop residues and other consumable dry matter that can be found. Animals are often tethered during the day and kept in some kind of shelter at night. There is no definite mating season or control over breeding and little health care. Ewes, on average, lamb once a year. No milk is taken and the only product is meat from surplus male lambs and cull ewes.

At the intermediate technology level there is controlled breeding and introduction of a better class of sire, usually Droper rams, to improve meat production. The preferred crossbreed seems to be  $\frac{3}{4}$  Droper and  $\frac{1}{4}$  Maasai. In conjunction with this, there is a more frequent joining programme, regular dipping and drenching, improvement in provided fodder and mineral supplementation. These inputs are accompanied by fenced paddocks rather than tethering or shepherding.

At the high level of technology, the production system is characterized by the Red Maasai x Droper crosses for meat production. At higher elevations — thermal zones T5, T6, T7 and T8 — another system, dominated by dual-purpose wool and meat production, using crossbred wool sheep such as Corriedale-Hampshire, is also considered in the model.

Herd structure parameters are presented for the three sheep herd types in Table 55. Base herd structures are defined on the basis of a notional herd of 100 ewes.

### 6.2.4 Pastoral Systems: Meat and Milk

Pastoral systems have evolved as a method of producing human food under climatic conditions where normal rainfed crop production is not possible. It operates in the semi-arid zones where the rainfall is low in total quantity and is erratic both geographically and in time, that is within seasons and between seasons.

The system comprises various combination of large and small domesticated ruminants with the variations dictated by climate, notably temperature. As a source of food the large ruminants provide milk and some blood and meat, while the small ruminants are a source of meat and, in certain locations, of milk. Camels play no part in the market food economy so they are not managed with a view to producing a saleable surplus. The role of the camel is mainly to provide milk and be a beast of burden.

**TABLE 55**  
Sheep herd structures

Numbers in herd	Input levels		
	Low	Intermediate	High
Breeding ewes	100	100	100
Lambs (under 6 months)	115	148	150
Replacement yearlings			
- female	19	22	22
- male	2	2	2
Rams	4	3	3
Total head	240	275	277
Total adult animals	125	127	127
TLU/adult head	0.10	0.10	0.10
Total TLU	12.5	12.7	12.7

**TABLE 56**  
Herd proportions (%) by districts in Kenya of nomadic herds in areas with LGPs < 120 days, expressed in TLUs

District	Cattle	Camel	Smallstock	Donkey
Mandera	21.0	65.8	13.0	0.2
Wajir	28.0	64.7	7.0	0.3
Turkana	31.0	29.2	37.5	2.3
Marsabit	54.0	27.5	16.5	2.0
Garissa	76.8	15.6	7.5	0.1
Lamu	76.8	15.6	7.5	0.1
Tana River	66.4	21.0	11.6	1.0
Kiliji	66.4	21.0	11.6	1.0
Isiolo	64.3	16.4	17.5	1.8
Baringo	65.4	12.2	21.9	0.5
Samburu	61.9	6.6	29.3	2.2
Taita Taveta	83.2	-	14.2	2.6
Kwale	83.2	-	14.2	2.6
Kajiado	80.0	-	18.6	1.4
Narok	80.0	-	18.6	1.4

All of the pastoral systems operate on various combinations of cattle, camels, sheep and goats, with some donkeys as pack animals. The combinations are a function of climate, available herbage and water, and local preferences. In the north the herds are principally camels/smallstock, with some cattle in certain locations, while in the centre and south the herds are almost exclusively cattle/smallstock. The herd proportions, expressed in TLU equivalents, for the principal pastoral districts are set out in Table 56.

The proposed herd structures for cattle, derived from Unesco (1982), Semenye (1982) and Meadows and White (1981), are presented in Table 57. Herd structures for sheep and goat, derived from Unesco (1982), de Leeuw and Peacock (1982), Peacock (1983, 1984) and King *et al.* (1982), are presented in Table 58. The proposed herd structure for camels is given in Table 59.

**TABLE 57**  
Pastoral cattle herd<sup>1</sup> structures

Numbers in herd	Semi-nomadic	Nomadic with market access	Nomadic distant
Breeding cows			
- in milk	23	23	23
- dry	13	22	22
- total	36	45	45
Replacement heifers (1 to 4 yr. old)	22	22	22
Heifer calves	10	10	10
Sub-total females	68	77	76
Steers 1-2 yrs	7	5	6
2-4 yrs	13	9	4
Bull calves	8	8	5
Bulls	5	5	6
Sub-total males	33	27	21
Herd total	101	104	97
Total TLU	70.7	72.8	67.9

<sup>1</sup> Nomadic distant - low inputs; Nomadic with market access - intermediate inputs; Semi-nomadic - high inputs.

**TABLE 58**  
Pastoral sheep and goat herd<sup>1</sup> structures

Numbers in herd	Semi-nomadic	Nomadic distant
Sheep : Goat ratio	1 : 1.2	1 : 1
Sheep		50
- Ewes	50	13
- Ewes weaners	18	16
- Ewes lambs	20	79
Sub-total females	88	15
- Ram lambs	20	24
- Wethers	20	4
- Rams	4	43
Sub-total males	44	122
Total Sheep	132	12.2
Total TLU	13.2	
Goat		60
- Doe	54	13
- Weaner does	18	18
- Kid does	24	91
Sub-total females	96	18
- Kid billies	23	23
- Wethers	33	4
- Billies	4	45
Sub-total males	60	136
Total Goat	156	10.2
Total TLU	12.5	

<sup>1</sup> Nomadic distant - low inputs; Semi-nomadic - high inputs.

**TABLE 59**  
Pastoral camel herd<sup>1</sup> structure

Numbers in herd	Nomadic
Breeding females (6-13 yrs)	
- in milk	21
- dry	21
- total breeders	42
Breeder replacements (2-6 yrs)	22
Female calves	2
Total females	70
Bull calves	4
Bull replacements (2-4 yrs)	13
Bulls (5-12 yrs)	6
Castrates (5-12 yrs)	12
Total males	35
Total Herd	105
Total TLU	131

<sup>1</sup> Nomadic - low inputs.

**TABLE 60**  
Suitability ratings for livestock systems by thermal zone

Livestock system	Thermal zone								
	1	2	3	4	5	6	7	8	9
Cattle:									
1 Dairy and meat	S1	S1	S1	S1	S1	S1	S1	S3	N
2 Pastoral	S1	S1	S1	S1	S2	S3	S3	N	N
Goat:									
3 Dairy and meat	S1	S1	S1	S1	S1	S1	S1	S3	N
4 Pastoral	S1	S1	S1	S1	S2	S3	S3	N	N
Sheep:									
5 Meat and wool	S1 <sup>1</sup>	S1 <sup>1</sup>	S1 <sup>1</sup>	S1 <sup>1</sup>	S1	S1	S1	S2	N
6 Pastoral	S1	S1	S1	S1	S2	S3	S3	N	N
Camel:									
7 Pastoral	S1	S1	N	N	N	N	N	N	N
Others:									
8 Poultry	S	S	S	S	S	S	S	N	N
9 Pig	S	S	S	S	S	S	S	N	N

<sup>1</sup> N for wool production in T1,T2,T3,T4 and S2 in T5.

### 6.3 QUANTIFICATION OF HERD PERFORMANCE

Part III of the livestock productivity model (Figure 10) assesses the livestock productivity potential of each livestock system by quantifying herd performance in acceptable climatic zones. The thermal zone suitability ratings for livestock systems are given in Table 60, and the moisture zone screen, indicating which livestock systems can be considered in which LGP zones, is given in Table 61.

Livestock products per reference herd TLU for cattle, goat, sheep and camel systems at low, intermediate and high levels of technology are presented in Table 62 for zones that are considered as S1 for these livestock systems. Where a thermal zone rating is S2, S3 or S4, reference output must be decreased by 25%, 50% and 75% respectively. Where a thermal zone rating is N, the zone is either deemed not suitable because of temperature constraints (and therefore not considered further), or it is deemed not applicable for further consideration because the zone has not been selected for assessment within a particular planning scenario. Where the thermal zone rating is S, as in the case of poultry and pig under intensive system, it represents a screening device to indicate that the zone is deemed suitable for further consideration.

The herd performance parameters calculations for cattle, goat, sheep and camel system are given in FAO/IIASA (1991: Tech. Annex 5), and show how output performance values set out in Table 62 are derived.

### 6.3.1 Cattle Systems: Dairy and Meat

These systems are considered in thermal zones T1, T2, T3, T4, T5, T6, T7 and T8 (Table 60) where  $LGP \geq 120$  days (Table 61).

For the low technology system, output performance per TLU is 264.8 litres milk and 24.6 kg meat. If draught animals were desired then up to 0.09 TLU of draught animals per TLU could be produced but there would be up to 45% proportional reduction in the meat output (Table 62).

For the intermediate technology system, output performance per TLU is 768.4 litres milk and 26.0 kg of meat. If draught animals were desired then up to 0.11 TLU of draught animals per TLU could be produced but there would be up to 49% proportional reduction in the meat output (Table 62).

For the high technology system, output performance per TLU is 901.5 litres milk and 19.8 kg meat. If draught animals were desired, then up to 0.02 TLU of draught animals per TLU could be produced but there would be up to 13% proportional reduction in the meat output (Table 62).

### 6.3.2 Goat Systems: Dairy and Meat

These systems are considered in thermal zones T1, T2, T3, T4, T5, T6, T7 and T8 (Table 60), and where  $LGP \geq 120$  days (Table 61).

For the low technology system, output performance per TLU is 92.6 kg meat. For the intermediate technology system, output performance per TLU is 263.7 litres milk and 114.6 kg meat. For the high technology system, output performance per TLU is 2166.7 litres of milk and 132.7 kg meat (Table 62).

### 6.3.3 Sheep Systems: Meat and Wool

These systems are considered in thermal zones T1, T2, T3, T4, T5, T6, T7 and T8 (Table 60), and in LGP zones  $\geq 120$  days (Table 61).

**TABLE 61**  
Suitability ratings for livestock systems by LGP zone

Livestock system	Length of growing period zone (days)					
	0	1-29	30-59	60-89	90-119	> 120
<b>Cattle:</b>						
1 Dairy and meat	N	N	N	N	N	S
2 Pastoral	S <sup>1</sup>	S <sup>1</sup>	S <sup>1</sup>	S <sup>1,2</sup>	S <sup>1,2</sup>	N
<b>Goat:</b>						
3 Dairy and meat	N	N	N	N	N	S
4 Pastoral	S <sup>1</sup>	S <sup>1</sup>	S <sup>1,2</sup>	S <sup>1,2</sup>	S <sup>1,2</sup>	N
<b>Sheep:</b>						
5 Meat and wool	N	N	N	N	N	S
6 Pastoral	S <sup>1</sup>	S <sup>1</sup>	S <sup>1,2</sup>	S <sup>1,2</sup>	S <sup>1,2</sup>	N
<b>Camel:</b>						
7 Pastoral	S <sup>1</sup>	S <sup>1</sup>	S <sup>1</sup>	S <sup>1</sup>	N	N
<b>Others:</b>						
8 Poultry	N	N	N	N	S	S
9 Pig	N	N	N	N	S	S

<sup>1</sup> Nomadic

<sup>2</sup> Semi-nomadic

S – Suitable for consideration

N – Not suitable for consideration

**TABLE 62**  
Output of livestock products per herd TLU

Livestock system	Product	Input technology		
		Low	Intermediate	High
<b>Cattle:</b>				
1 Dairy and meat	Milk <sup>1</sup>	264.8	567.8	901.5
	Meat <sup>1</sup>	24.6	27.9	19.8
	Draught <sup>2</sup>	0.09	0.1	0.02
2 Pastoral	Milk	59.3	60.0	67.9
	Meat	15.4	18.6	24.6
<b>Goat:</b>				
3 Dairy and meat	Milk	-	263.7	2166.7
	Meat	92.6	114.6	132.7
4 Pastoral	Meat	7.6	13.7	19.8
<b>Sheep:</b>				
5 Meat and wool	Meat	70.5	123.0	132.2 <sup>3</sup>
	Wool	-	-	107.2 <sup>4</sup>
6 Pastoral	Meat	8.9	14.2	19.4
<b>Camel:</b>				
7 Pastoral	Milk	96.2	120.6	144.3
	Meat	1.9	2.4	2.9

<sup>1</sup> Milk in litres; Meat in kg dressed weight; Draught animals in TLUs.

<sup>2</sup> Reduce meat output by 45%, 49% and 13% in low, intermediate and high input systems respectively when considering draught animal output.

<sup>3</sup> Meat output of 132 kg/TLU applies when there is no wool production.

<sup>4</sup> Meat output of 107.2 kg/TLU applies when there is wool production of 25.0 kg/TLU in thermal zones T5, T6, T7, and T8 (Table 60).

For the low technology system, output performance per TLU is 70.5 kg of meat. For the intermediate technology system, output performance is 123 kg meat. In the high technology system output performance per TLU is 151.8 kg of meat. In thermal zones 6 and 7, output performance per TLU is 126.9 kg of meat and 25 kg wool (Table 62) for the meat and wool system.

#### 6.3.4 Pastoral Systems

##### i. Cattle: Meat and Milk

These systems are considered in thermal zones T1 to T7 (Table 60), and in LGPs < 120 days (Table 61), except for the semi-nomadic herd (high technology) which is considered only in LGP zones 60-89 and 90-119 days (Table 62). For the nomadic distant herd (low technology), output performance per TLU is 59.3 l milk and 15.4 kg meat. For the nomadic herd with market access (intermediate technology), output performance per TLU is 60 l milk and 18.6 kg meat. For the semi-nomadic herd (high technology), output performance per TLU is 67.9 l milk and 24.6 kg meat (Table 62).

##### ii. Goat: Meat

These systems are considered in thermal zones T1 to T7 (Table 60). The nomadic distant herd is considered in LGP zones < 120 days. The semi-nomadic herd is considered in LGP zones 30-59, 60-89 and 90-119 days (Table 61).

The nomadic distant herd is assumed to represent the low technology system, and its output performance per TLU is 7.6 kg meat. The semi-nomadic herd is assumed to represent the high technology system, and its output performance per TLU is 19.8 kg meat (Table 62). The output performance per TLU for the intermediate technology system is assumed to be half-way between low and high technology performances, at 13.7 kg meat/TLU.

##### iii. Sheep: Meat

These systems are considered in thermal zones T1 to T7 (Table 60). The nomadic distant herd is considered in LGPs < 120 days, and the semi-nomadic herd is considered in LGP zones 30-59, 60-89 and 90-119 days (Table 61).

The nomadic distant herd is assumed to represent the low technology system, with an output performance per TLU of 8.9 kg meat. The semi-nomadic herd is assumed to represent the high technology system, with an output performance per TLU of 19.4 kg meat (Table 62). At the intermediate level output is assumed to be half-way between the others, at 14.2 kg meat/TLU.

##### iv. Camel: Meat and Milk

The system is considered only in thermal zones T1 and T2 (Table 60), and in LGPs < 90 days (Table 61).

Output per TLU for the nomadic herd is 96.2 l milk and 1.9 kg meat (Table 62) at the low input level and 25% (120.6 l milk and 2.4 kg meat) and 50% (144.3 l milk and 2.9 kg meat) greater at the intermediate high levels respectively.

#### 6.3.5 Poultry and Pig: Meat and Egg

Poultry and pig production has been considered only under intensive systems. The feed conversion ratios for poultry meat and eggs and pig meat are given in Section 6.4.5.

Performance parameters have not been explicitly formulated for poultry and pig system at this stage of the model development, but it is envisaged that these would be incorporated at a later stage.

### 6.3.6 Pests and Diseases

Major diseases of cattle include rinderpest, trypanosomiasis, contagious bovine pleuropneumonia, dermatophilosis (strepto-thricosis), East Coast fever and other tick-borne diseases, and foot and mouth disease. Brucellosis occurs widely and parasitic gastro-enteritis is common, and takes a heavy toll of calves at low management levels. Fairly satisfactory control measures for a number of these diseases are available but continued vigilance is necessary to ensure that herds receive protection.

Foot and mouth disease is not important at the low input level, although its occurrence may prevent the export of meat. Ticks can be controlled by dipping or spraying but the provision of facilities and supervision is sometimes difficult.

Sheep and goats are susceptible to a variety of diseases including bacterial pneumonia, internal parasites, foot-rot and, in the case of goats, caprine pleuropneumonia, and, in sheep, sheep pox. Treatment is not normally available or sought, and losses can be heavy, although sick animals are killed and the carcasses utilized.

Camels are very susceptible to tick-borne disease and trypanosomiasis. However, they are rarely kept in zones with more than 90 days growing period.

The distribution of trypanosomiasis and its tse-tse vector in Kenya has been mapped and was included as one of the overlays in the land resources data base (Chapter 3). It has been assumed that in thermal zones 1, 2, 3 and 4, loss in livestock production performance would be of the order of 75% in the low technology systems and 50% in intermediate and high technology systems due to trypanosomiasis.

## 6.4 ESTIMATION OF FEED REQUIREMENTS

Part IV of the livestock productivity model (Figure 10) formulates the livestock feed requirements, taking into account maintenance and production needs, for support of the herd performances quantified in Section 6.3 for the individual livestock systems.

In order to support the body's processes and promote production, animals must consume regular supplies of various nutrients. These nutrients may be broadly defined as energy (from carbohydrates and fats), protein, vitamins, minerals and water. They are contained in animal feeds, which are largely of plant origin, in different concentrations and combinations. Under most intensive systems of animal husbandry, the animal may not always be able to obtain a balanced diet throughout the year because of seasonal variation in herbage composition.

Water is also needed by the animal, and this is obtained from three sources: drinking water; as part of the herbage or other feed; and as a result of metabolic oxidation of carbohydrates. Availability of water is a problem in some parts of Kenya, and much of the pastoral zone has limited permanent water, forcing nomadic behaviour. Certain stretches of the country have no water resources at all and such a constraint must be taken into account in final estimates of livestock carrying capacities. The available sources of information include data which would enable these areas to be identified and measured at the district level and this should be incorporated in the model for a more effective treatment.

**TABLE 63**  
**Feed requirements per herd TLU (kg/day dry weight)**

Livestock system	Inputs level		
	Low	Intermediate	High
Pastoral (< 120 days LGP)			
- Cattle	7.0	7.2	7.4
- Goat	6.6	6.8	7.0
- Sheep	6.6	6.8	7.0
- Camel	6.5	6.6	6.7
Non-pastoral (> 120 days LGP)			
- Cattle	7.8	8.5	8.9 <sup>1</sup>
- Goat	10.0	11.5	16.1 <sup>2</sup>
- Sheep	9.1	11.3	11.6

<sup>1</sup> Includes 1.2 kg/day primary products (3.2 kg/day per lactating cow)

<sup>2</sup> Includes 4.8 kg/day primary products (0.6 kg/day per lactating doe).

A summary of reference feed requirements per herd TLU is given in Table 63 for non-pastoral and pastoral systems for three input levels. In the non-pastoral systems, intake requirements for cattle, goat and sheep are based on field verification for the herd structures presented in Section 6.2 for the performance output levels described in Section 6.3. In the model, crop residue intake in the non-pastoral systems is limited to 30%, 20%, and 10% of total feed intake respectively in the low, intermediate and high technology systems.

For pastoral systems, feed requirements are based on Boudet and Riviere (1968) for the herd structures and performances presented in Sections 6.2 and 6.3. For poultry and pig, the standard requirements are used (FAO 1988b).

Feed requirements for each system are presented below.

#### 6.4.1 Cattle Systems: Dairy and Meat

In the low technology system, one cow unit requires about 3 740 kg/year of dry matter (DM), corresponding to 1 650 kg total digestible nutrients (TDN) and 210 kg digestible crude protein (DCP), for maintenance and production. These feed requirements are met by grazing Kikuyu/star grass pasture and maize stover.

In the intermediate technology system, one cow unit requires about 5 200 kg DM/yr (2 560 kg TDN and 300 kg DCP) for maintenance and production, met by grazing Kikuyu/star grass pasture and maize stover.

In the high technology system, one cow unit requires about 7 200 kg DM/yr (3 500 kg TDN and 420 kg DCP) for maintenance and production, provided by napier/bana grass pasture, by feeding maize stover and by feeding 1 165 kg concentrates.

The above requirements correspond to 7.8, 8.5 and 8.9 kg/day per reference herd TLU for the low, intermediate and high technology systems respectively (Table 63).

#### 6.4.2 Goat Systems: Dairy and Meat

In the low technology system, one doe unit requires about 470 kg DM/yr, provided by natural pasture.

In the intermediate technology system, one doe unit requires about 700 kg DM/yr, provided by a combination of sources: natural pasture (280 kg), fodder crops (280 kg) and crop residues (140 kg).

In the high technology system, one doe unit requires about 960 kg DM/yr, provided by fodder crops (610 kg), crop residues (140 kg) and concentrates (210 kg).

These requirements correspond to 10.0, 11.5 and 16.1 kg/yr per reference herd TLU for the low, intermediate and high technology systems respectively (Table 63).

#### 6.4.3 *Sheep Systems: Meat and Wool*

In the low technology system, one ewe unit needs about 360 kg DM/yr, provided by natural pasture.

In the intermediate technology system, one ewe unit requires about 610 kg DM/yr, provided by a combination of sources: natural pasture, fodder crops and crop residues.

In the high technology system, one ewe unit requires about 750 kg DM/yr, provided by natural pasture, fodder crops, crop residues and concentrates.

These requirements correspond to 9.1, 11.3 and 11.6 kg/year per reference herd TLU for the low, intermediate and high technology systems respectively (Table 63).

#### 6.4.4 *Pastoral Systems: Milk and Meat*

For the pastoral systems (LGP < 120 days), feed requirements are based on a daily intake of 2.5 kg DM per 100 kg liveweight, or 6.25 kg DM for the 250 kg reference TLU. Maintenance requirements are 2.9 feed units (FU) per day and 160 g/day digestible protein (DP). The annual maintenance dietary needs of a reference TLU are thus 1 060 FU or 2 280 kg DM (1FU = 2.15 kg DM) and 58 kg DP. Production requirements are in addition to this, at 350 extra FU/year (0.95 FU/day) and 28 kg DP (75 g/day) for weight gain of 100 kg/yr (300 g/day) or a production of 1 000 kg/year (2.74 kg/day) of milk.

These requirements correspond to 7.0, 7.2 and 7.4 kg DM/day per TLU for the low, intermediate and high technology systems respectively for cattle; 6.6, 6.8 and 7.0 kg DM/day per TLU for goats and sheep; and 6.5, 6.6 and 6.7 kg DM/day per TLU for camels (Table 63).

#### 6.4.5 *Poultry and Pig: Meat and Eggs*

These animals are considered only under intensive systems and standard requirements are used (FAO 1988). For poultry these are 2.5 kg of feed (primary products) for 1 kg of meat, and 3.5 kg of feed for 1 kg of egg mass. For pigs it is 4 kg of feed for 1 kg of meat.

### 6.5 LIVESTOCK PRODUCTIVITY POTENTIAL

Part V of the livestock productivity model (Figure 10) quantifies the livestock productivity potential (secondary productivity) of land (agro-ecological cells) by setting feed requirements of livestock systems from Part IV against feed supply from Part I.

However, before it is possible to set feed requirements against feed supply, the latter from its various sources as applicable must be quantified by agro-ecological cell in relation to the objective function driving the model.

The permissible thermal and LGP zones for the different livestock systems is taken from the Tables 60 and 61, and the expected output of the products per herd TLU is taken from Table 62 for cattle, goat, sheep and camel, and from Section 6.4.5 for poultry and pig. Where output performance is assumed to be affected by constraints, such as temperature stress or tse-tse, the expected loss in performance output is taken into account.



## Chapter 7

## Fuelwood productivity

This chapter describes the fuelwood productivity model schematically shown in Figure 13, and is structured along the lines of the crop suitability model<sup>1</sup> of the FAO-AEZ Project (FAO 1978-81). It is applied within the framework of land evaluation guidelines for forestry (FAO 1984c), and consists of the following activities:

- i. Selection of tree species and definition of LUTs (e.g., species; technology and input level; labour; capital; markets).
- ii. Determination of climatic requirements of species and LUTs and matching climatic requirements with the characteristics of the inventoried climatic zones (thermal and LGP zones), and quantifying the climatically attainable potential yields.
- iii. Determination of edaphic requirements of species and LUTs, and matching edaphic requirements with the characteristics of the inventoried soil units, textures, phases and stoniness to rate edaphic limitations.
- iv. Quantifying soil erosion hazards (topsoil loss) in each climate-soil unit of the land resources inventory by LUT, and the associated productivity losses.
- v. Modifying the potential yields from (ii) according to soil limitations (iii) and erosion hazards (iv) to quantify potential yields and ecological land suitabilities of each inventoried climatic-soil land unit for each LUT.

The model operates on the land resources database described in Chapter 3, and the above activities are described in the following sections.

### 7.1 TREE SPECIES AND LUTs

A large number of species can be considered in the model, but only the 31 listed in Table 64 were included in the model for Kenya as they provided a sufficiently wide range of possibilities to meet all the perceived requirements. The list gives information on height, coppicing ability, nitrogen fixing ability, density, calorific value and utilization. Each tree species is considered for fuelwood production at three levels of inputs — low, intermediate and high. The attributes of the three input levels are listed in Table 65, and they formed the basis for definition of the LUTs.

<sup>1</sup> In the AEZ rainfed suitability model, the term productivity normally refers to land's production potential for the total length of growing period over years. Perennial fuelwood species utilize all the time available in a growing period over the rotation age so that the term fuelwood productivity is synonymous with the term fuelwood yield.

**FIGURE 13**  
**Schematic presentation of the land suitability assessment model for fuelwood production**

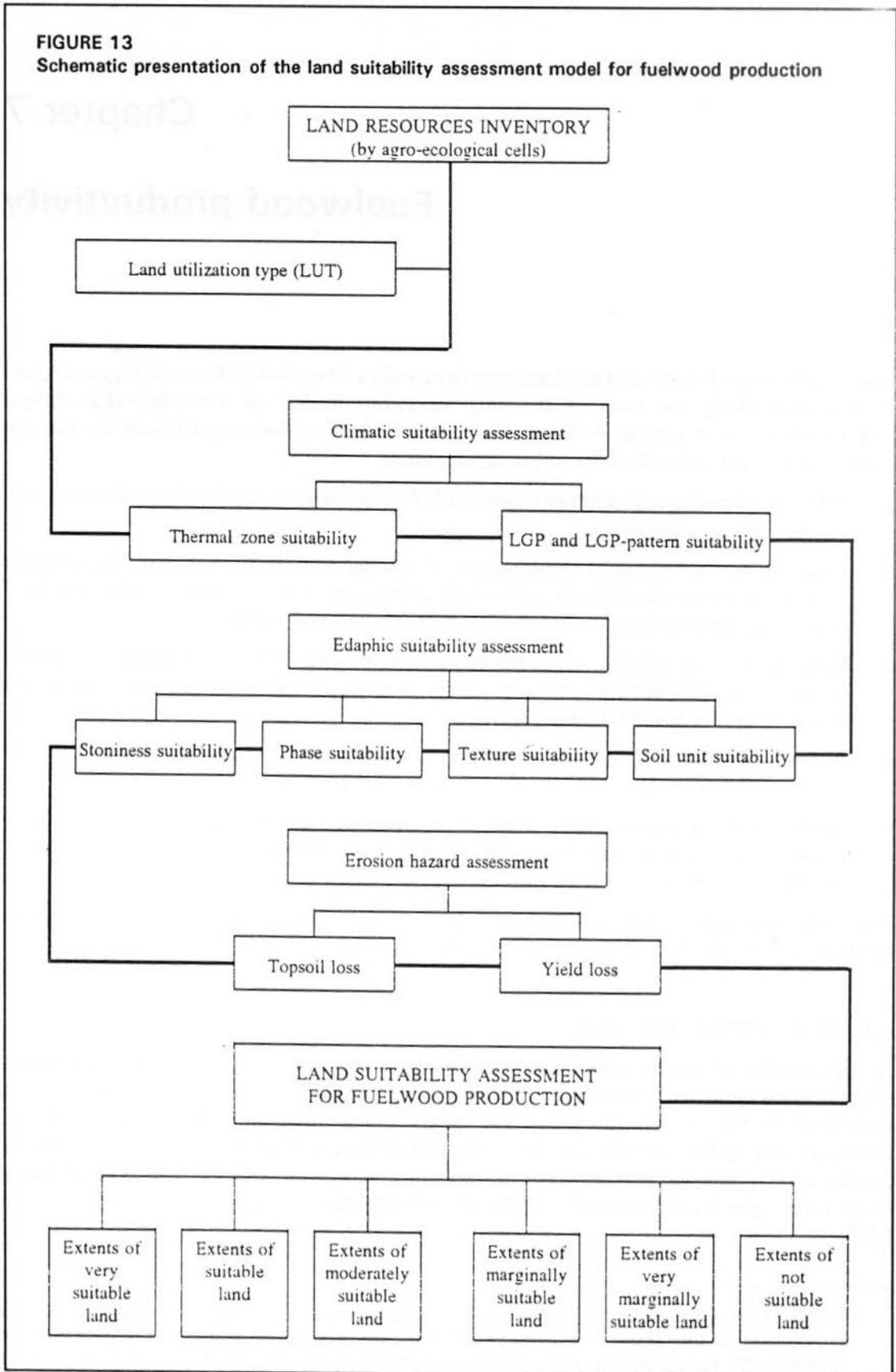


TABLE 64  
Fuelwood species characteristics

Species	Mature height (m)	Coppicing ability	N-fixer	Density (gm/cm <sup>3</sup> )	Calorific value (Kcal/kg)	Utilization
<i>Acacia albida</i>	20-30		✓			Fo
<i>Acacia gerrardii</i>	10-15		✓			Fo
<i>Acacia nilotica</i>	15-20	++	✓	0.65-0.70	4800-4950	C,Fo,G,Ho,S
<i>Acacia senegal</i>	2-5	++	✓			C,Fo,G,T
<i>Acacia tortilis</i>	4-10		✓			Fo
<i>Bridelia micrantha</i>	8-15					C,T
<i>Calliandra calothyrsus</i>	8-12	++	✓	0.50-0.80	4500	Fo,Ho,M,Or
<i>Calodendrum capense</i>	10-20					C,Or,T
<i>Cassia siamea</i>	15-20	++		0.60-0.80	4500-4600	C,D,Fo*,H,M,Or,S,T,Wb
<i>Casuarina equisetifolia</i>	25-30	+	✓	0.80-1.20	4950	C,D,Fo,P,T,Wb
<i>Casuarina cunninghamiana</i>	25-30		✓			C
<i>Conocarpus lancifolius</i>	15-18		✓	0.81		C,Fo,T
<i>Croton megalocarpus</i>	15-25		✓			C,T
<i>Cupressus lucitanica</i>	25-30			0.45-0.48		-
<i>Eucalyptus camaldulensis</i>	30-40	++		0.55-0.85	4800	C,Fo,H,Ho,Or,P,S,T,Wb
<i>Eucalyptus citriodora</i>	30-40	+		0.65-1.10	4750	C,Fo,Ho,O.P.T
<i>Eucalyptus globulus</i>	40-50	++		0.55-0.78		C,P,Pl,T
<i>Eucalyptus grandis</i>	40-55	++		0.48-0.64		C,P,Pl,T
<i>Eucalyptus microcorys</i>	25-30	++		0.90-0.99		T
<i>Eucalyptus microtheca</i>	10-20	+		0.75-0.85		C,T
<i>Eucalyptus saligna</i>	35-45	++		0.48-0.64		C,O,P,Pl,T
<i>Eucalyptus tereticornis</i>	35-45	++		0.65-1.05	4800	C,Fo,Ho,O,P,Pl,S,Sb,T
<i>Faurea saligna</i>	5-10					C,Ho,T
<i>Gliricidia sepium</i>	5-15	++	✓	0.40-0.65	4900	C,Fb,Fo*,Ho,M,Or,S,T
<i>Grevillea robusta</i>	25-35		✓	0.54-0.66		C,Pl,T
<i>Leucaena leucocephala</i>	10-20	++	✓	0.50-0.70	4200-4600	C,Fo*,M,Or,P,S,T
<i>Olea africana</i>	3-6					C,Fr,T
<i>Parkinsonia aculeata</i>	4-5	++				Fo,Wb
<i>Prunus africanum</i>	25-30					T
<i>Sesbania sesban</i>	4-8	++	✓	0.40-0.50	4500-4600	Fo
<i>Tamarindus indica</i>	20-30		✓			C,T

Sources: C.M. Ndegwa, Project GCP/KEN/051/AUL, 'Fuelwood afforestation and extension in Baringo', pers. comm. 1988; Davidson 1985; Teel 1984; Skerman 1982; Goehl 1981; Webb, Wood and Smith 1980; FAO 1981.

Coppicing ability: ++ = good; + = fair; no entry indicates poor or none.  
Utilization: C = charcoal; D = dye; Fb = firebreak; Fo = fodder; Fo\* = fodder (but potentially toxic); Fr = fruit; G = gum; H = hedge; Ho = honey; M = green manure; O = oil; Or = ornamental; P = pulp (wood); Pl = plywood, board, etc.; S = shade; Sb = shelterbelt; T = timber, etc.; Wb = windbreak.

## 7.2 CLIMATE ADAPTABILITY AND YIELD POTENTIAL

Understanding the relationships between the climatic environment and ecophysiological processes of growth, development and yield in trees forms the basis of formulating quantitative descriptions of the climatic adaptability of improved and unimproved provenances and their productivity potentials in land use. Principles of climatic adaptability for plants are described in Kassam, Kowal and Sarraf (1977) and (FAO 1978-81).

Photosynthesis produces the source of assimilates which plants use for growth, and the rate of photosynthesis is influenced by both temperature and radiation. However, plants are also obliged to undergo sequences of phenological and morphological developments in time and space to allow photosynthetic assimilates to be converted into growth of plant parts and economically useful yields of satisfactory quantity and quality. Tree phenology is influenced primarily by climatic factors, and, in general, temperature determines the rate of growth and development of plant parts and the tree as a whole. However, in some tree species, temperature may also determine whether a particular development process will or will not begin (e.g., a chilling requirement for bud formation and floral initiation), the time when bud break will occur, the subsequent rate of development and the time when the process will stop (Cannell and Last 1976).

**TABLE 65**  
**Attributes of LUTs considered for fuelwood production**

Attribute	Low inputs	Intermediate inputs	High inputs
Produce and production	Rainfed production of fuelwood tree species for firewood or charcoal		
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 source	Manual labour with hand tools	Manual labour with handtools, some mechanization	Complete mechanization, including harvesting
Technology	Local provenances; no agro-chemicals; minimum conservation measures	Improved provenances as available; appropriate extension packages, including some fertilizer application and pest and disease control; some conservation measures	High yielding provenances; optimum fertilizer use; chemical pest and disease control; full conservation measures
Infrastructure	Market access not necessary; inadequate advisory services	Some market accessibility necessary, with access to nurseries, demonstration plots and advisory services	Market access essential; high level of nursery and advisory services; application of research findings
Land holding	Small, fragmented	Small, sometimes fragmented	Large, consolidated
Income level	Low	Moderate	High

In the seasonally dry climates of Kenya, ability to survive the dry period is an important adaptability characteristic, just as frost hardiness is for survival in the cooler thermal zones at higher altitudes. Accordingly, in assessments of land suitabilities, consideration has to be given to the specific climatic requirements and adaptability for survival, growth and development.

### 7.2.1 Photosynthetic Characteristics

All the fuelwood species considered for Kenya have a  $C_3$  photosynthetic pathway and were classified into two adaptability groups (Table 66): group I adapted to cooler conditions (mean temperatures  $10^{\circ}$ - $20^{\circ}$ C) and group II adapted to warmer conditions (mean temperatures  $20^{\circ}$ - $30^{\circ}$ C). Both groups include species with nitrogen fixing capability.

Rates of maximum photosynthesis ( $P_{max}$ ) for both groups are in the range 5-30 kg  $CH_2O$ /ha/hr (Landsberg 1986), so they can be further classified into three photosynthesis productivity classes with  $P_{max} = 5-10, 10-20$  or  $20-30$  kg  $CH_2O$ /ha/hr (classed A, B, and C respectively) corresponding to mean annual total (including foliage, stem and roots) biomass increments of 12.5-25.0, 25.0-40.0 and 40.0-60.0 t/ha dry weight respectively, or annual wood biomass (stem and branch wood) increments of 8.0-15.0, 15.0-25.0 and 25.0-40.0 t/ha dry weight respectively. The relationships between photosynthesis and temperature for these six adaptability classes are presented in Table 67.

### 7.2.2 Rotation Length

Rotation length in the model is taken as the age at 'maximum yield', and is when annual increment is equal to mean annual increment over the total period since establishment (Nilsson 1983). Rotation length is affected by the photosynthetic productivity class of the species and by LGP, and the rotation lengths used in the model for Kenya are given in Table 68.

**TABLE 66**  
Adaptability groups for fuelwood species

Characteristics	Group I (< 20°C)	Group II (> 20°)
Photosynthetic pathway	C <sub>3</sub>	C <sub>3</sub>
Rate of maximum photosynthesis (P <sub>max</sub> ) (kg CH <sub>2</sub> O/ha/hr)	5-30	5-30
Optimum temperature (mean) for P <sub>max</sub> (°C)	15-20	20-30
Productivity class A (P <sub>max</sub> = 5-10 kg CH <sub>2</sub> O/ha/hr)	<i>Acacia gerrardii</i> (N) <i>Croton megalocarpus</i> (N) <i>Grevillea robusta</i> (N) <i>Oleo africana</i> (N)	<i>Acacia albida</i> (N) <i>Acacia nilotica</i> (N) <i>Acacia tortilis</i> (N) <i>Calliandra calothyrsus</i> (N) <i>Conocarpus lancifolius</i> (N) <i>Gliricidia sepium</i> (N) <i>Tamarindus indica</i> (N)
Productivity class B (P <sub>max</sub> = 10-20 kg CH <sub>2</sub> O/ha/hr)	<i>Bridella micrantha</i> <i>Calodendrum capense</i> <i>Casuarina cunninghamiana</i> (N) <i>Cupressus lucitanica</i> <i>Eucalyptus microcorys</i> <i>Faurea saligna</i> <i>Prunus africanum</i>	<i>Bridella micrantha</i> <i>Cassia siamea</i> (N) <i>Casuarina equisetifolia</i> (N) <i>Eucalyptus citriodora</i> <i>Eucalyptus microtheca</i> <i>Eucalyptus tereticornis</i> <i>Parkinsonia aculeata</i>
Productivity class C (P <sub>max</sub> = 20-30 kg CH <sub>2</sub> O/ha/hr)	<i>Eucalyptus globulus</i> <i>Eucalyptus saligna</i> (N) <i>Sesbania sesban</i>	<i>Eucalyptus camaldulensis</i> <i>Eucalyptus grandis</i> <i>Eucalyptus saligna</i> <i>Leucaena leucocephala</i> (N) <i>Sesbania sesban</i> (N)

(N) - Nitrogen fixer

**TABLE 67**  
Relationships between temperature and rate of photosynthesis (kg CH<sub>2</sub>O/ha/hr) for six adaptability classes of fuelwood species

Adaptability class	Temperature (°C)							
	5	10	15	20	25	30	35	40
I - A	0.75	3.0	6.0	7.5	7.5	6.0	3.0	1.5
I - B	1.5	6.0	12.0	15.0	15.0	12.0	6.0	3.0
I - C	2.5	10.0	20.0	25.0	25.0	20.0	10.0	5.0
II - A	-	0.75	4.0	6.0	6.0	7.5	6.0	4.0
II - B	-	1.5	8.0	12.0	12.0	25.0	12.0	8.0
II - C	-	2.5	15.0	20.0	20.0	25.0	20.0	15.0

**TABLE 68**  
Rotation length (years) by moisture zones

Photosynthetic productivity class	Semi-arid	Dry Sub-humid	Moist Sub-humid	Humid
	60-119 days	120-179 days	180-269 days	≥270 days
A	15.0-17.5	12.5-15.0	10.0-12.5	7.5-10.0
B	12.5-15.0	10.0-12.5	7.5-10.0	5.0-7.5
C	10.0-12.5	7.5-10.0	5.0-7.5	< 5.0

**TABLE 69**  
Thermal zone suitability ratings for fuelwood species

Species	T1 >25°	T2 22.5- 25.0°	T3 20.0- 22.5°	T4 17.5- 20.0°	T5 15.0- 17.5°	T6 12.5- 15.0°	T7 10.0- 12.5°	T8 5.0- 10.0°	T9 <5.0°
<i>Acacia albida</i>	S1	S1	S1	S3	S4	N	N	N	N
<i>Acacia gerrardii</i>	S4	S3	S1	S1	S1	S1	S3	N	N
<i>Acacia nilotica</i>	S1	S1	S1	S1	S3	N	N	N	N
<i>Acacia senegal</i>	S1	S1	S1	S3	S4	N	N	N	N
<i>Acacia tortilis</i>	S1	S1	S1	S3	S4	N	N	N	N
<i>Bridelia micrantha</i>	S1	S1	S1	S1	S1	S1	S3	N	N
<i>Calliandra calothyrsus</i>	S1	S1	S1	S3	S4	N	N	N	N
<i>Calodendrum capense</i>	S4	S3	S1	S1	S1	S1	S3	N	N
<i>Cassia siamea</i>	S1	S1	S1	S3	S4	N	N	N	N
<i>Casuarina equisetifolia</i>	S1	S1	S1	S1	S3	N	N	N	N
<i>Casuarina cunninghamiana</i>	S4	S3	S1	S1	S1	S1	S3	N	N
<i>Conocarpus lancifolius</i>	S1	S3	S4	N	N	N	N	N	N
<i>Croton megalocarpus</i>	S4	S3	S1	S1	S1	S1	S3	N	N
<i>Cupressus lucitanica</i>	N	S4	S3	S1	S1	S1	S3	N	N
<i>Eucalyptus camaldulensis</i>	S1	S1	S1	S3	N	N	N	N	N
<i>Eucalyptus citriodora</i>	S1	S1	S1	S1	S3	N	N	N	N
<i>Eucalyptus globulus</i>	S4	S3	S1	S1	S1	S3	N	N	N
<i>Eucalyptus grandis</i>	S1	S1	S1	S1	S3	N	N	N	N
<i>Eucalyptus microcorys</i>	S4	S3	S1	S1	S1	S1	S3	N	N
<i>Eucalyptus microtheca</i>	S1	S1	S1	S3	N	N	N	N	N
<i>Eucalyptus saligna</i>	S1	S1	S1	S1	S1	S1	S3	N	N
<i>Eucalyptus tereticornis</i>	S1	S1	S1	S1	S3	N	N	N	N
<i>Faurea saligna</i>	S4	S3	S1	S1	S1	S1	S2	N	N
<i>Gliricidia sepium</i>	S1	S1	S1	S1	S3	N	N	N	N
<i>Grevillea robusta</i>	S4	S3	S1	S1	S1	S1	S2	N	N
<i>Leucaena leucocephala</i>	S1	S1	S1	S3	S4	N	N	N	N
<i>Oleo africana</i>	N	S4	S3	S1	S1	S1	S3	N	N
<i>Parkinsonia aculeata</i>	S1	S1	S1	S3	S4	N	N	N	N
<i>Prunus africanum</i>	N	S4	S1	S1	S1	S1	S3	N	N
<i>Sesbania sesban</i>	S1	S1	S1	S1	S1	S1	S3	N	N
<i>Tamarindus indica</i>	S1	S1	S1	S3	S4	N	N	N	N

### 7.2.3 Climatic Yield Potentials

Thermal zone ratings for each of the species are given in Table 69. Five suitability classes are employed (i.e., S1, very suitable; S2, suitable; S3, moderately suitable; S4, marginally suitable; and N, not suitable), and the ratings apply to production at all the three levels of inputs. The correction factors applied in the model to reflect temperature constrained depressions in potential yields are reductions of 25% for S2, 50% for S3, 75% for S4, with N as not suitable.

Growing period zones which have been considered for yield assessments for each species are shown in Table 70, which represents a moisture screen, and is based on actual research information obtained from local experiments and permanent sample plots.

Although ecophysiological models have not been widely applied elsewhere in the estimation of stand and site productivity potentials, a useful description of the state-of-the art is given in Landsberg (1986). Potential attainable yields (total and wood biomass) were derived according to the method developed by the FAO-AEZ Project (Kassam 1977; FAO 1978-81), and modified to take into account the generally accepted fact that for fuelwood tree species, total biomass yield at 50% of rotation length is 38% of the standing total biomass yield at 100% rotation length (Nilsson 1983).

It is assumed that wood biomass (stem wood and branch wood) is 0.6 of total biomass, foliage biomass 0.2 and root biomass 0.2. Partitioning of total wood biomass into main stem

and branch wood biomass is assumed to be in the ratio of 4:1. Leaf area index at maximum annual growth rate is assumed to be 5 or more, and the period of annual growth is equal to the inventoried lengths of growing period. These reference model variables can be modified as appropriate to take into account differences between species and environments.

Total biomass productivity estimates (Bm) in terms of mean annual increments (t/ha dry weight) are given in the Appendix in Table A7.1 for high level of inputs by length of growing period for species with and without nitrogen fixing ability for the three photosynthesis productivity classes. Site yield potentials at low input levels are assumed to be 50% of those at the high level and 75% at intermediate levels of inputs. Total biomass productivity for intermediate and low levels of inputs are given in the Appendix in Tables A7.2 and A7.3 respectively.

Wood biomass yield estimates (Bw) in terms of mean annual increments (t/ha dry weight) are given in the Appendix in Tables A7.4, A7.5 and A7.6 respectively for high, intermediate and low input levels. Wood biomass estimates in Tables A7.4, A7.5 and A7.6 apply in the growing period zones allowable by the moisture screen in Table 70.

All tree species are matched to total lengths of L1, L2, L3 and L4. Yields in Tables A7.1 to A7.6 apply to years with normal LGP, i.e., growing period with a humid period during which precipitation is greater than potential evapotranspiration. For years with intermediate growing periods, i.e., growing periods with no humid period, full water requirements cannot be met and yield reductions are assumed to be of the order of 50% on all soils except Fluvisols and Gleysols. The percentage of occurrence of intermediate lengths of growing periods in all LGP-Pattern zones is 100% in LGP zone 1-29 days; 65% in LGP zone 30-59 days; 25% in LGP zone 60-89 days; 10% in LGP zone 90-119 days; and 5% in LGP zone 120-149 days.

At this stage in the model development it has not been possible to take into account in the climatic suitability assessment other climatically driven constraints such as pests and diseases and workability, which may reduce yield. It should be possible to take such constraints into account in the future as the information and research base for fuelwood production improves.

An exception to the general methodology for climatic suitability assessment applies to areas occupied by Fluvisols, as the nominal LGP does not fully reflect their particular moisture regime characteristics. Fluvisols ratings are given in FAO/IIASA (1991: Tech. Annex 6) for the three input levels.

### 7.3 EDAPHIC ADAPTABILITY AND SUITABILITY

In order to assess soil suitability for fuelwood production, the soil requirements of tree species must be determined. Further, these requirements must be understood within the context of limitation imposed by landform and other features (e.g., soil phases) which do not form part of soil composition but have a significant influence on the use that can be of the soil.

#### 7.3.1 Basic Soil Requirements

From the basic soil requirements for forestry land use, a number of responses related to soil characteristics have been derived for the fuelwood species, and the correlations between the basic soil requirements listed in Section 5.1.3.ii and soil characteristics given in Table 42 have been used as soil factors to rate tree crop performance and soil requirements for fuelwood species, as summarized in Table 71.



TABLE 71  
Soil requirements of fuelwood species

Species	Texture		Drainage		Soil depth (cm)		Reaction (pH)		Salinity (mmhos)		Flooding	
	optimum	range	optimum	range	optimum	marginal	optimum	range	optimum	marginal	optimum	marginal
<i>Acacia albida</i>	SL-SC	LS-KS	W	MW-SE	> 120	75-120	5.5-7.0	5.0-7.5	< 4	4-6	F0	F1
<i>Acacia gerrardii</i>	L-C	SL-KC	MW-W	I-SE	> 120	75-120	5.5-7.0	5.0-7.5	< 4	4-6	F1	F2
<i>Acacia nilotica</i>	L-C	SL-KC	W	MW-SE	> 120	75-120	5.5-7.5	5.0-8.0	< 4	4-8	F1	F2
<i>Acacia senegal</i>	SL-SC	LS-KC	W	MW-SE	> 120	75-120	5.5-7.0	5.0-7.5	< 4	4-6	F0	F1
<i>Acacia tortilis</i>	SL-SC	LS-KC	W	MW-SE	> 75	50-75	6.5-8.0	6.0-8.5	< 4	4-8	F0	F1
<i>Bridelia micrantha</i>	SL-SC	LS-KC	W	MW-SE	> 120	75-120	5.5-7.0	5.0-7.5	< 4	4-6	F0	F1
<i>Calliandra calothyrsus</i>	SL-SC	LS-KC	W	MW-SE	> 120	75-120	6.0-7.0	5.5-7.5	< 4	4-6	F0	F1
<i>Calodendrum capense</i>	SL-SC	LS-KC	W	MW-SE	> 120	75-120	5.5-7.0	5.0-7.5	< 4	4-8	F0	F1
<i>Cassia siamea</i>	SL-CL	LS-SiC	W	MW-SE	> 150	100-150	6.0-7.0	5.5-7.5	< 4	4-6	F0	F1
<i>Casuarina equisetifolia</i>	SL-SiL	LS-CL	W	MW-SE	> 120	75-120	6.5-8.0	6.0-8.5	< 12	12-16	F1	F2
<i>Casuarina cunninghamiana</i>	SL-SC	LS-KC	W	MW-SE	> 120	75-120	5.5-7.0	5.0-7.5	< 4	4-6	F1	F2
<i>Conocarpus lancifolius</i>	SL-CL	LS-SC	W	MW-W	> 120	75-120	6.5-8.0	6.0-8.5	< 8	8-12	F1	F2
<i>Conocarpus lanicifolius</i>	SL-SC	LS-KC	W	MW-SE	> 120	75-120	6.5-8.0	6.0-8.5	< 4	4-8	F0	F1
<i>Croton megalocarpus</i>	SL-SC	LS-KC	W	MW-SE	> 150	100-150	5.5-7.0	5.0-7.5	< 4	4-6	F1	F2
<i>Cupressus lucitanica</i>	L-CL	SL-SC	W	MW-SE	> 120	75-120	5.0-6.5	4.5-7.5	< 2	2-4	F1	F2
<i>Eucalyptus cameldulensis</i>	SL-SC	LS-KC	MW-W	I-SE	> 120	75-120	5.5-7.0	5.0-7.5	< 4	4-6	F0	F1
<i>Eucalyptus citriflora</i>	SL-CL	LS-SiC	W	MW-SE	> 150	100-150	5.5-7.0	5.0-7.5	< 2	2-4	F0	F1
<i>Eucalyptus globulus</i>	L-C	SL-KC	W	MW-SE	> 120	75-120	5.5-7.0	5.0-7.5	< 4	4-6	F0	F1
<i>Eucalyptus grandis</i>	L-CL	SL-SiC	W	MW-SE	> 120	75-120	5.5-7.5	5.0-8.0	< 4	4-8	F1	F2
<i>Eucalyptus microcorys</i>	L-C	SL-KC	W	MW-SE	> 120	75-120	5.5-7.5	5.0-8.0	< 4	4-8	F1	F2
<i>Eucalyptus microtheca</i>	L-C	SL-KC	MW-W	I-SE	> 120	75-120	6.5-8.0	6.0-8.5	< 4	4-8	F0	F1
<i>Eucalyptus saligna</i>	SL-CL	LS-SiC	W	MW-SE	> 120	75-120	5.5-7.0	5.0-7.5	< 4	4-6	F0	F1
<i>Eucalyptus tereticornis</i>	SL-SC	LS-KC	W	MW-SE	> 120	75-120	5.5-7.0	5.0-7.5	< 4	4-6	F0	F1
<i>Faurea saligna</i>	SL-SC	LS-KC	W	MW-SE	> 120	75-120	5.5-7.0	5.0-7.5	< 4	4-8	F0	F1
<i>Girardinia sepium</i>	SL-SC	LS-SiC	W	MW-SE	> 120	75-120	5.0-6.5	4.5-7.0	< 2	2-4	F0	F1
<i>Grevillea robusta</i>	SL-CL	LS-SiC	W	MW-SE	> 120	75-120	5.5-7.0	5.0-7.5	< 4	4-8	F0	F0
<i>Leucaena leucocephala</i>	SL-SC	LS-KC	W	MW-SE	> 75	50-75	5.5-7.0	5.5-8.5	< 8	8-12	F0	F0
<i>Oleo africana</i>	SL-SC	LS-KC	W	MW-SE	> 120	75-120	6.5-8.0	6.0-8.5	< 4	4-8	F0	F1
<i>Parkinsonia aculeata</i>	SL-CL	LS-SiC	W	MW-SE	> 120	75-120	6.5-8.0	6.0-8.5	< 8	8-12	F0	F1
<i>Prunus africana</i>	SL-SC	LS-KC	W	MW-SE	> 120	75-120	5.5-7.0	5.0-7.5	< 4	4-6	F0	F1
<i>Sesbania sesban</i>	SL-SC	LS-KC	MW-W	I-SE	> 120	75-120	6.0-7.0	5.5-7.5	< 12	12-16	F1	F2
<i>Tamarindus indica</i>	SL-SC	LS-KC	W	MW-SE	> 120	75-120	5.5-7.5	5.0-7.5	< 4	4-6	F0	F1

Texture classes: LS = loamy sand; SL = sandy loam; SiL = silty loam; L = loam; CL = clay loam; SC = sandy clay; SiC = silty clay; C = clay; KC = kaolinitic clay.  
 Drainage classes: I = imperfectly; MW = moderately well; W = well; SE = somewhat excessive.  
 Flooding classes: FO = no flooding; F1 = occasional floods; F2 = frequent floods.

As explained earlier, the soil units have been defined in terms of measurable and observable properties of the soil itself; and specific clusters of such properties combined into diagnostic horizons and diagnostic properties. They are also used in rating soil suitability.

### 7.3.2 Edaphic Suitability

The edaphic suitability classification is input-specific and based on:

- i. matching the soil requirements of fuelwood species with the soil conditions of the soil units described in the soil inventory (soil unit evaluation); and
- ii. modification of the soil unit evaluation by limitations imposed by texture, phase and slope conditions.

The soil unit evaluation for fuelwood species production is expressed as five ratings for each of three input levels, based on how far the soil conditions of a soil unit meet the growth and production requirements, the usual S1 to S4, and N, with a 25% depression of yield in S2, 50% in S3, 75% in S4 and not suitable in N.

The soil unit ratings used in the Kenya example for fuelwood are given in FAO/IIASA (1991: Tech. Annex 6), and were applied as given there, except where it was necessary to modify them to account for additional limitations imposed by soil texture, phase or stoniness.

In the case of soil texture, soil unit ratings remained unchanged if the soil was an albic, cambic, ferralic, calcareo-cambic or luvic Arenosol (Q, Qa, Qc, Qf, Qkc, Ql) or a vitric Andosol (Tv), or where textures were medium (fine sandy loam, sandy loam, loam, sandy clay loam, clay loam, silty clay loam, silt), or fine (sandy clay, silty clay, peaty clay, clay). In all other cases (i.e., with coarse textures: sand, loamy coarse sand, fine sand, loamy fine sand, loamy sand) the soil unit rating was one class (25%) lower.

Limitations imposed by phase and stoniness were rated using the five basic classes already described, and are presented in FAO/IIASA (1991: Tech. Annex 6).

## 7.4 SLOPE LIMITATIONS AND SOIL EROSION

Limitations imposed by slope are taken into account in three steps, as described in Chapter 4. Step one defines the slopes which are permissible for fuelwood production, and as a model variable this is defined as slopes less than 45% (Table 26).

Step two involves the computation of potential topsoil loss which is estimated, by input level, through a modified Universal Soil Loss Equation (Wischmeier and Smith 1978).

Step three relates the estimated topsoil losses to yield losses through the set of equations given in Table 29, taking into account soil susceptibility (Table 28), level of inputs and regeneration capacity of topsoil (Table 27).

## 7.5 LAND SUITABILITY ASSESSMENT

### 7.5.1 Fuelwood Productivity Potential

All three assessments — the climatic suitability, the edaphic suitability and the soil erosion hazard — are required to determine the ecological land suitability for fuelwood production of each climate-soil unit of the land resources inventory. In essence the land suitability assessment takes account of all the inventoried attributes of land and compares them with the requirements

of the fuelwood species, to give an easy to understand picture of the suitability of land for the production of fuelwood.

The results of the land suitability assessment are grouped into six suitability classes linked to attainable yields (mean annual increment) for the three levels of inputs considered. At each input level the land classes are: very suitable, VS —  $\geq 80\%$  of maximum attainable yield; suitable, S —  $< 80\%$  to  $\geq 60\%$ ; moderately suitable, MS —  $< 60\%$  to  $\geq 40\%$ ; marginally suitable, mS —  $< 40\%$  to  $\geq 20\%$ ; very marginally suitable, Vms —  $< 20\%$  to  $\geq 5\%$ ; and not suitable, NS —  $< 5\%$ .

Land suitability for fuelwood production is assessed by applying the steps shown schematically in Figure 13. The assessment is carried out separately for each species and level of inputs in a manner analogous to the steps explained in Section 5.1.5 for crops.

The six classes of land suitabilities are related to attainable yield as a percentage of the maximum attainable under the optimum climatic, edaphic and landform conditions, and so provide an assessment of fuelwood productivity potential of each land unit for calculation of the rainfed production potential of any given area.

The generalized results of land suitability assessment for *Eucalyptus camaldulensis* at the intermediate input level are presented in Plate 16. Land suitability results for all fuelwood species considered in the Kenya exercise are presented in FAO/IIASA (1991: Tech. Annex 8).

#### 7.5.2 Linkage to Crop and Livestock Productivity Models

Within the overall population supporting capacity model, the fuelwood productivity model is interlinked with crop and livestock productivity models. The interlinkage in essence allows the possibility of considering:

- i. fuelwood production on land assessed as not suitable for crops;
- ii. any portion of crop land for fuelwood production depending on how much land is required for other land uses to meet demand; and
- iii. fodder from fuelwood trees for livestock production.

Any land which is allocated to fuelwood production with species having palatable foliage would have the potential of contributing a portion of this foliage to fodder for livestock production.

Fuelwood species which offer palatable fodder for livestock are indicated in Table 64. The amount of fodder which can be utilized by stock without affecting fuelwood yields would depend on the species and ecological situation. However, at this stage of the model interlinkage development, it is assumed that about 10% of the foliage may be utilized by stock without affecting fuelwood yields. The nominal foliage utilization coefficient values may be modified as appropriate for each species and environment.

*The following maps are based on the land resources inventory of 1980-1982 in generalized form.*

*The designations employed and the presentation of the material in these maps do not imply the expression of any opinion whatsoever on the part of FAO or IIASA concerning the legal or constitutional status of any sea area or concerning the delineation of frontiers.*

*Any part of the national land resources data base and the productivity models described in this report may be modified in the light of new knowledge or new objectives. The data base and the models are part of a larger district and national level planning tool and they are expected to be expanded and refined with use.*

PLATE 1

Generalized map of thermal zones in Kenya

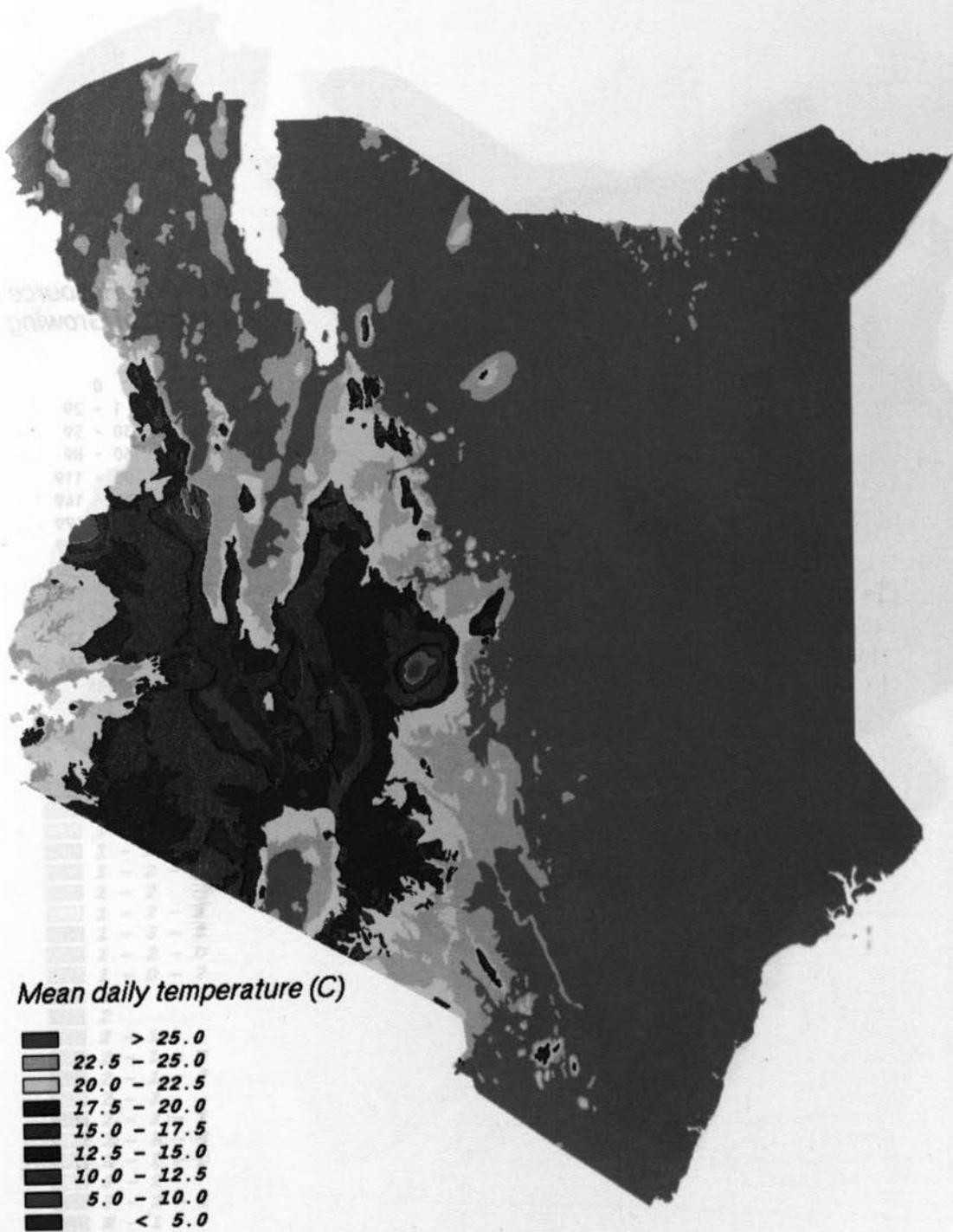


PLATE 1

Generalized map of thermal zones in Kenya

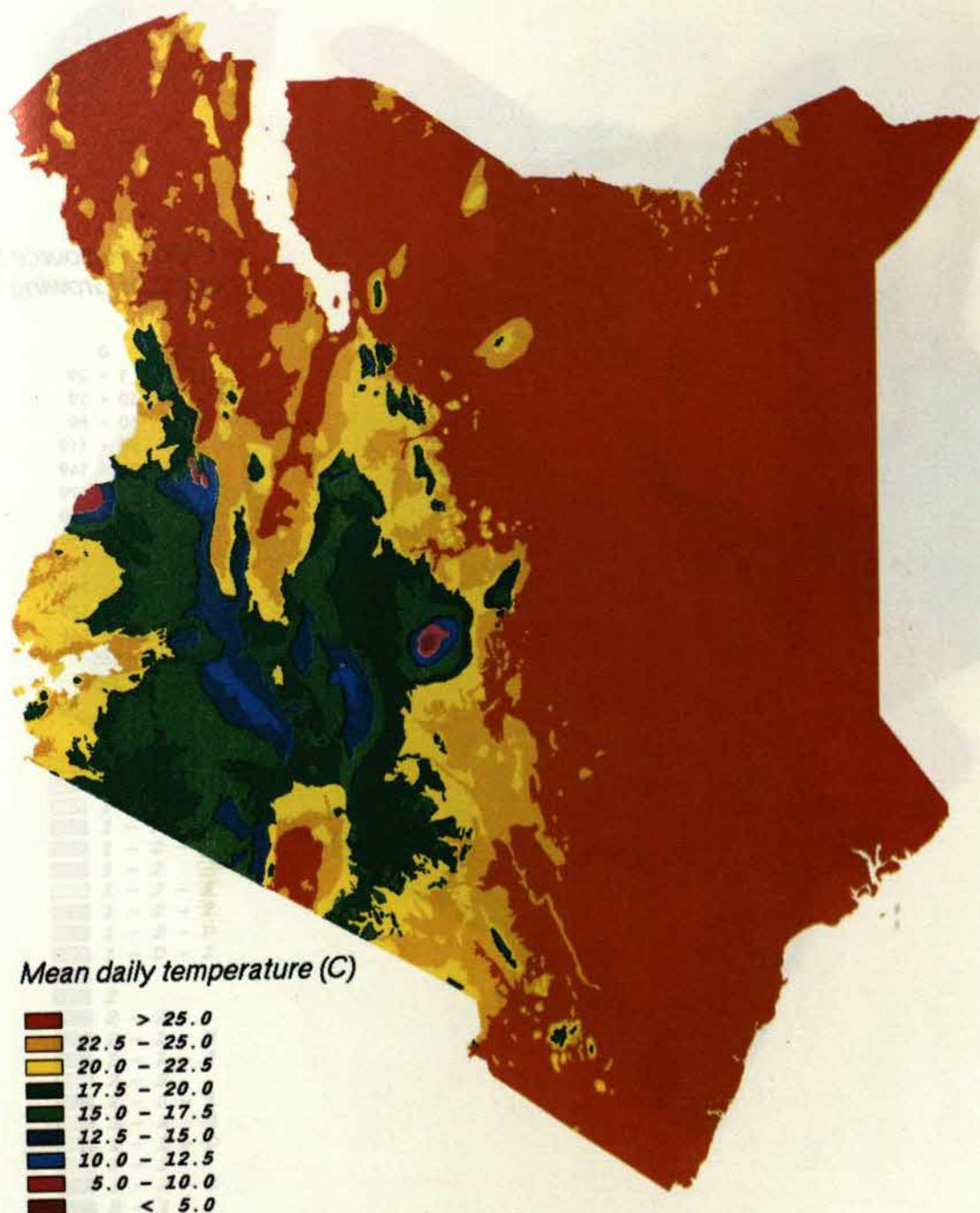


PLATE 2

Generalized map of mean total dominant LGP zones in Kenya

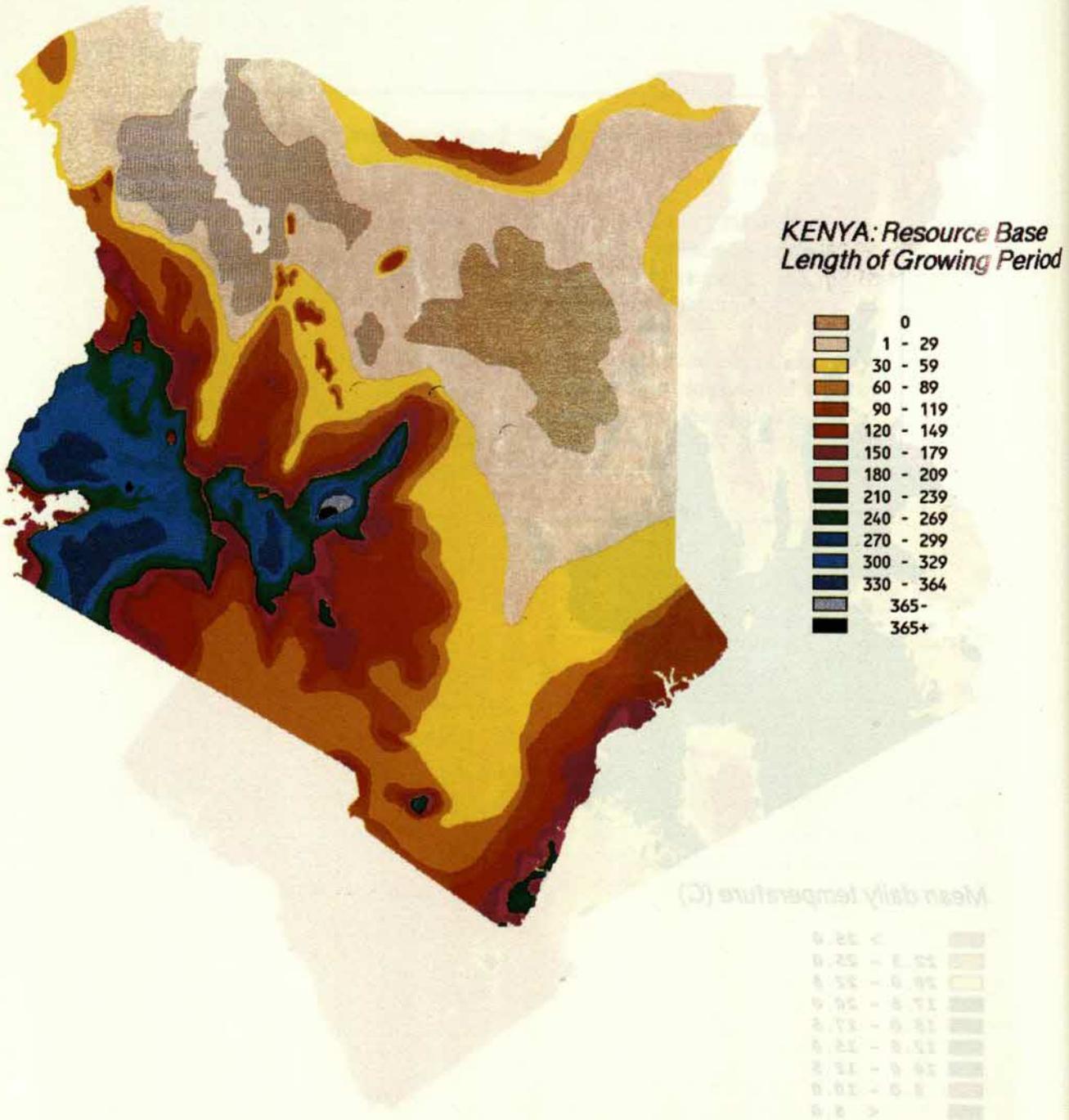
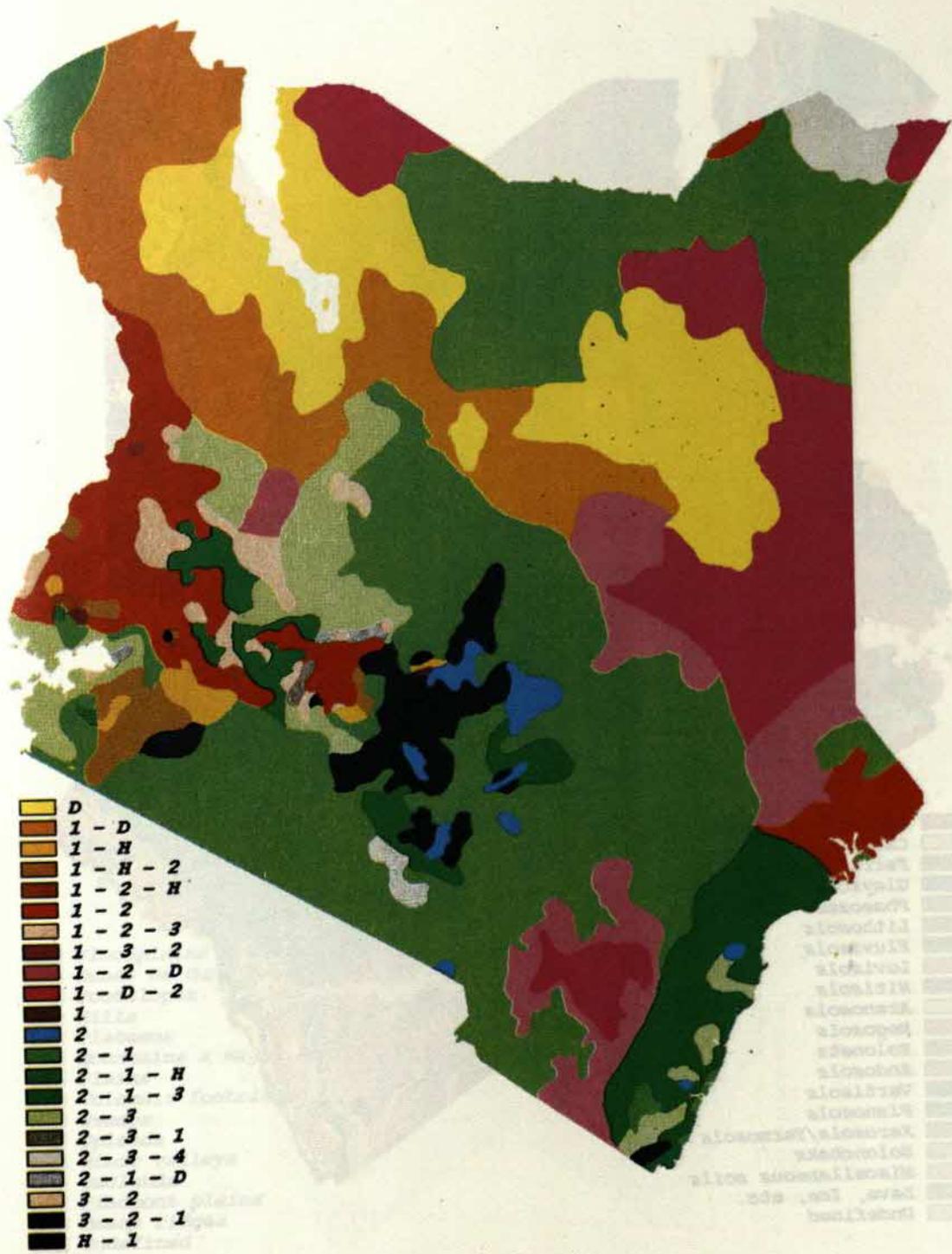


PLATE 3

Generalized map of LGP-pattern zones in Kenya



## PLATE 4

## Generalized soil map of Kenya

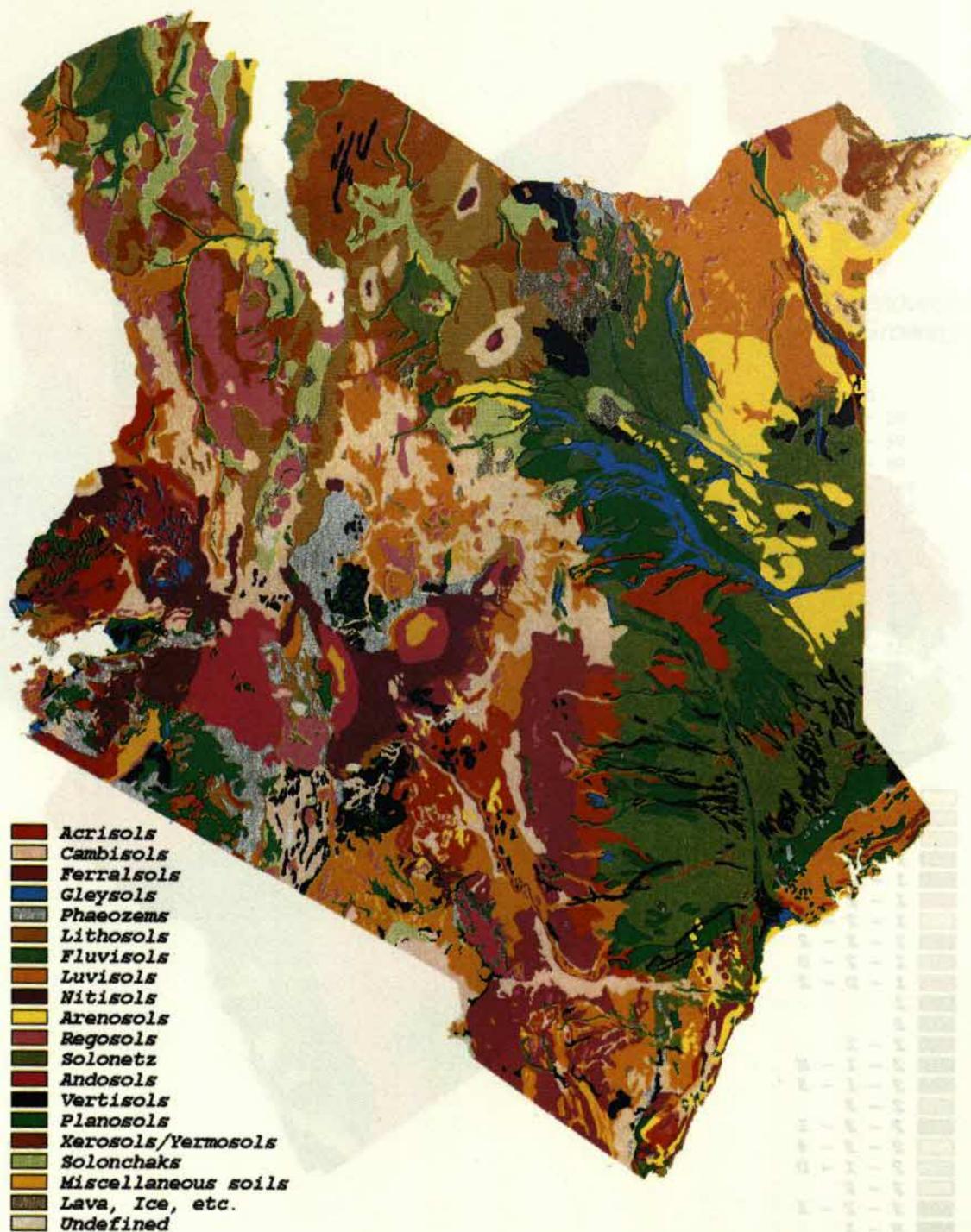
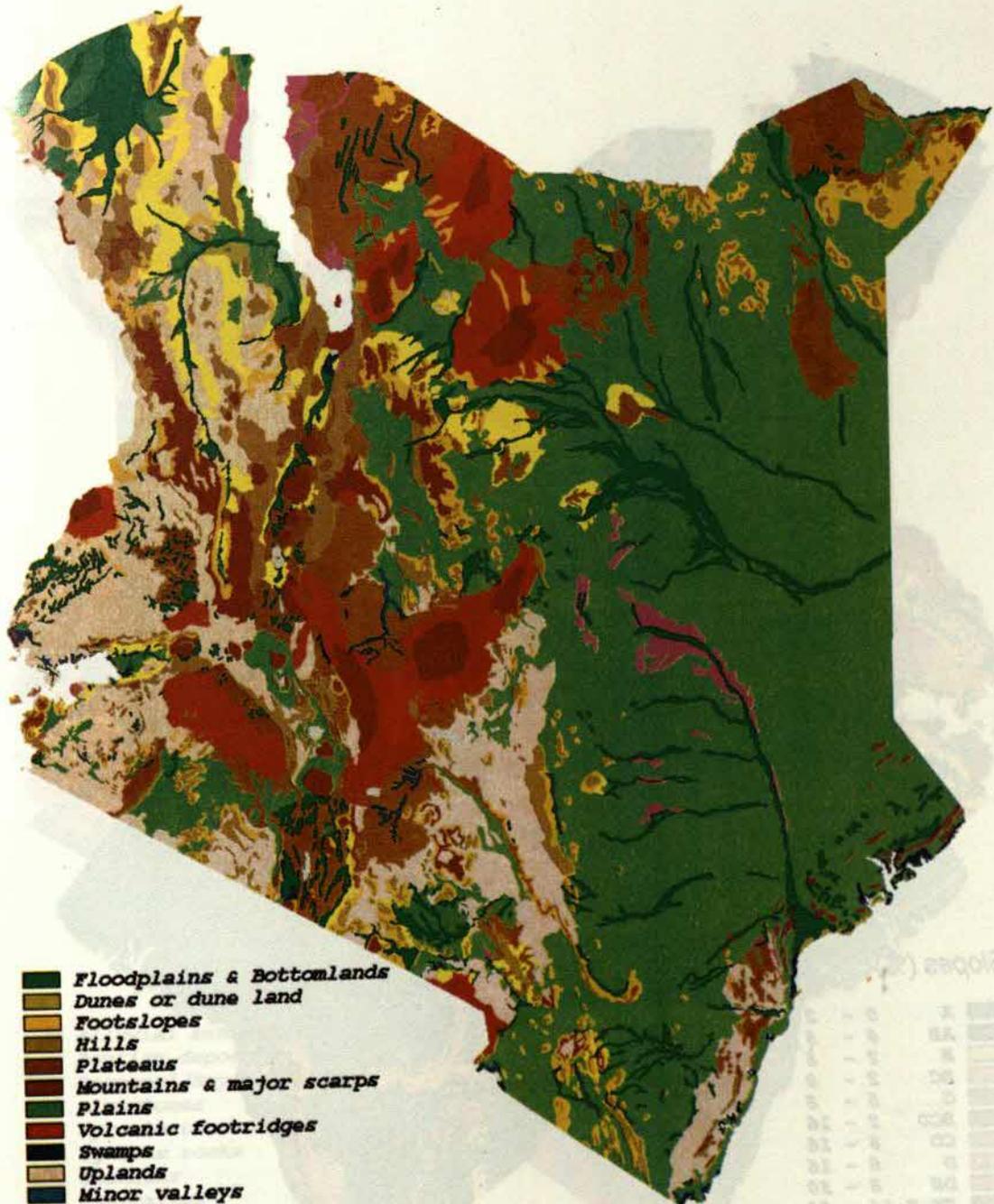


PLATE 5

Generalized map of landforms in Kenya



- Floodplains & Bottomlands
- Dunes or dune land
- Footslopes
- Hills
- Plateaus
- Mountains & major scarps
- Plains
- Volcanic footridges
- Swamps
- Uplands
- Minor valleys
- Badlands
- Piedmont plains
- Beach ridges
- Undefined

## PLATE 6

## Generalized map of slope-gradient classes in Kenya

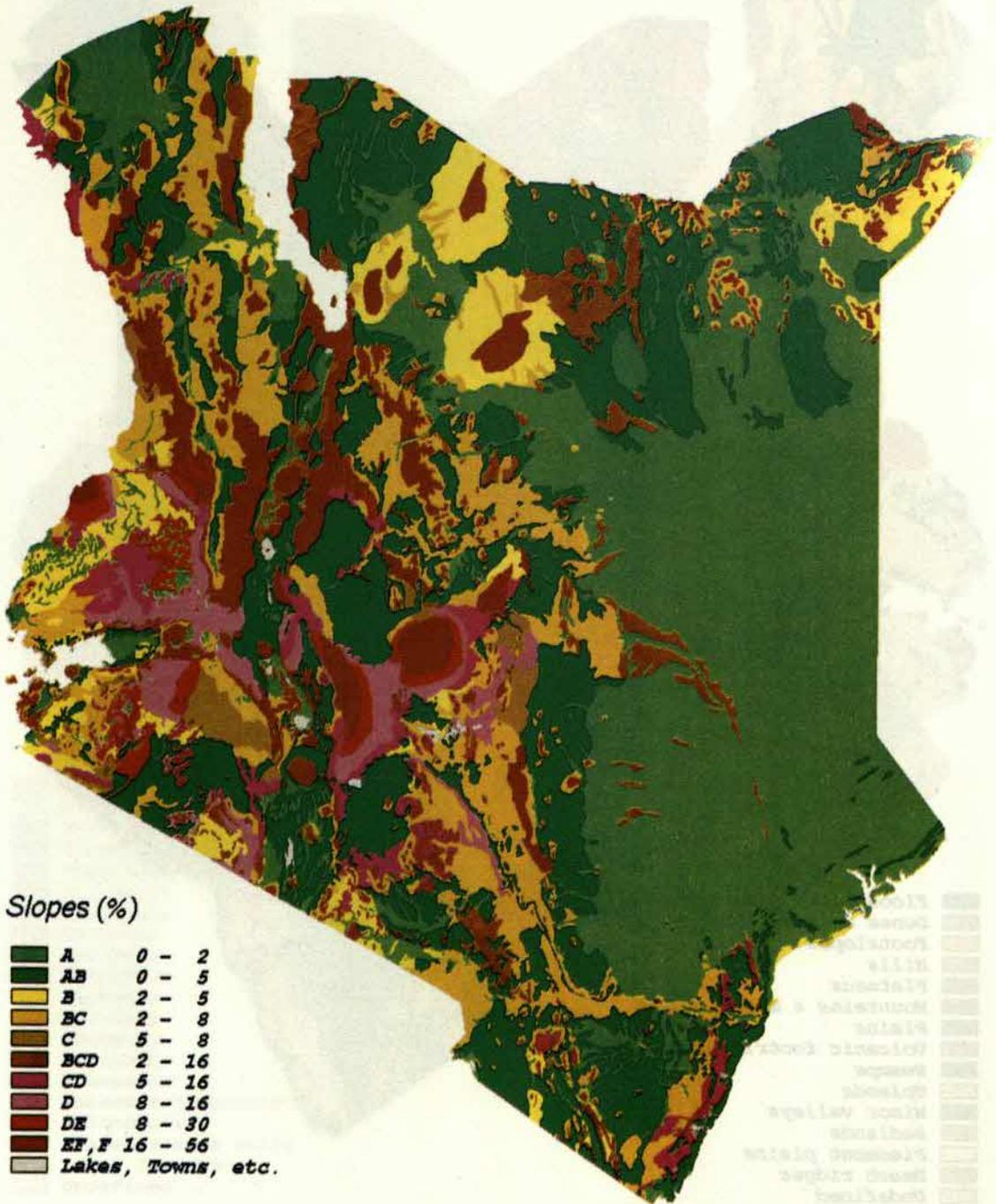


PLATE 7

Generalized map of geology/parent material in Kenya

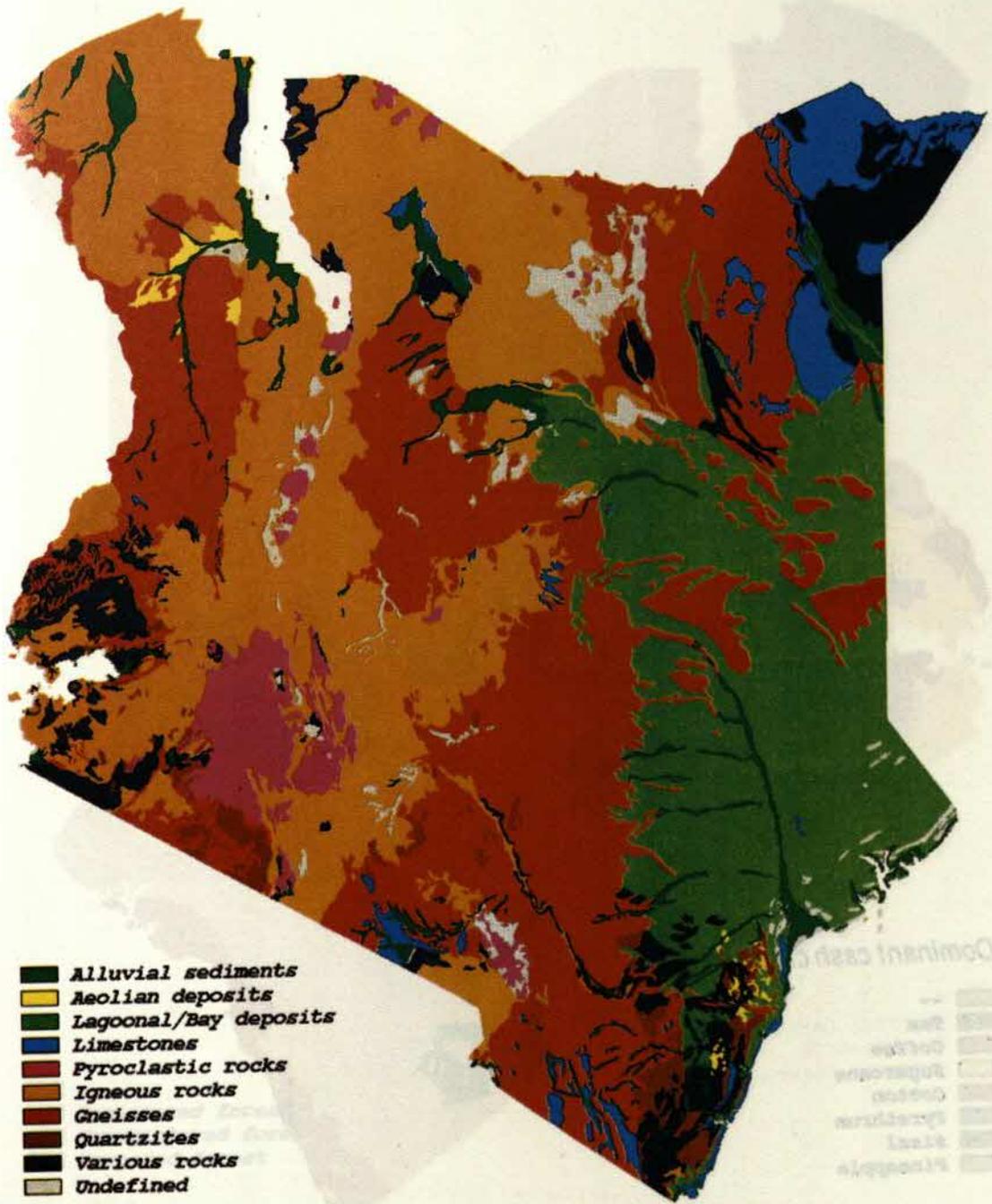


PLATE 8

Generalized map of cash crop zones in Kenya

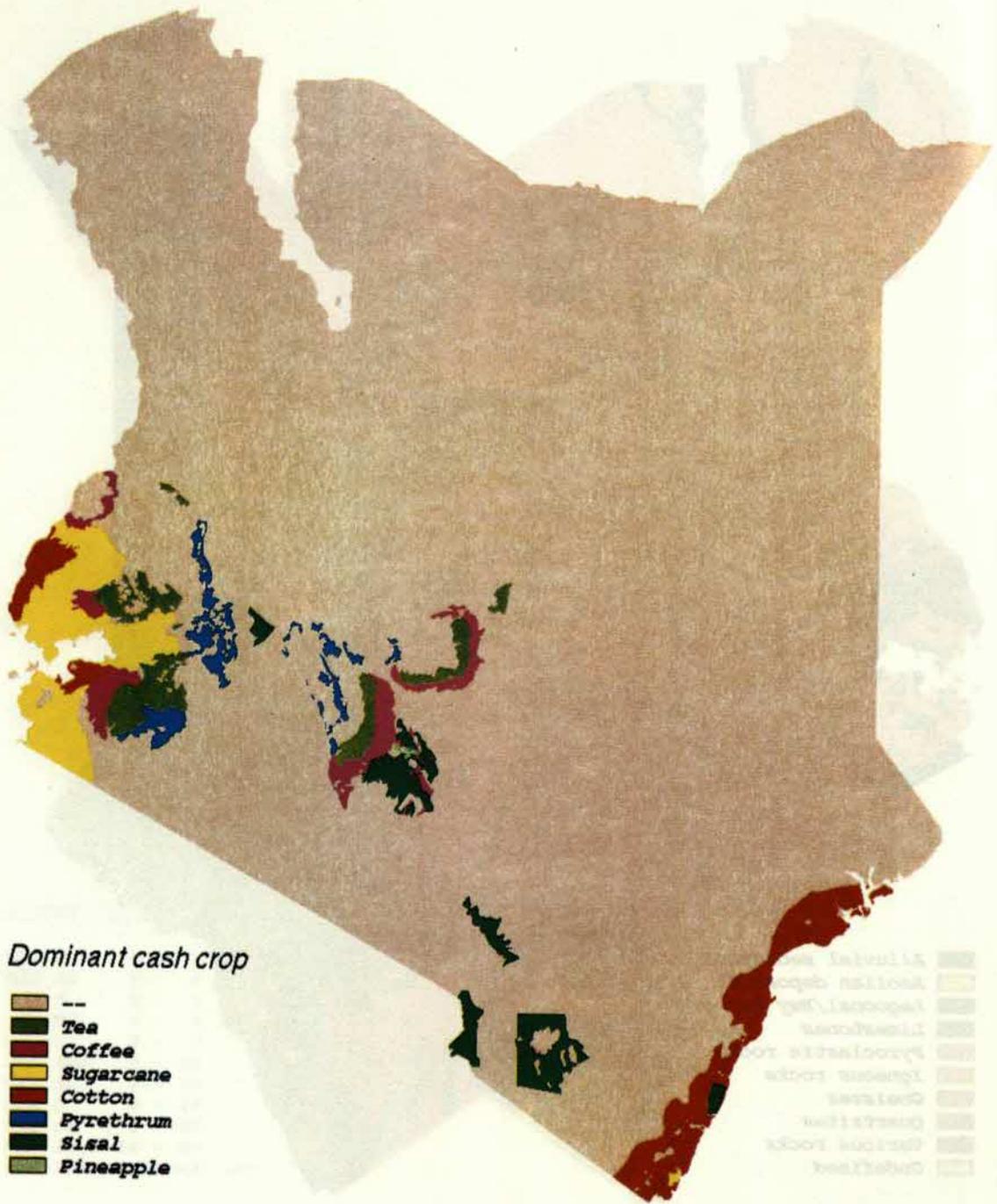


PLATE 9

Generalized map of forest zones in Kenya



## PLATE 10

Generalized map of parkland areas in Kenya

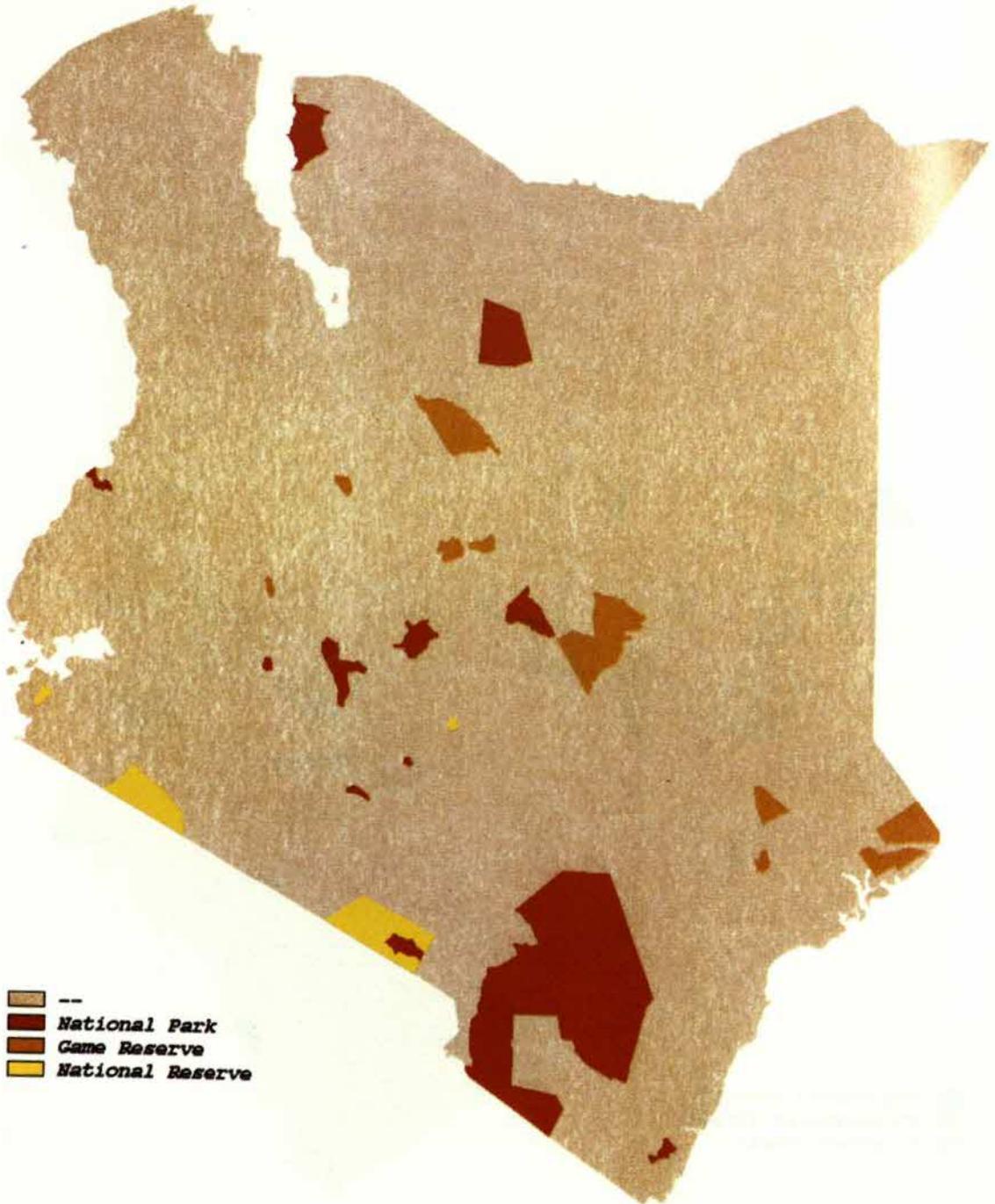


PLATE 11

Generalized map of irrigation schemes in Kenya

PLATE 11

Generalized map of irrigation schemes in Kenya

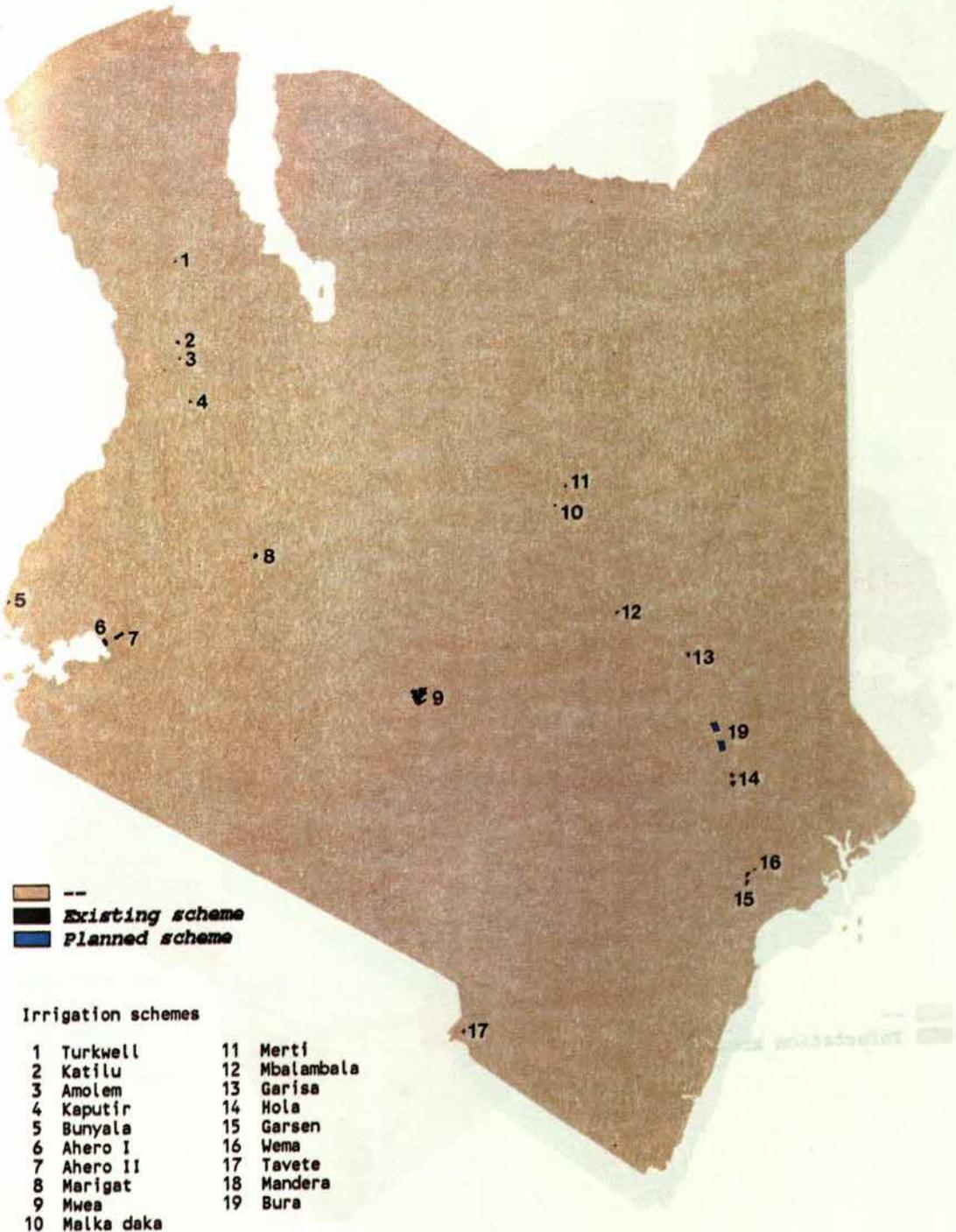


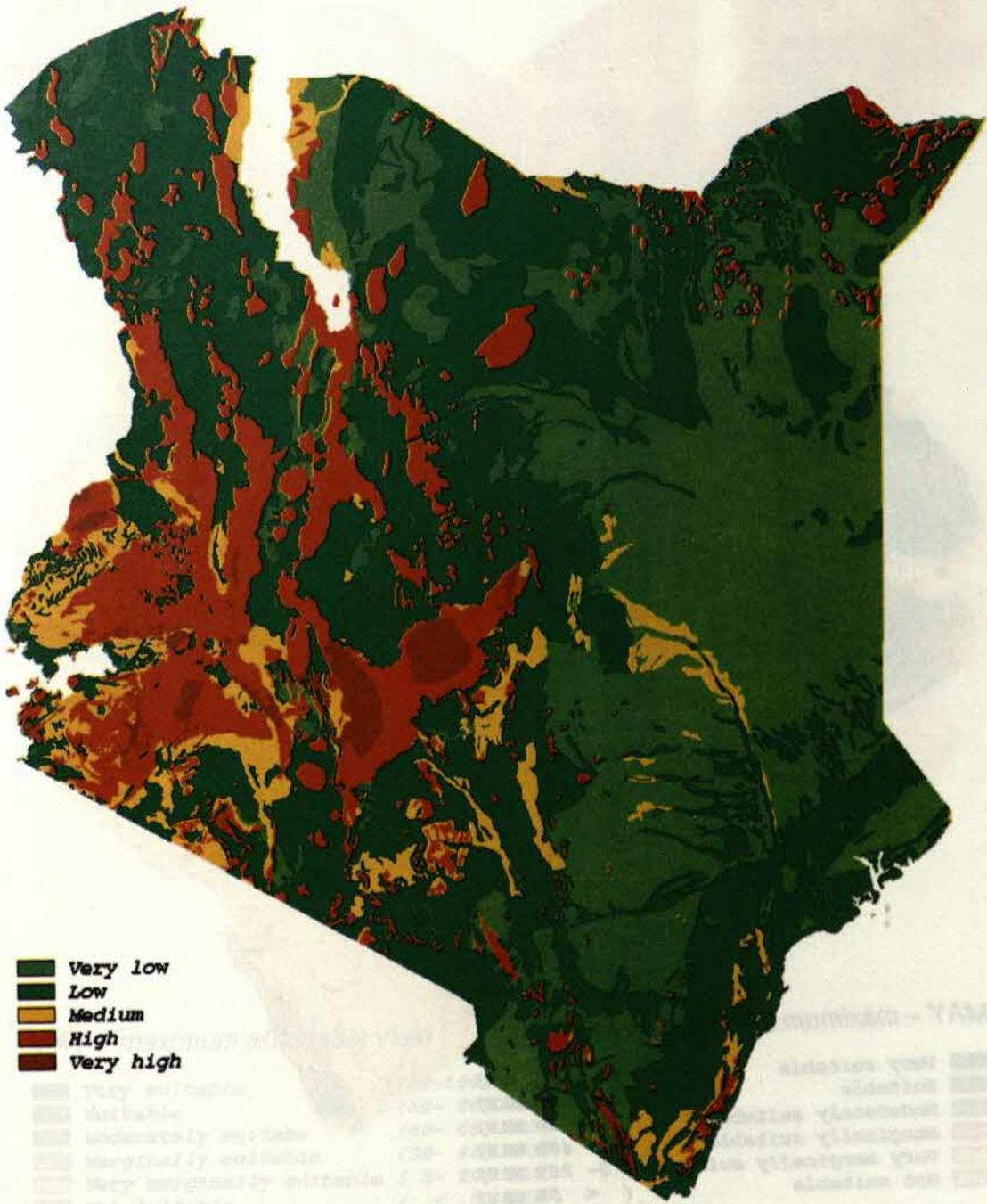
PLATE 12

Generalized map of tse-tse infestation areas in Kenya



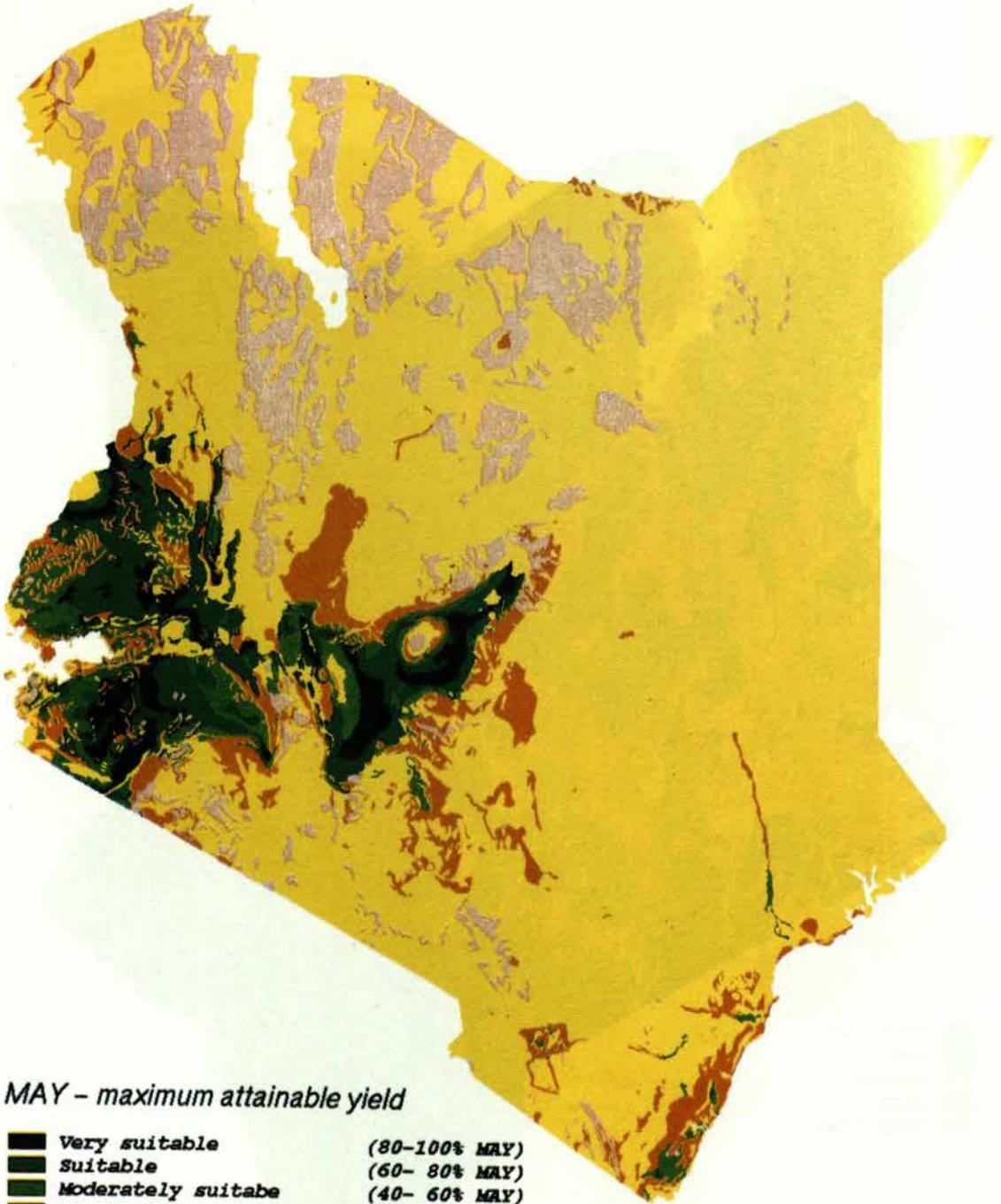
PLATE 13

Generalized map of potential erosion hazard in Kenya



## PLATE 14

Generalized map of land suitability for rainfed production of cowpea in Kenya at the intermediate level of inputs

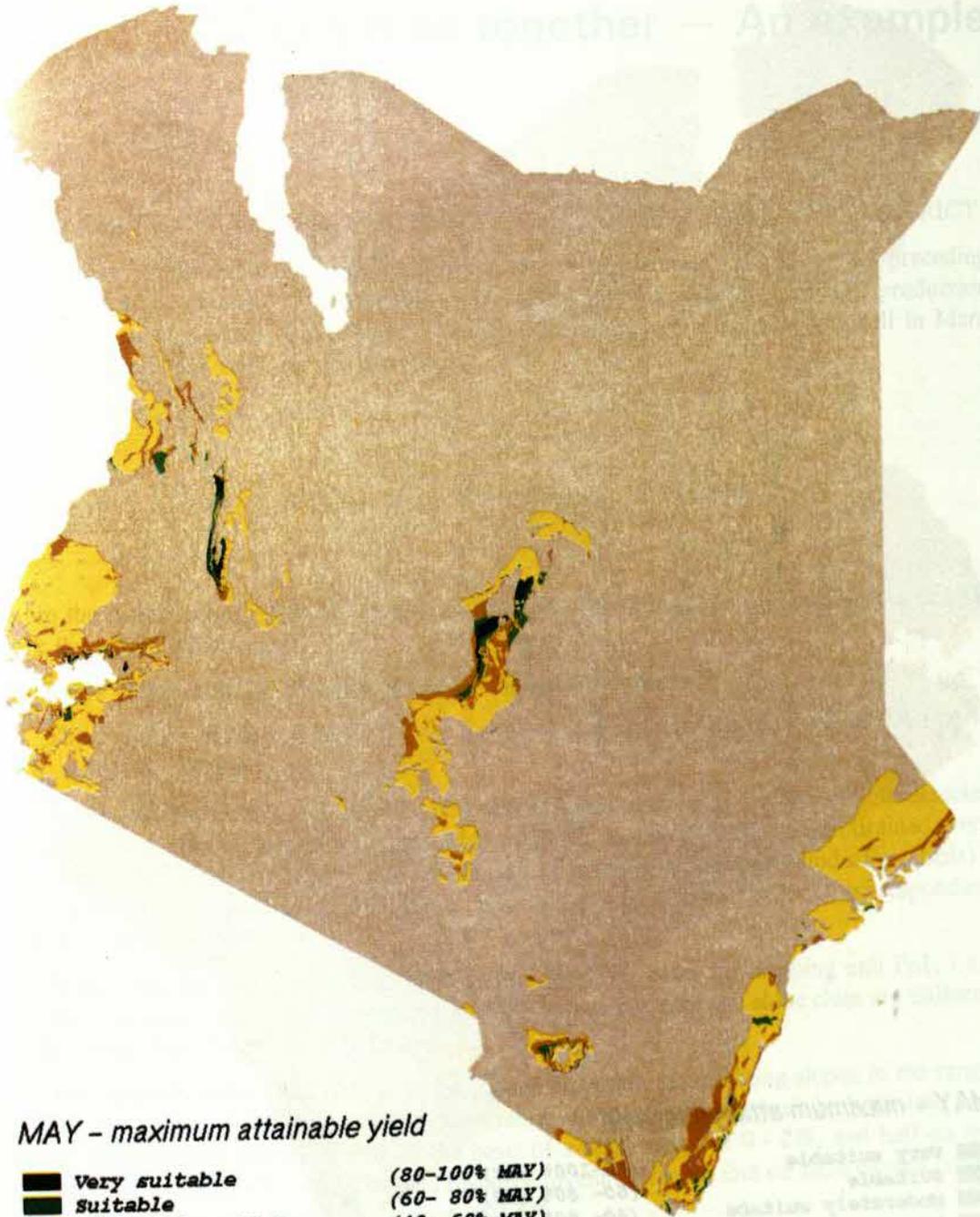


*MAY* - maximum attainable yield

■	Very suitable	(80-100% <i>MAY</i> )
■	Suitable	(60- 80% <i>MAY</i> )
■	Moderately suitable	(40- 60% <i>MAY</i> )
■	Marginally suitable	(20- 40% <i>MAY</i> )
■	Very marginally suitable	( 5- 20% <i>MAY</i> )
■	Not suitable	( < 5% <i>MAY</i> )

PLATE 15

Generalized map of land suitability for rainfed pasture production in Kenya at the intermediate level of inputs

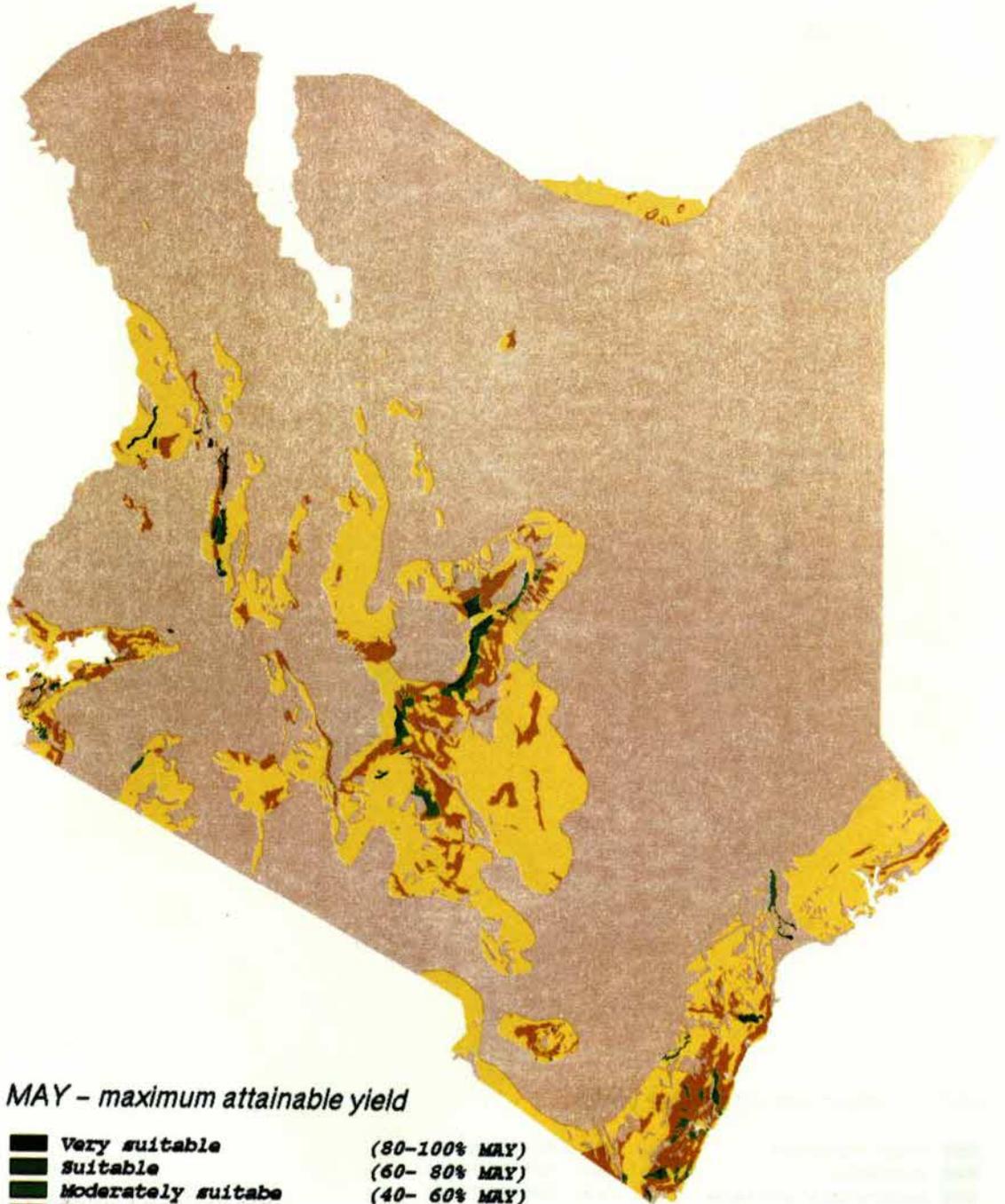


MAY - maximum attainable yield

- |                            |               |
|----------------------------|---------------|
| ■ Very suitable            | (80-100% MAY) |
| ■ Suitable                 | (60- 80% MAY) |
| ■ Moderately suitable      | (40- 60% MAY) |
| ■ Marginally suitable      | (20- 40% MAY) |
| ■ Very marginally suitable | ( 5- 20% MAY) |
| ■ Not suitable             | ( < 5% MAY)   |

## PLATE 16

Generalized map of land suitability for rainfed production of *Eucalyptus camaldulensis* in Kenya at the intermediate level of inputs



*MAY* - maximum attainable yield

■	Very suitable	(80-100% <i>MAY</i> )
■	Suitable	(60- 80% <i>MAY</i> )
■	Moderately suitable	(40- 60% <i>MAY</i> )
■	Marginally suitable	(20- 40% <i>MAY</i> )
■	Very marginally suitable	( 5- 20% <i>MAY</i> )
■	Not suitable	( < 5% <i>MAY</i> )



TABLE 72

Information in a land resources data record

Field	Column	Value	Contents	Explanation
1	1 - 2	3	province code	Eastern Province
2	3 - 4	6	district code	Meru
3	5 - 6	1	thermal code	mean daily temperature >25°C
4	7 - 8	11	mean total LGP	growing period 270 to 299 days
5	9 - 10	13	LGP-pattern	2 - 1, with a probability of 70:30
6	11 - 13	224	mapping unit	soil mapping unit 'Pn1'
7	14 - 16	33	soil unit code	nito-rhodic Ferralsols
8	17	0	coarse material	no coarse material indicated
9	18 - 19	34	texture code	clay
10	20 - 21	0	phase combination	no soil phase indicated
11	22 - 23	2	slope class	slope class AB: 0 - 5%
12	24 - 26	35	slope gradient	average slope gradient of 3.5%
13	27 - 28	0	cash-crop zone	no cash crop indicated
14	29	0	forest zone	no forest indicated
15	30 - 31	0	irrigation scheme	no irrigation scheme indicated
16	32	0	tse-tse infestation	no potential for tse-tse infestation
17	33	0	game park	cell does not belong to game park
18	34 - 41	1150	cell extent	size of agro-ecological cell (ha)

TABLE 73

Potential yields (in t/ha dry weight) of three maize crop types by LGP

Crop	Code	Growth Cycle (days)	----- Length of Growing Period (days) -----						
			90	120	150	180	210	240	270
			-	-	-	-	-	-	-
			119	149	179	209	239	269	299
Maize 1	021	70-90	1.00	1.86	2.57	2.54	1.79	1.26	1.03
Maize 2	022	90-110	1.30	2.53	3.51	3.45	2.50	1.73	1.37
Maize 3	023	110-130	0.00	3.20	4.45	4.35	3.20	2.20	1.70

TABLE 74

Maize production potential (t/ha) - an example

LGP (days)	---One Crop---			---Two Crops---			---Three Crops---					
	Crop Code <sup>1</sup>	--- Yield ---			Crop Code <sup>1</sup>	--- Yield ---			Crop Code <sup>1</sup>	--- Yield ---		
		min	avg	max		min	avg	max		min	avg	max
210-239	023	2.6	2.9	3.5	023 021	2.8	3.5	5.1	n.a.	0.0	0.0	0.0
240-269	023	1.8	3.4	3.6	023 022	2.6	4.0	4.7	021 021 021	2.4	3.8	4.5
270-299	023	1.4	3.0	3.7	023 022	2.2	3.9	4.6	022 021 021	2.4	4.0	4.7

<sup>1</sup> 021 - lowland maize, 70-90-day growth cycle; 022 - lowland maize, 90-110-day growth cycle; 023 - lowland maize, 110-130-day growth cycle.

LGP-Pattern code 13 indicates that there are usually two (shorter) growing periods, in seven out of ten years according to historical profiles, and one growing period in about one-third of the years. The reference table relating the mean total dominant LGP to the corresponding mean total associated LGPs (FAO/IIASA 1991: Tech. Annex 1, App. 5.1) lists the following for the bimodal case: the first associated LGP,  $L_{2_1}$  with code 7, is 150 - 179 days; the second associated LGP,  $L_{2_2}$  with code 5, is 90 - 119 days.

The list of crop types considered in the AEZ assessment for Kenya (Table 33) includes nine maize crop types, in two groups — highland or lowland — and with a sequence of lengths of growth cycle. The highland maize types are adapted to cooler conditions and have therefore been rated as not suitable in the thermal zone suitability screen. This leaves us with three lowland maize types, with growth cycles of 70-90, 90-110 and 110-130 days, and adapted to the local temperatures regime. The potential agronomically attainable yields for the relevant LGPs (in t/ha, dry weight), assuming suitable soils and terrain, at the intermediate level of inputs, and with cultivars with appropriate crop cycle lengths, are given in Table 73.

The maximum unconstrained yields are 2.59, 3.51 and 4.45 t/ha, respectively. For all three crop types, the highest yields can be achieved in the LGP with 150 to 179 days (LGP code 7). In shorter LGPs water stress constrains attainable yields, and in longer LGPs pests, weeds and workability constraints are assumed to increasingly limit attainable maize yields. From the LGP-Pattern weightings we derive average attainable yields of 2.1 t/ha (min. 1.00 t/ha and max. 2.57 t/ha) for the fastest maturing maize type (code 021), 2.9 t/ha (min. 1.37 t/ha and max. 3.51 t/ha) for the second maize type (code 022), and 3.6 t/ha (min. 1.70 t/ha and max. 4.45 t/ha) for the slowest maturing lowland maize type (code 023).

The soil unit rating of nito-rhodic Ferralsols for maize is S2, as with most Ferralsols, i.e., suitable with some limitations, depressing yields by 25%. The clay texture does not affect the rating. Combining agroclimatic and agro-edaphic suitability ratings we arrive at average yields of 1.7, 2.4 and 3.0 t/ha respectively. The modest average slope gradient of 3.5% passes the slope-cultivation association screen, which tolerates dryland crops on terrain with slope gradients of up to 30%.

In a relatively long growing season, as we are considering here, additional yields from multicropping must be considered. The intercropping increment, as explained earlier, depends on the level of inputs, the LGP and the overall crop suitabilities. At the intermediate level of inputs, with moisture availability well above 120 days, the intercropping increment for maize is estimated at around 10%, i.e., a land equivalent ratio (LER) of 1.1.

The LGP allows also for two or even three crops to be grown each year. Since we consider only lowland maize in this example, the optimal sequential crop combination with two crops grown in sequence would be the maize type with the longest cycle as the first crop, followed by the medium maturity maize type. The maize crop with the shortest growth cycle requires 80 days on average (growth cycle 70 - 90 days). Assuming a 10-day turn-around time, three sequential crops can be grown within 270 days. In the dominantly bimodal LGP-Pattern (code 13), two maize crops (the medium and the fast maturing cultivars) could be grown in the first growing season, 150 - 179 days, with a third maize crop (a fast maturer) in the shorter, second growing season of 90 - 119 days. Table 74 summarizes the best performing sequential maize crop combinations in the given cell, as well as for LGPs of 240 - 269 and 210 - 239 days, when one, two or three crops are grown. The results have to be understood as an illustration of the crop combination algorithm rather than a likely or even viable option. In fact, the crop combination requirement constraints imposed to avoid continuous mono-cropping would normally rule out the sequential cropping patterns illustrated in Table 74. For the quantification of maximum potential crop production, including multiple mono-cropping, as in the results

**TABLE 75**  
**Areas (km<sup>2</sup>) of land in Kenya variously suitable for rainfed crop production, including pasture and fuelwood**

Crops	Suitability ratings <sup>1</sup>					
	VS	S	MS	mS	VmS	NS
Barley	4 771	7 081	7 030	17 689	18 794	519 458
Maize	3 953	5 515	11 038	23 223	47 958	483 136
Oats	1 541	4 312	10 077	13 610	22 354	522 929
Millet	1 632	4 401	11 729	21 242	36 113	499 706
Rice	95	756	1 572	8 960	21 925	541 515
Sorghum	3 573	6 456	9 405	23 787	51 582	480 020
Wheat	2 764	6 232	5 537	16 155	20 482	523 653
Cowpea	716	648	3 099	9 532	14 982	545 846
Green gram	190	1 758	4 027	8 136	39 571	521 141
Groundnut	714	702	3 132	9 979	14 330	545 966
<i>Phaseolus</i> bean	4 713	6 585	7 696	13 656	21 089	521 084
Pigeon pea	2 128	1 191	3 866	9 640	9 383	548 615
Soybean	774	927	2 766	9 679	15 258	545 419
Cassava	893	2 355	3 233	7 632	18 277	542 433
Sweet potato	944	1 312	2 324	6 588	14 395	549 260
White potato	2 211	5 096	8 644	12 825	20 881	525 166
Banana	0	182	647	5 253	5 271	563 470
Oil palm	0	40	88	426	609	573 660
Sugarcane	108	600	2 033	6 571	12 595	552 916
Coffee (arabica)	1 952	3 812	3 358	7 691	13 672	544 388
Cotton	71	200	1 112	3 984	4 869	564 587
Pineapple	133	481	2 080	2 277	150	569 702
Pyrethrum	2 205	8 276	10 618	10 482	4 212	539 030
Sisal	544	2 115	5 156	9 773	20 609	536 626
Tea	1 785	7 556	8 926	10 035	10 492	536 029
Fuelwood (N <sup>+</sup> ) <sup>2</sup>	4 569	33 010	24 512	44 241	64 948	403 543
Fuelwood (N <sup>-</sup> ) <sup>3</sup>	9 583	26 942	22 509	27 599	75 969	412 221
Pasture	14 323	23 647	15 551	36 943	194 366	289 993

<sup>1</sup> Suitability ratings and the proportion of maximum attainable yield that they signify: VS = Very Suitable, 80-100%; S = Suitable, 60-80%; MS = Moderately Suitable, 40-60%; mS = marginally Suitable, 20-40%; VmS = Very marginally Suitable, 5-20%; NS = Not Suitable, <5%.

<sup>2</sup> Species with nitrogen-fixing ability.

<sup>3</sup> Species without nitrogen-fixing ability.

Note: The land suitability data by crops is non-additive — the figures show the extents of land suitable for the production of one crop or the extent for another crop.

presented in (FAO/IIASA 1991: Tech. Annex 8, Appendixes C and D), these combinations would however be acceptable.

Fallow requirements to maintain soil fertility and ensure sustainable production, under the given conditions and input level, are set at 25%, i.e., 5 years out of 20, the land would not be permitted to be under maize cultivation.

The soil erosion hazard is quantified by the modified USLE, involving estimates of rain erosivity, soil erodibility, slope effect (slope length factor), crop cover factor and protective management practices. An average growing period of 285 days implies a mean average rainfall of about 1550 mm, resulting in an estimated rainfall erosivity factor of 600. Nito-rhodic Ferralsols with clay texture are considered to be of low erodibility. Hence, they are grouped into the second of seven soil erodibility classes, with an average soil erodibility factor of 0.11.

With a slope length factor of 0.8 and a crop cover factor of 0.4, adjusted to 0.36 for an assumed crop/fallow cycle with 25% fallow finally results in an estimated annual soil loss of 19 t/ha/year, corresponding to about 1.6 mm topsoil loss per year. The regeneration capacity of topsoil, a function of thermal zone and LGP, is calculated to be an annual addition of topsoil of 1.7 mm, making up for the estimated erosion losses. Therefore, maize productivity is assumed to be not adversely influenced by water erosion in the given agro-ecological cell.

Such calculations have to be repeated for every agro-ecological cell and for each LUT. In this way, the production potential of each crop type is determined in all locations. The results can then be aggregated in various ways, i.e., over crop types, to district, province or national level., including all land or excluding specific parts of the land area. An example of the general results for the Kenya assessment is given in Table 75, which shows the extents by productivity classes of all land variously suitable for alternative rainfed crop production. This includes the three elements of plant related land productivity, i.e., crop, pasture and fuelwood.

The calculations used earlier for the example for Meru have to be repeated for all agro-ecological cells, for all crops and for all cropping combinations. The sheer number of calculations involved demonstrates clearly why such an exercise could only be cost-effectively carried out with the general availability of low-cost but powerful PC computers. Such exercises have been manually carried out — in a simplified form admittedly — for some areas, but they required several man-years of university-level professional competence to succeed, and the cost can be imagined.

With the general availability of computers capable of handling the necessary quantities of data, and indeed computerized techniques for acquiring the necessary data, the possibility of exploiting the methodology for national planning purposes becomes a practical one. No one can claim that it is a cheap operation, but technology has made it a simple one. There is a great deal of work that must be done to provide the local values for all the variables included in the calculations. The quality of the data in the system is a key factor in determining the validity of any results. A simple data set such as that of the weather records needed to establish rainfall, temperature, solar radiation, etc., patterns and to determine their variability is, in terms of the number of numbers to be entered, and verified, huge. Again, the AEZ assessment is dependent for its effectiveness on the availability of a detailed soil map, and that soil map has to be digitized. It will be evident that the whole process requires a considerable commitment in terms of manpower and time. Results cannot be looked for in the short term, *vide* the Kenya exercise, which was carried out part-time over a period of eight years, and that was after the soil map had already been completed. If one considers the effort that went into that and the time it took, one can more realistically appreciate the results.

Some of the work done in connection with the Kenya AEZ assessment was of an innovative nature, and the benefits of the lessons learnt can be transferred. Thus many of the suite of computer software programs used to implement the assessment are freely available for use by others. A companion volume to this one is under preparation, which will consider in detail the necessary computer software and hardware required for such AEZ studies, and a volume is planned on the practical step-by-step implementation of such a study. However, it must be noted that many of the programs require associated, commercial, propriety programs, such as a database management system (DBMS) or a geographic information system (GIS), and these and any associated computer hardware specifically needed can be fairly expensive.

Kenya, *Zeitschrift für Geomorphologie*, 29(Suppl.), 59-100.

Edwards, D.C., & Bogdan, A.V., 1961. *Importance of grassland plants of Kenya*. Nairobi: Pitman and Sons.

## 8.2 USING THE RESULTS IN THE NATIONAL PLANNING CONTEXT

The prosperity of most countries depends ultimately of the prosperity of the rural sector, and the long-term viability of that sector is intimately connected with the sensible use of available natural resources. To promote and ensure national prosperity in the long term, activities in the present must use the existing potentials in a rational way taking into account the constraints necessary to ensure sustainability of production in the rural sector. This implies taking a responsible attitude toward protection of the environment and conservation of the natural productive resources upon which the well-being of the nation depends. Plans cannot be made in ignorance. They must be based on informed knowledge, and the AEZ concept has as its principle focus that of providing a sound scientific basis for decision making.

The recent information technology revolution has made possible this powerful aid to decision making, and the developing countries, which have suffered most from uninformed development policies, can benefit most by seizing the opportunity to investigate in advance the likely consequences of decisions and investments, and to systematize their planning procedures.

The immediate outputs of an AEZ study are the estimates of production of appropriate crops in each tract of land. This is a valuable output in itself: by comparing it with the existing production it can draw attention to the priority areas for research and investment. It can also serve as the basis for the crop forecasting and early warning programmes that are at the heart of food security. By using the optimization programs that can operate on the results of the AEZ production figures, the most advantageous crops and management regimes for specific areas can be selected, according to policy objectives. These can be to maximize food production in terms of calories, or to meet a particular employment level, or to optimize profit on an area or cash crop basis, or some other perceived need. From the maximum calory production (constrained by the need to balance crude calory production with necessary minimum protein requirements) it is possible to estimate the potential population supporting capacity, on the basis of agro-ecological units or administrative units, and to orient population planning, agricultural and related reseach and development, and food security measures according to the indicated priorities. Similar aids to land and resource allocation can be provided for other economic and social objectives.

The sequential use of the models described in Chapters Two to Seven give gross production values. The next step is to convert these values into food values, expressed as calories and protein and derived from standard nutritional compositions for the crops and livestock considered. The subsequent steps of calculating optimum production according to the selected limiting parameters will be covered in reasonable detail in companion volumes at present under preparation.

## References

- Andrews, D.J., & Kassam, A.H., 1976. Importance of multiple cropping in increasing world food supplies. pp. 1-10. In: *Multiple Cropping*. ASA Special Publication, No. 27.
- Barr, D.A., 1957. The effect of sheet erosion on wheat yield. *J. Soil Conservation Service of New South Wales*, 13(1): 27-32.
- Blair Rains, A. & Kassam, A.H., 1980. Land resources and animal production [in Africa]. Working Paper No. 8, In: FAO 1980, q.v.
- Boonman, J.G., 1979. Development of cultivated pastures in the highlands of East Africa. Nairobi: Ministry of Agriculture.
- Boudet, G., & Riviere, R., 1968. Emploi pratique des analyses fourrageres pour la l'appréciation des pasturages tropicaux. *Revue de l'Elevage et de Medecine Veterinaire des Pays Tropicaux*, 211: 227-266.
- Brammer, H., Antoine, J., Kassam, A.H., & van Velthuisen, H.T., 1988. Land resources appraisal of Bangladesh for agricultural development. Technical Reports Nos. 1-7, FAO/UNDP project BGD/81/035, 'Agricultural development advice'. Dhaka: Bangladesh.
- Bruinsma, J., Hrabovszky, J., Alexandratos, N., & Petri, P., 1983. Crop production and input requirements in developing countries. *European Review of Agricultural Ecology*, 10: 197-222.
- Cannell, M.G.R., & Last, F.T., 1976. *Tree Physiology and Yield Improvement*. London: Academic Press.
- Colvin, T.S., & Laflen, J.M., 1981. Effect of corn and soybean row spacing on canopy, erosion and runoff. *Trans. ASEA*, 24(5): 1227-1229.
- CRIES [Comprehensive Resource Inventory and Evaluation System], 1983. Kenya Natural Resource Assessment. The Comprehensive Resource Inventory and Evaluation System (CRIES) Project. Michigan State University.
- Critchley, W., 1984. Runoff harvesting for crop range and tree production in the BPSAAP [Baringo Pilot Semi-arid and Arid Lands Project] Area. Draft report BPSAAP. Marigat, Kenya: Ministry of Agriculture and Livestock Development.
- Davidson, J., 1985. Species and site: what to plant and where to plant. UNDP/FAO project BGD/79/017, 'Assistance to the forestry sector of Bangladesh'. Field Doc. No. 5. Dhaka.
- Doorenbos, J., & Kassam, A.H., 1979. Yield Response to Water. [FAO] *Irrigation and Drainage Paper*, 33. Rome.
- Dunne, T., Dietrich, W.E., & Brunengo, M.J., 1978. Recent and past rates of erosion in semi-arid Kenya. *Zeitschrift fur Geomorphologie*, 29(Suppl.): 99-100.
- Edwards, D.C., & Bogdan, A.V., 1968. *Importance of grassland plants of Kenya*. Nairobi: Pitman and Sons.

- FAO, 1974. *FAO-Unesco Soil Map of the World*. Vol. 1. *Legend*. Paris: Unesco.
- FAO, 1976. A Framework for Land Evaluation. *FAO Soils Bulletin*, 32.
- FAO, 1977. Agroclimatological data bank. Rome, FAO/AGPC.
- FAO, 1978-81. Report on the Agro-ecological Zones Project. Vol.1, Methodology and results for Africa; Vol.2, Results for Southwest Asia; Vol.3, Methodology and results for South and Central America; Vol.4, Results for Southeast Asia. *[FAO] World Soil Resources Report*, 48/1,-4.
- FAO, 1980. Report on the Second FAO/UNFPA Expert Consultation on Land Resources for Populations of the Future. Rome, FAO.
- FAO, 1981. Eucalypts for planting. *FAO Forestry Series*, 11.
- FAO, 1984a. Land, Food and People. *FAO Econ. Soc. Dev. Series*, 30.
- FAO, 1984b. Population supporting capacity assessment of Kenya. Mission Report. Rome, AGL-FAO.
- FAO, 1988. Pig Production in the Tropics. Proceedings of a seminar. Suchow, China. 21-25 September 1987. Edited N.R. Standal. Rome: FAO.
- FAO, 1991. Guidelines: land evaluation for extensive grazing. *FAO Soils Bulletin*, 58.
- FAO/IIASA, 1991. Agro-ecological land resources assessment for agricultural development planning: A case study of Kenya: Resources database and land productivity. Main Report and 8 Technical Annexes. Rome, AGL-FAO. 9 vols. 1150p.
- FAO/UNFPA, 1980. Report on the Second FAO/UNFPA Expert Consultation on Land Resources for Populations of the Future. Rome, Italy, 4-6 December 1979. Rome: FAO. 379 p.
- Goehl, B., 1981. Tropical feeds. *FAO Animal Production and Health Series*, 12.
- Hammer, W.I., 1981. Soil Conservation Consultancy Report. Technical Note No.7, Centre for Soil Research, Bogor, Indonesia.
- Higgins, G.M., & Kassam, A.H., 1981. Relating potential productivity to soil base. *[FAO] Land and Water Development Division Technical Newsletter*, 9 (July 1981).
- Higgins, G.M., Kassam, A.H., Naiken, L., Fischer, G., & Shah, M.M., 1982. Potential population supporting capacities of lands in the developing world. Technical Report of project INT/75/P13, 'Land resources for populations of the future', undertaken by FAO/IIASA for UNFPA.
- Houerou, H.N. Le, & Hoste, C.H., 1977. Rangeland production and annual rainfall relations in the Mediterranean Basin and the African Sahelo-Sudanian Zone. *Journal of Range Management*, 30(3): 181-189.
- Hudson, N.W., 1981. *Soil Conservation*. London: Batsford.
- Jaetzold, R. & Kutsch, H., 1980. Climatic data bank of Kenya. Department of Cultural and Regional Geography, University of Trier, Germany.
- Jaetzold, R., & Schmidt, H., 1982. *Farm Management Handbook of Kenya*. Vol. II, Parts A, B & C. Nairobi: Ministry of Agriculture in cooperation with German Agency of Technical Cooperation.
- Kassam, A.H., 1977. Net biomass production and yields of crops. Consultant's Report. Agroecological Zones project. FAO-AGL.

- Kassam, A.H., 1980. Multiple cropping and rainfed crop productivity in Africa. pp. 123-195, In: FAO 1980, q.v.
- Kassam, A.H., Kowal, J.M., & Sarraf, S., 1977. Climatic adaptability of crops. Consultants' Report. Agroecological Zones project. FAO-AGL, Rome.
- Kassam, A.H., van Velthuizen, H.T., Higgins, G.M., Christoforides, A., Voortman, R.L., & Spiers, B., 1982. Assessment of land resources for rainfed crop production in Mozambique. Field Documents Nos. 32-37, FAO/UNDP project MOZ/75/011, 'Land and Water Use Planning'. Maputo, Mozambique.
- King, J.M., Sayers, A.F., Peacock, C.P., & Kontrohr, E., 1982. Maasai herd and flock structure in relation to household livestock wealth and group ranch development. *ILCA Working Document*, 27.
- Kowal, J.M., & Kassam, A.H., eds., 1978. *Agricultural Ecology of Savanna*. Oxford: Clarendon Press.
- KSS [Kenya Soil Survey], 1975. Soils of the Kindaruma Area (Weg, R.F. van de, & Mbuvi, J.P., eds.). Nairobi: Kenya Soil Survey.
- KSS, 1976. Soils of the Kapenguria Area (Weg, R.F. van de, ed.). Nairobi: Kenya Soil Survey.
- KSS, 1982a. Exploratory Soil Map and Agroclimatic Zone Map of Kenya. Eds. Sombroek, W.G., Braun, H.M.H., & van der Pouw, B.J.A. Nairobi: Kenya Soil Survey.
- KSS, 1982b. Soils of the Kisii Area (Wielemaker, W.G., & Boxem, H., eds.). Nairobi: Kenya Soil Survey.
- Lal, R., 1976a. Soil erosion on alfisols in Western Nigeria, I: Effects of slope, crop rotation and residue management. *Geoderma*, 16(5): 363-375.
- Lal, R., 1976b. Soil erosion on alfisols in Western Nigeria, III: Effects of rainfall characteristics. *Geoderma*, 16(5): 389-401.
- Lal, R., 1976c. Soil erosion on alfisols in Western Nigeria, V: The changes in physical properties and the response of crops. *Geoderma*, 16(5): 419-431.
- Landsberg, J.J., 1986. *Physiological Ecology of Forest Production*. London: Academic Press.
- Leeuw, P.N. de, & Peacock, C.P., 1982. The productivity of small ruminants in the Maasai Pastoral System in Kajiado District of Kenya. *ILCA Working Document*, 25.
- Meadows, S.J., & White, J.M., 1981. Cattle structure in Kenya's pastoral rangelands. *ODI Pastoral Network Paper*, 11e.
- Mitchell, A.J., 1986. Soil erosion and soil conservation. Consultancy Report. FAO-AGLS, Rome.
- Nilsson, N.E., 1983. An alley model for forest resources planning. Statistics in Theory and Practice. Umea: Dept. Biometry and Forest Management, Swedish Univ. Agr. Sciences.
- Nye, P.H., & Greenland, D.J., 1960. *The Soil Under Shifting Cultivation*. Bucks: Commonwealth Agricultural Bureaux.
- Peacock, C.P., 1983. A rapid appraisal of goat and sheep flock demography in East and West Africa. Method, results and application to livestock research and development. *ILCA Working Document*, 28.
- Peacock, C.P., 1984. Sheep and goat production on Maasai group ranches. PhD Thesis. University of Reading, UK.

- Pratt, D.J., & Gwynne, M.D., 1977. *Rangeland Management and Ecology in East Africa*. London: Hodder and Stoughton.
- Rattray, J.M., 1960. *The grass cover of Africa*. Rome: FAO.
- Sanchez, P.A., Couto, W., & Buol, S.W., 1982. The fertility capability soil classification system: interpretation, application and modification. *Geoderma*, 27: 283-309.
- Semenye, P.P., 1982. A preliminary report of cattle productivity in Olkarkar, Merueshi and Mbirikani group ranches. ILCA.
- Siderius, W., & van der Pouw, B.J.A., 1980. The application of the FAO-Unesco terminology of the Soil Map of the World Legend for soil classification in Kenya. *Kenya Soil Survey Miscellaneous Soil Paper*, No. M15.
- Skerman, P.J., 1982. Tropical Forage Legumes [1<sup>st</sup> edition]. *FAO Plant Production and Protection Series*, No. 2.
- Stallings, J.H., 1957. *Soil Conservation*. Englewood Cliffs, NJ: Prentice-Hall.
- Stotz, D., 1983. Production Techniques and Economics of Smallholder Livestock Production Systems in Kenya. Farm Management Handbook of Kenya, Vol. IV. Nairobi: Ministry of Agriculture.
- Teel, W., 1980. *A Pocket Directory of Trees and Shrubs in Kenya*. Nairobi: KENGO.
- Unesco, 1982. Resource management for the Rendille Area of Northern Kenya. Integrated Project on Arid Lands (IPAL), Marsabit.
- Van der Pouw, B.J.A., 1983. Detailed composition of the soil mapping units of the Exploratory Soil Map of Kenya at scale 1:1 million. Wageningen: Stiboka.
- Webb, D.B., Wood, P.J., & Smith, J., 1980. A guide to species selection for tropical and subtropical plantations. [Commonwealth Forestry Institute, Oxford] *Tropical Forestry Paper*, 15.
- Wiggins, S.L., & Palma, O.G., 1989. Cost benefit analysis of soil conservation. Land Resources Development Centre [Tolworth, UK] Project Report, 104.
- Wischmeier, W.H., & Smith, D.D., 1978. Predicting rainfall erosion losses. United States Department of Agriculture Handbook, No. 536.
- Young, A., & Wright, A.C.S., 1980. Rest period requirements of tropical and subtropical soils under annual crops. pp. In: FAO 1980, q.v.

Appendix tables

Annual Area Miles	1980-1990										1990-2000										2000-2010										2010-2020										2020-2030										2030-2040										2040-2050										2050-2060										2060-2070										2070-2080										2080-2090										2090-2100																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																		
	180-190	190-200	200-210	210-220	220-230	230-240	240-250	250-260	260-270	270-280	280-290	290-300	300-310	310-320	320-330	330-340	340-350	350-360	360-370	370-380	380-390	390-400	400-410	410-420	420-430	430-440	440-450	450-460	460-470	470-480	480-490	490-500	500-510	510-520	520-530	530-540	540-550	550-560	560-570	570-580	580-590	590-600	600-610	610-620	620-630	630-640	640-650	650-660	660-670	670-680	680-690	690-700	700-710	710-720	720-730	730-740	740-750	750-760	760-770	770-780	780-790	790-800	800-810	810-820	820-830	830-840	840-850	850-860	860-870	870-880	880-890	890-900	900-910	910-920	920-930	930-940	940-950	950-960	960-970	970-980	980-990	990-1000	1000-1010	1010-1020	1020-1030	1030-1040	1040-1050	1050-1060	1060-1070	1070-1080	1080-1090	1090-1100	1100-1110	1110-1120	1120-1130	1130-1140	1140-1150	1150-1160	1160-1170	1170-1180	1180-1190	1190-1200	1200-1210	1210-1220	1220-1230	1230-1240	1240-1250	1250-1260	1260-1270	1270-1280	1280-1290	1290-1300	1300-1310	1310-1320	1320-1330	1330-1340	1340-1350	1350-1360	1360-1370	1370-1380	1380-1390	1390-1400	1400-1410	1410-1420	1420-1430	1430-1440	1440-1450	1450-1460	1460-1470	1470-1480	1480-1490	1490-1500	1500-1510	1510-1520	1520-1530	1530-1540	1540-1550	1550-1560	1560-1570	1570-1580	1580-1590	1590-1600	1600-1610	1610-1620	1620-1630	1630-1640	1640-1650	1650-1660	1660-1670	1670-1680	1680-1690	1690-1700	1700-1710	1710-1720	1720-1730	1730-1740	1740-1750	1750-1760	1760-1770	1770-1780	1780-1790	1790-1800	1800-1810	1810-1820	1820-1830	1830-1840	1840-1850	1850-1860	1860-1870	1870-1880	1880-1890	1890-1900	1900-1910	1910-1920	1920-1930	1930-1940	1940-1950	1950-1960	1960-1970	1970-1980	1980-1990	1990-2000	2000-2010	2010-2020	2020-2030	2030-2040	2040-2050	2050-2060	2060-2070	2070-2080	2080-2090	2090-2100	2100-2110	2110-2120	2120-2130	2130-2140	2140-2150	2150-2160	2160-2170	2170-2180	2180-2190	2190-2200	2200-2210	2210-2220	2220-2230	2230-2240	2240-2250	2250-2260	2260-2270	2270-2280	2280-2290	2290-2300	2300-2310	2310-2320	2320-2330	2330-2340	2340-2350	2350-2360	2360-2370	2370-2380	2380-2390	2390-2400	2400-2410	2410-2420	2420-2430	2430-2440	2440-2450	2450-2460	2460-2470	2470-2480	2480-2490	2490-2500	2500-2510	2510-2520	2520-2530	2530-2540	2540-2550	2550-2560	2560-2570	2570-2580	2580-2590	2590-2600	2600-2610	2610-2620	2620-2630	2630-2640	2640-2650	2650-2660	2660-2670	2670-2680	2680-2690	2690-2700	2700-2710	2710-2720	2720-2730	2730-2740	2740-2750	2750-2760	2760-2770	2770-2780	2780-2790	2790-2800	2800-2810	2810-2820	2820-2830	2830-2840	2840-2850	2850-2860	2860-2870	2870-2880	2880-2890	2890-2900	2900-2910	2910-2920	2920-2930	2930-2940	2940-2950	2950-2960	2960-2970	2970-2980	2980-2990	2990-3000	3000-3010	3010-3020	3020-3030	3030-3040	3040-3050	3050-3060	3060-3070	3070-3080	3080-3090	3090-3100	3100-3110	3110-3120	3120-3130	3130-3140	3140-3150	3150-3160	3160-3170	3170-3180	3180-3190	3190-3200	3200-3210	3210-3220	3220-3230	3230-3240	3240-3250	3250-3260	3260-3270	3270-3280	3280-3290	3290-3300	3300-3310	3310-3320	3320-3330	3330-3340	3340-3350	3350-3360	3360-3370	3370-3380	3380-3390	3390-3400	3400-3410	3410-3420	3420-3430	3430-3440	3440-3450	3450-3460	3460-3470	3470-3480	3480-3490	3490-3500	3500-3510	3510-3520	3520-3530	3530-3540	3540-3550	3550-3560	3560-3570	3570-3580	3580-3590	3590-3600	3600-3610	3610-3620	3620-3630	3630-3640	3640-3650	3650-3660	3660-3670	3670-3680	3680-3690	3690-3700	3700-3710	3710-3720	3720-3730	3730-3740	3740-3750	3750-3760	3760-3770	3770-3780	3780-3790	3790-3800	3800-3810	3810-3820	3820-3830	3830-3840	3840-3850	3850-3860	3860-3870	3870-3880	3880-3890	3890-3900	3900-3910	3910-3920	3920-3930	3930-3940	3940-3950	3950-3960	3960-3970	3970-3980	3980-3990	3990-4000	4000-4010	4010-4020	4020-4030	4030-4040	4040-4050	4050-4060	4060-4070	4070-4080	4080-4090	4090-4100	4100-4110	4110-4120	4120-4130	4130-4140	4140-4150	4150-4160	4160-4170	4170-4180	4180-4190	4190-4200	4200-4210	4210-4220	4220-4230	4230-4240	4240-4250	4250-4260	4260-4270	4270-4280	4280-4290	4290-4300	4300-4310	4310-4320	4320-4330	4330-4340	4340-4350	4350-4360	4360-4370	4370-4380	4380-4390	4390-4400	4400-4410	4410-4420	4420-4430	4430-4440	4440-4450	4450-4460	4460-4470	4470-4480	4480-4490	4490-4500	4500-4510	4510-4520	4520-4530	4530-4540	4540-4550	4550-4560	4560-4570	4570-4580	4580-4590	4590-4600	4600-4610	4610-4620	4620-4630	4630-4640	4640-4650	4650-4660	4660-4670	4670-4680	4680-4690	4690-4700	4700-4710	4710-4720	4720-4730	4730-4740	4740-4750	4750-4760	4760-4770	4770-4780	4780-4790	4790-4800	4800-4810	4810-4820	4820-4830	4830-4840	4840-4850	4850-4860	4860-4870	4870-4880	4880-4890	4890-4900	4900-4910	4910-4920	4920-4930	4930-4940	4940-4950	4950-4960	4960-4970	4970-4980	4980-4990	4990-5000	5000-5010	5010-5020	5020-5030	5030-5040	5040-5050	5050-5060	5060-5070	5070-5080	5080-5090	5090-5100	5100-5110	5110-5120	5120-5130	5130-5140	5140-5150	5150-5160	5160-5170	5170-5180	5180-5190	5190-5200	5200-5210	5210-5220	5220-5230	5230-5240	5240-5250	5250-5260	5260-5270	5270-5280	5280-5290	5290-5300	5300-5310	5310-5320	5320-5330	5330-5340	5340-5350	5350-5360	5360-5370	5370-5380	5380-5390	5390-5400	5400-5410	5410-5420	5420-5430	5430-5440	5440-5450	5450-5460	5460-5470	5470-5480	5480-5490	5490-5500	5500-5510	5510-5520	5520-5530	5530-5540	5540-5550	5550-5560	5560-5570	5570-5580	5580-5590	5590-5600	5600-5610	5610-5620	5620-5630	5630-5640	5640-5650	5650-5660	5660-5670	5670-5680	5680-5690	5690-5700	5700-5710	5710-5720	5720-5730	5730-5740	5740-5750	5750-5760	5760-5770	5770-5780	5780-5790	5790-5800	5800-5810	5810-5820	5820-5830	5830-5840	5840-5850	5850-5860	5860-5870	5870-5880	5880-5890	5890-5900	5900-5910	5910-5920	5920-5930	5930-5940	5940-5950	5950-5960	5960-5970	5970-5980	5980-5990	5990-6000	6000-6010	6010-6020	6020-6030	6030-6040	6040-6050	6050-6060	6060-6070	6070-6080	6080-6090	6090-6100	6100-6110	6110-6120	6120-6130	6130-6140	6140-6150	6150-6160	6160-6170	6170-6180	6180-6190	6190-6200	6200-6210	6210-6220	6220-6230	6230-6240	6240-6250	6250-6260	6260-6270	6270-6280	6280-6290	6290-6300	6300-6310	6310-6320	6320-6330	6330-6340	6340-6350	6350-6360	6360-6370	6370-6380	6380-6390	6390-6400	6400-6410	6410-6420	6420-6430	6430-6440	6440-6450	6450-6460	6460-6470	6470-6480	6480-6490	6490-6500	6500-6510	6510-6520	6520-6530	6530-6540	6540-6550	6550-6560	6560-6570	6570-6580	6580-6590	6590-6600	6600-6610	6610-6620	6620-6630	6630-6640	6640-6650	6650-6660	6660-6670	6670-6680	6680-6690	6690-6700	6700-6710	6710-6720	6720-6730	6730-6740	6740-6750	6750-6760	6760-6770	6770-6780	6780-6790	6790-6800	6800-6810	6810-6820	6820-6830	6830-6840	6840-6850	6850-6860	6860-6870	6870-6880	6880-6890	6890-6900	6900-6910	6910-6920	6920-6930	6930-6940	6940-6950	6950-6960	6960-6970	6970-6980	6980-6990	6990-7000	7000-7010	7010-7020	7020-7030	7030-7040	7040-7050	7050-7060	7060-7070	7070-7080	7080-7090	7090-7100	7100-7110	7110-7120	7120-7130	7130-7140	7140-7150	7150-7160	7160-7170	7170-7180	7180-7190	7190-7200	7200-7210	7210-7220	7220-7230	7230-7240	7240-7250	7250-7260	7260-7270	7270-7280	7280-7290	7290-7300	7300-7310	7310-7320	7320-7330	7330-7340	7340-7350	7350-7360	7360-7370	7370-7380	7380-7390	7390-7400	7400-7410	7410-7420	7420-7430	7430-7440	7440-7450	7450-7460	7460-7470	7470-7480	7480-7490	7490-7500	7500-7510	7510-7520	7520-7530	7530-7540	7540-7550	7550-7560	7560-7570	7570-7580	7580-7590	7590-7600	7600-7610	7610-7620	7620-7630	7630-7640	7640-7650	7650-7660	7660-7670	7670-7680	7680-7690	7690-7700	7700-7710	7710-7720	7720-7730	7730-7740	7740-7750	7750-7760	7760-7770	7770-7780	7780-7790	7790-7800	7800-7810	7810-7820	7820-7830	7830-7840	7840-7850	7850-7860	7860-7870	7870-7880	7880-7890	7890-7900	7900-7910	7910-7920	7920-7930	7930-7940	7940-7950	7950-7960	7960-7970	7970-7980	7980-7990	7990-8000	8000-8010	8010-8020	8020-8030	8030-8040	8040-8050	8050-8060	8060-8070	8070-8080	8080-8090	8090-8100	8100-8110	8110-8120	8120-8130	8130-8140	8140-8150	8150-8160	8160-8170	8170-8180	8180-8190	8190-8200	8200-8210	8210-8220	8220-8230	8230-8240	8240-8250	8250-8260	8260-8270	8270-8280	8280-8290	8290-8300	8300-8310	8310-8320	8320-8330	8330-8340	8340-8350	8350-8360	8360-8370	8370-8380	8380-8390	8390-8400	8400-8410	8410-8420	8420-8430	8430-8440	8440-8450	8450-8460	8460-8470	8470-8480	8480-8490	8490-8500	8500-8510	8510-8520	8520-8530	8530-8540	8540-8550	8550-8560	8560-8570	8570-8580	8580-8590	8590-8600	8600-8610	8610-8620	8620-8630	8630-8640	8640-8650	8650-8660	8660-8670	8670-8680	8680-8690	8690-8700	8700-8710	8710-8720	8720-8730	8730-8740	8740-8750	8750-8760	8760-8770	8770-8780	8780-8790	8790-8800	8800-8810	8810-8820	8820-8830

TABLE A5.1  
Crop yields (t/ha dry weight) at the high input level by LGPs (days)

Crop	Growth cycle (days)	Max. yield	LGP													
			0	1-29	30-59	60-89	90-119	120-149	150-179	180-209	210-239	240-269	270-299	300-329	330-364	365+
Barley	90-120	4.55	0.00	0.00	0.00	0.60	3.10	4.50	4.55	4.40	2.50	1.85	0.55	0.55	0.55	0.55
	120-150	4.55	0.00	0.00	0.00	0.00	0.00	3.10	4.50	4.55	2.50	1.85	0.55	0.55	0.55	0.55
	150-180	4.55	0.00	0.00	0.00	0.00	0.00	0.00	0.00	4.50	4.55	1.85	0.55	0.55	0.55	0.55
Maize (lowland)	70-90	4.14	0.00	0.00	0.67	1.63	3.11	4.14	4.04	2.81	1.92	1.42	1.32	0.99	0.99	0.40
	90-110	5.62	0.00	0.00	0.00	2.18	4.25	5.62	5.52	3.96	2.66	1.96	1.86	1.40	1.40	0.60
	110-130	7.10	0.00	0.00	0.00	0.00	5.40	7.10	7.00	5.10	3.40	2.50	2.40	1.80	1.80	0.80
Maize (highland)	120-140	8.50	0.00	0.00	0.23	1.78	5.89	8.50	7.80	5.85	3.90	2.93	2.93	2.19	0.98	0.98
	140-180	9.40	0.00	0.00	0.00	0.00	0.00	7.09	8.37	9.40	8.26	6.22	3.40	2.55	1.14	1.14
	180-200	10.30	0.00	0.00	0.00	0.00	0.00	3.69	6.59	10.30	10.30	7.73	3.86	2.90	1.29	1.29
	200-220	10.90	0.00	0.00	0.00	0.00	0.00	0.00	7.13	10.90	10.90	8.18	4.09	3.07	1.36	1.36
	220-280	10.90	0.00	0.00	0.00	0.00	0.00	2.09	3.96	6.51	7.02	7.19	5.65	3.34	1.48	1.48
	280-300	10.90	0.00	0.00	0.00	0.00	0.00	0.49	0.78	2.12	3.13	6.19	7.20	3.60	1.60	1.60
Oats	90-120	4.10	0.00	0.00	0.50	2.80	4.10	4.00	3.90	2.20	1.60	0.45	0.45	0.45	0.45	0.45
	120-150	4.10	0.00	0.00	0.00	0.00	2.80	4.10	4.00	2.20	1.60	0.45	0.45	0.45	0.45	0.45
	150-180	4.10	0.00	0.00	0.00	0.00	0.00	2.80	4.10	4.00	1.60	0.45	0.45	0.45	0.45	0.45
Pearl millet	60-80	2.80	0.00	0.00	1.10	2.20	2.20	2.80	2.00	1.10	0.30	0.30	0.30	0.30	0.30	0.30
	80-100	3.90	0.00	0.00	0.00	3.10	3.10	2.80	2.80	1.60	0.50	0.50	0.50	0.50	0.50	0.50
Rice (dryland)	90-110	3.30	0.00	0.00	0.20	0.71	0.90	1.30	1.90	2.50	3.30	3.30	3.30	2.40	1.80	1.20
	110-130	4.20	0.00	0.00	0.00	0.00	1.10	1.60	2.40	3.20	4.20	4.20	4.10	3.00	2.30	1.50
Rice (wetland)	80-100	2.49	0.00	0.00	0.00	0.00	0.00	1.31	1.93	2.49	2.49	2.44	2.42	2.36	2.36	1.58
	100-120	3.28	0.00	0.00	0.00	0.00	0.00	1.71	2.52	3.28	3.28	3.23	3.20	3.15	3.15	2.10
	120-140	4.04	0.00	0.00	0.00	0.00	0.00	2.09	3.09	4.04	4.04	3.96	3.86	3.86	3.86	2.57
Sorghum (lowland)	70-90	2.97	0.00	0.00	0.51	1.52	2.33	2.97	2.87	1.50	0.67	0.50	0.30	0.30	0.30	0.30
	90-110	4.04	0.00	0.00	0.00	2.08	3.70	4.04	3.94	2.10	0.94	0.70	0.45	0.45	0.45	0.45
	110-130	5.10	0.00	0.00	0.00	0.00	3.80	5.10	5.00	2.70	1.20	0.90	0.60	0.60	0.60	0.60
Sorghum (highland)	120-140	6.00	0.00	0.00	0.23	1.24	4.20	6.00	5.60	3.15	1.40	1.05	0.70	0.70	0.70	0.70
	140-180	6.65	0.00	0.00	0.00	0.00	0.00	5.31	6.65	6.46	4.25	2.35	1.28	0.81	0.81	0.81
	180-200	7.30	0.00	0.00	0.00	0.00	0.00	2.59	4.68	7.30	5.48	2.74	1.37	0.91	0.91	0.91
	200-220	7.80	0.00	0.00	0.00	0.00	0.00	2.59	5.14	7.80	5.85	2.93	1.46	0.98	0.98	0.98
	220-280	7.80	0.00	0.00	0.00	0.00	0.00	1.47	2.94	4.61	4.39	3.65	2.46	1.26	1.26	1.26
	280-300	7.80	0.00	0.00	0.00	0.00	0.00	0.35	0.74	1.42	2.93	4.36	3.45	1.53	1.53	1.53
Wheat	100-130	5.10	0.00	0.00	0.43	1.76	3.76	5.10	5.00	2.82	2.07	0.62	0.62	0.62	0.62	0.62
Wheat	130-160	5.00	0.00	0.00	0.00	0.00	3.12	5.00	5.00	2.82	2.07	0.62	0.62	0.62	0.62	0.62
Wheat	160-190	5.00	0.00	0.00	0.00	0.00	0.00	3.23	5.00	5.00	2.07	0.92	0.62	0.62	0.62	0.62

Crop	Growth cycle (days)	Max. yield	LGP															365 <sup>+</sup>
			0	1-29	30-59	60-89	90-119	120-149	150-179	180-209	210-239	240-269	270-299	300-329	330-364	365 <sup>-</sup>		
Cowpea	80-100	2.40	0.00	0.00	0.05	0.35	0.90	1.50	2.40	2.40	2.30	1.70	1.70	1.20	0.60	0.40	0.30	
Cowpea	100-140	3.40	0.00	0.00	0.00	0.00	1.92	3.40	3.30	3.30	2.50	2.40	2.40	1.70	0.90	0.60	0.40	
Green gram	60-80	1.90	0.00	0.08	0.27	1.00	1.40	1.90	1.90	2.50	1.80	1.40	1.40	0.60	0.50	0.30	0.40	
Green gram	80-100	2.50	0.00	0.00	0.40	1.30	1.90	2.50	2.50	2.50	1.90	1.70	0.80	0.60	0.60	0.40	0.40	
Groundnut	80-100	2.40	0.00	0.00	0.41	0.90	1.50	2.40	2.40	2.30	1.30	1.00	0.80	0.60	0.40	0.30	0.40	
Groundnut	100-140	3.30	0.00	0.00	0.00	1.10	1.90	3.30	3.30	3.30	1.90	1.40	1.20	0.90	0.60	0.40	0.40	
Phaseolus bean	90-120	2.65	0.00	0.00	0.32	0.92	2.00	2.65	2.55	1.92	1.92	0.96	0.72	0.48	0.32	0.32	0.32	
Phaseolus bean	120-150	2.65	0.00	0.00	0.00	0.37	1.00	2.65	2.55	1.92	1.92	0.96	0.72	0.48	0.32	0.32	0.32	
Phaseolus bean	150-180	2.65	0.00	0.00	0.00	0.00	0.44	1.49	2.65	2.55	1.92	0.96	0.72	0.48	0.32	0.32	0.32	
Pigeon pea	130-150	3.30	0.00	0.00	0.07	0.35	1.38	3.30	3.30	3.20	2.40	2.40	1.70	0.90	0.60	0.40	0.40	
Pigeon pea	150-170	3.80	0.00	0.00	0.00	0.00	1.50	3.80	3.70	3.70	2.80	2.70	2.00	1.00	0.70	0.40	0.40	
Pigeon pea	170-190	4.04	0.00	0.00	0.00	0.00	0.00	3.55	3.98	4.04	3.08	2.91	2.21	1.07	0.77	0.40	0.40	
Soybean	80-100	2.40	0.00	0.00	0.35	0.90	1.90	2.40	2.40	1.70	1.10	0.90	0.60	0.40	0.30	0.30	0.40	
Soybean	100-140	3.40	0.00	0.00	0.00	1.00	2.50	3.40	3.30	2.50	1.60	1.20	0.90	0.60	0.40	0.40	0.40	
Cassava	150-330	13.15	0.00	0.00	0.00	0.00	0.00	0.00	8.75	10.85	11.90	12.40	13.1	7.40	7.40	5.00	5.00	
Sweet potato	115-125	7.70	0.00	0.00	0.00	2.05	3.90	7.60	7.60	7.40	7.40	5.50	2.70	2.70	2.70	1.80	1.80	
Sweet potato	125-145	8.90	0.00	0.00	0.00	0.00	4.50	8.75	8.75	8.55	8.55	6.30	3.10	3.05	3.05	2.05	2.05	
Sweet potato	145-155	10.10	0.00	0.00	0.00	0.00	0.00	10.1	9.90	9.70	9.70	7.10	3.50	3.40	3.40	2.30	2.30	
White potato	90-110	5.70	0.00	0.00	1.20	2.08	3.26	5.70	5.48	3.05	3.05	1.05	0.70	0.70	0.70	0.70	0.70	
White potato	110-130	7.30	0.00	0.00	0.00	2.25	4.15	7.30	7.05	3.95	3.95	1.35	0.90	0.90	0.90	0.90	0.90	
White potato	130-170	9.70	0.00	0.00	0.00	0.00	4.84	9.70	9.40	5.30	5.30	1.80	1.20	1.20	1.20	1.20	1.20	
Banana	300-365	9.60 <sup>1</sup>	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.30	4.30	6.70	9.60	9.60	9.60	
Oil palm	270-365	5.30 <sup>2</sup>	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.81	3.28	4.44	5.30	5.30	5.30	
Sugarcane	210-365	11.60 <sup>1</sup>	0.00	0.00	0.00	0.00	0.00	0.00	0.00	4.40	6.30	8.10	9.80	10.82	11.60	8.70	8.70	

1 Adjusted as appropriate for turn-round time (15 days) between crops where LGP > 330.

2 Adjusted for the non-productive establishment period (20% of total rotation age).

TABLE A5.2  
Crop yields (t/ha dry weight) at the intermediate input level by LGPs (days)

Crop	Growth cycle (days)	Max. yield	LGP													
			0	1-29	30-59	60-89	90-119	120-149	150-179	180-209	210-239	240-269	270-299	300-329	330-364	365-365+
Barley	90-120	2.85	0.00	0.00	0.00	0.38	1.93	2.83	2.85	2.75	1.55	1.15	0.38	0.35	0.35	0.35
	120-150	2.85	0.00	0.00	0.00	0.00	0.00	1.93	2.83	2.85	1.68	1.25	0.38	0.35	0.35	0.35
	150-180	2.85	0.00	0.00	0.00	0.00	0.00	0.00	1.93	2.83	2.85	1.35	0.38	0.35	0.35	0.35
Maize (lowland)	70-90	2.59	0.00	0.00	0.36	1.00	1.86	2.57	2.54	1.79	1.26	1.03	0.91	0.70	0.58	0.29
	90-110	3.51	0.00	0.00	0.00	1.30	2.53	3.51	3.45	2.50	1.73	1.37	1.28	0.99	0.82	0.42
	110-130	4.45	0.00	0.00	0.00	0.00	3.20	4.45	4.35	3.20	2.20	1.70	1.65	1.25	1.05	0.55
Maize (highland)	120-140	5.32	0.00	0.00	0.14	1.06	3.50	5.32	4.88	3.66	2.50	2.02	2.02	1.37	0.61	0.61
	140-180	5.84	0.00	0.00	0.00	0.00	0.00	3.55	5.20	5.84	5.17	3.97	2.34	1.58	0.71	0.71
	180-200	6.44	0.00	0.00	0.00	0.00	0.00	0.00	4.12	6.44	6.44	4.83	2.66	1.81	0.81	0.81
	200-220	6.82	0.00	0.00	0.00	0.00	0.00	0.00	2.31	6.82	6.82	5.11	2.81	1.92	0.85	0.85
	220-280	6.82	0.00	0.00	0.00	0.00	0.00	0.00	1.31	7.23	4.07	4.49	3.66	2.09	0.93	0.93
	280-300	6.82	0.00	0.00	0.00	0.00	0.00	0.00	0.31	0.49	3.71	3.96	4.50	2.25	1.00	1.00
Oats	90-120	2.55	0.00	0.00	0.33	1.75	2.55	2.48	2.43	1.38	0.98	0.30	0.30	0.28	0.28	0.28
	120-150	2.55	0.00	0.00	0.00	0.00	1.75	2.55	2.43	1.58	1.08	0.30	0.30	0.28	0.28	0.28
	150-180	2.55	0.00	0.00	0.00	0.00	0.00	0.00	1.75	2.55	2.48	1.28	0.30	0.28	0.28	0.28
Pearl millet	60-80	1.75	0.00	0.00	0.70	1.35	1.35	1.75	1.25	0.75	0.25	0.20	0.20	0.20	0.20	0.20
	80-100	2.45	0.00	0.00	0.00	1.95	1.95	2.45	1.75	1.05	0.35	0.35	0.30	0.30	0.30	0.30
Rice (dryland)	90-110	2.07	0.00	0.00	0.13	0.45	0.57	0.82	1.19	1.57	2.07	2.07	2.07	1.50	1.13	0.75
	110-130	2.63	0.00	0.00	0.00	0.00	0.69	1.00	1.50	2.00	2.63	2.63	2.57	1.88	1.44	0.94
Rice (wetland)	80-100	1.56	0.00	0.00	0.00	0.00	0.00	0.79	1.21	1.56	1.56	1.53	1.52	1.48	1.48	0.99
	100-120	2.05	0.00	0.00	0.00	0.00	0.00	1.07	1.58	2.05	2.03	2.02	2.00	1.97	1.97	1.32
	120-140	2.53	0.00	0.00	0.00	0.00	0.00	1.31	1.93	2.53	2.53	2.48	2.47	2.42	2.42	1.61
Sorghum (lowland)	70-90	1.86	0.00	0.00	0.31	0.91	1.39	1.86	1.80	0.94	0.42	0.30	0.18	0.18	0.18	0.18
	90-110	2.53	0.00	0.00	0.00	1.24	2.14	2.51	1.97	1.32	0.59	0.42	0.27	0.27	0.27	0.27
	110-130	3.18	0.00	0.00	0.00	0.00	2.26	3.19	3.13	1.69	0.75	0.54	0.36	0.36	0.36	0.36
Sorghum (highland)	120-140	3.75	0.00	0.00	0.14	0.74	2.50	3.75	3.50	1.97	0.90	0.66	0.48	0.44	0.44	0.44
	140-180	4.15	0.00	0.00	0.00	0.00	0.00	3.35	4.15	4.07	2.69	1.51	0.79	0.51	0.51	0.51
	180-200	4.57	0.00	0.00	0.00	0.00	0.00	1.62	2.93	4.57	3.43	1.76	0.86	0.57	0.57	0.57
	200-220	4.88	0.00	0.00	0.00	0.00	0.00	1.62	3.22	4.88	3.66	1.88	0.92	0.61	0.62	0.62
	220-280	4.88	0.00	0.00	0.00	0.00	0.00	0.91	1.84	2.89	2.75	2.24	1.65	0.79	0.79	0.79
	280-300	4.88	0.00	0.00	0.00	0.00	0.00	0.20	0.46	0.89	1.83	2.59	2.37	0.96	0.96	0.96
Wheat	100-130	3.19	0.00	0.00	0.27	1.12	2.35	3.19	3.13	1.77	1.30	0.43	0.43	0.39	0.39	0.39
	130-160	3.13	0.00	0.00	0.00	0.00	1.95	3.13	3.13	1.88	1.38	0.43	0.43	0.39	0.39	0.39
	160-190	3.13	0.00	0.00	0.00	0.00	0.00	2.02	3.13	3.13	1.38	0.64	0.43	0.39	0.39	0.39



TABLE A5.3  
Crop yields (t/ha dry weight) at the low input level by LGPs (days)

Crop	Growth cycle (days)	Max. yield	LGP															
			0	1-29	30-59	60-89	90-119	120-149	150-179	180-209	210-239	240-269	270-299	300-329	330-364	365 <sup>+</sup>		
Barley	90-120	1.15	0.00	0.00	0.00	0.15	0.75	1.15	1.15	1.15	1.10	0.06	0.45	0.20	0.20	0.15	0.15	0.15
	120-150	1.15	0.00	0.00	0.00	0.00	0.75	1.15	1.15	1.15	1.15	0.85	0.65	0.20	0.20	0.15	0.15	0.15
	150-180	1.15	0.00	0.00	0.00	0.00	0.00	0.00	1.15	1.15	1.15	1.15	0.85	0.20	0.20	0.20	0.15	0.15
Maize (lowland)	70-90	1.03	0.00	0.00	0.12	0.37	0.60	0.99	1.03	1.03	0.76	0.60	0.60	0.50	0.50	0.40	0.17	0.17
	90-110	1.40	0.00	0.00	0.00	0.41	0.80	1.40	1.37	1.03	1.03	0.80	0.80	0.70	0.55	0.55	0.24	0.24
	110-130	1.80	0.00	0.00	0.00	0.00	1.00	1.80	1.70	1.30	1.30	1.00	1.00	0.90	0.70	0.70	0.30	0.30
Maize (highland)	120-140	2.13	0.00	0.00	0.05	0.34	1.10	2.13	1.95	1.46	1.10	1.10	1.10	1.10	1.10	0.55	0.24	0.24
	140-180	2.27	0.00	0.00	0.00	0.00	0.00	1.72	2.02	2.27	2.07	2.07	1.71	1.28	0.61	0.28	0.28	
	180-200	2.58	0.00	0.00	0.00	0.00	0.00	0.92	1.65	2.58	2.58	2.58	1.93	1.45	0.72	0.32	0.32	
	200-220	2.73	0.00	0.00	0.00	0.00	0.00	0.92	1.99	2.73	2.73	2.73	2.04	1.53	0.77	0.34	0.34	
	220-280	2.73	0.00	0.00	0.00	0.00	0.00	0.53	1.05	1.62	1.76	1.76	1.79	1.67	0.84	0.37	0.37	
	280-300	2.73	0.00	0.00	0.00	0.00	0.00	0.13	0.20	0.53	0.79	0.79	1.54	1.80	0.90	0.40	0.40	
Oats	90-120	1.00	0.00	0.00	0.15	0.70	1.00	0.95	0.95	0.55	0.35	0.35	0.15	0.15	0.10	0.10	0.10	0.10
	120-150	1.00	0.00	0.00	0.00	0.00	0.70	1.00	0.95	0.95	0.55	0.55	0.15	0.15	0.10	0.10	0.10	0.10
	150-180	1.00	0.00	0.00	0.00	0.00	0.00	0.70	1.00	0.95	0.95	0.95	0.15	0.15	0.10	0.10	0.10	0.10
Pearl millet	60-80	0.70	0.00	0.00	0.30	0.50	0.50	0.70	0.50	0.40	0.20	0.20	0.10	0.10	0.10	0.10	0.10	0.10
	80-100	1.00	0.00	0.00	0.00	0.80	1.00	1.00	0.70	0.50	0.50	0.20	0.20	0.20	0.20	0.20	0.20	0.20
Rice (dryland)	90-110	0.83	0.00	0.00	0.05	0.18	0.23	0.33	0.48	0.63	0.83	0.83	0.83	0.83	0.83	0.60	0.45	0.30
	110-130	1.05	0.00	0.00	0.00	0.00	0.28	0.40	0.60	0.80	1.05	1.05	1.05	1.03	0.75	0.58	0.38	0.38
Rice (wetland)	80-100	0.62	0.00	0.00	0.00	0.00	0.00	0.26	0.48	0.62	0.62	0.62	0.62	0.61	0.61	0.59	0.59	0.40
	100-120	0.82	0.00	0.00	0.00	0.00	0.00	0.43	0.63	0.82	0.82	0.82	0.82	0.81	0.80	0.79	0.79	0.53
	120-140	1.01	0.00	0.00	0.00	0.00	0.00	0.52	0.77	1.01	1.01	1.01	1.01	0.99	0.99	0.97	0.97	0.64
Sorghum (lowland)	70-90	0.74	0.00	0.00	0.10	0.29	0.44	0.74	0.72	0.38	0.17	0.17	0.09	0.06	0.06	0.06	0.06	0.06
	90-110	1.01	0.00	0.00	0.00	0.39	0.58	1.01	0.99	0.53	0.24	0.24	0.13	0.08	0.08	0.08	0.08	0.08
	110-130	1.28	0.00	0.00	0.00	0.00	0.71	1.28	1.25	0.68	0.30	0.30	0.17	0.11	0.11	0.11	0.11	0.11
Sorghum (highland)	120-140	1.50	0.00	0.00	0.05	0.23	0.79	1.50	1.40	0.79	0.39	0.39	0.26	0.26	0.18	0.18	0.18	0.18
	140-180	1.67	0.00	0.00	0.00	0.00	0.00	1.38	1.65	1.68	1.13	1.13	0.67	0.30	0.21	0.21	0.21	0.21
	180-200	1.83	0.00	0.00	0.00	0.00	0.00	0.65	1.17	1.83	1.37	1.37	0.77	0.34	0.23	0.23	0.23	0.23
	200-220	1.95	0.00	0.00	0.00	0.00	0.00	0.65	1.29	1.95	1.46	1.46	0.82	0.37	0.24	0.24	0.24	0.24
	220-280	1.95	0.00	0.00	0.00	0.00	0.00	0.35	0.74	1.16	1.10	1.10	0.82	0.83	0.32	0.32	0.32	0.32
	280-300	1.95	0.00	0.00	0.00	0.00	0.00	0.05	0.18	0.36	0.73	0.73	0.81	1.29	0.39	0.39	0.39	0.39
Wheat	100-130	1.28	0.00	0.00	0.11	0.47	0.94	1.28	1.25	0.71	0.52	0.52	0.23	0.23	0.15	0.15	0.15	0.15
	130-160	1.25	0.00	0.00	0.00	0.00	0.78	1.25	1.25	0.94	0.69	0.69	0.23	0.23	0.15	0.15	0.15	0.15
	160-190	1.25	0.00	0.00	0.00	0.00	0.00	0.81	1.25	1.25	0.69	0.69	0.35	0.23	0.15	0.15	0.15	0.15

Crop	Growth cycle (days)	Max. yield	LGP													
			0	1-29	30-59	60-89	90-119	120-149	150-179	180-209	210-239	240-269	270-299	300-329	330-364	365-365+
Cowpea	80-100	0.50	0.00	0.00	0.00	0.05	0.10	0.20	0.40	0.50	0.30	0.30	0.30	0.20	0.20	0.20
	100-140	0.60	0.00	0.00	0.00	0.10	0.30	0.30	0.50	0.60	0.50	0.50	0.50	0.40	0.20	0.20
Green gram	60-80	0.50	0.00	0.02	0.07	0.20	0.40	0.50	0.50	0.50	0.20	0.20	0.20	0.10	0.10	0.10
	80-100	0.60	0.00	0.00	0.10	0.30	0.50	0.60	0.60	0.60	0.30	0.30	0.20	0.10	0.10	0.10
Groundnut	80-100	0.60	0.00	0.00	0.14	0.20	0.40	0.60	0.60	0.40	0.30	0.20	0.20	0.20	0.10	0.10
	100-140	0.80	0.00	0.00	0.00	0.30	0.50	0.80	0.80	0.60	0.50	0.40	0.20	0.20	0.20	0.10
Phaseolus bean	90-120	0.67	0.00	0.00	0.07	0.23	0.56	0.67	0.80	0.36	0.18	0.18	0.18	0.08	0.08	0.08
	120-150	0.67	0.00	0.00	0.00	0.09	0.25	0.67	0.90	0.36	0.24	0.18	0.18	0.08	0.08	0.08
	150-180	0.67	0.00	0.00	0.00	0.00	0.11	0.37	1.00	0.36	0.24	0.18	0.18	0.08	0.08	0.08
Pigeon pea	130-150	0.80	0.00	0.00	0.03	0.08	0.36	0.80	0.80	0.80	0.60	0.40	0.40	0.20	0.10	0.10
	150-170	1.00	0.00	0.00	0.00	0.00	0.40	1.00	0.90	0.90	0.70	0.50	0.50	0.20	0.20	0.10
	170-190	1.01	0.00	0.00	0.00	0.00	0.00	0.89	1.00	1.01	0.77	0.73	0.55	0.27	0.20	0.10
Soybean	80-100	0.60	0.00	0.00	0.07	0.20	0.50	0.60	0.60	0.30	0.30	0.20	0.10	0.10	0.10	0.10
	100-140	0.80	0.00	0.00	0.00	0.25	0.60	0.80	0.60	0.50	0.50	0.30	0.20	0.10	0.10	0.10
Cassava	150-330	3.30	0.00	0.00	0.00	0.00	0.00	0.00	1.20	1.65	2.93	3.07	3.33	2.53	2.53	1.87
Sweet potato	115-125	1.90	0.00	0.00	0.00	0.50	1.00	1.90	1.90	1.80	1.40	1.40	1.40	0.90	0.90	0.70
	125-145	2.20	0.00	0.00	0.00	0.00	1.15	2.20	2.20	2.10	1.60	1.60	1.60	1.05	1.05	0.85
	145-155	2.50	0.00	0.00	0.00	0.00	0.00	0.00	2.50	2.40	1.80	1.80	1.80	1.20	1.20	0.90
White potato	90-110	1.40	0.00	0.00	0.26	0.50	0.82	1.40	1.40	1.05	0.80	0.37	0.13	0.13	0.13	0.13
	110-130	1.80	0.00	0.00	0.00	0.55	1.05	1.80	1.80	1.35	1.00	0.50	0.20	0.20	0.20	0.20
	130-170	2.40	0.00	0.00	0.00	0.00	1.40	2.40	2.40	1.80	1.30	0.70	0.30	0.30	0.30	0.30
Banana	300-365	2.40 <sup>1</sup>	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.60	1.10	1.60	2.40	2.40
Oil palm	270-365	1.33 <sup>2</sup>	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.56	0.82	1.11	1.33	1.33
Sugarcane	210-365	2.91 <sup>1</sup>	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.10	1.60	2.00	2.40	2.71	2.91	2.18

1 Adjusted as appropriate for turn-round time (15 days) between crops where LGP > 330.

2 Adjusted for the non-productive establishment period (20% of total rotation age).

TABLE A7.1

Total biomass yield potential (Bm) without constraints (mean annual increment in t/ha dry weight) at high level of inputs

Length of growing period (days)	Species without nitrogen fixing ability			Species with nitrogen fixing ability		
	Pm = 7.5	Pm = 15.0	Pm = 25.0	Pm = 7.5	Pm = 15.0	Pm = 25.0
1 - 29	0.0-0.3	0.0-0.4	0.0-0.6	0.0-0.2	0.0-0.4	0.0-0.6
30 - 59	0.3-0.2	0.4-3.3	0.6-4.7	0.2-1.7	0.4-2.9	0.6-4.0
60 - 89	2.0-4.2	3.3-7.1	4.7-10.0	1.7-3.4	2.9-5.8	4.0-8.1
90 - 119	4.2-6.2	7.1-10.6	10.0-14.9	3.4-4.8	5.8-8.2	8.1-11.5
120 - 149	6.2-9.0	10.6-15.4	14.9-21.6	4.8-6.6	8.2-11.3	11.5-16.0
150 - 179	9.0-11.0	15.4-18.7	21.6-26.3	6.6-7.8	11.3-13.3	16.0-18.7
180 - 209	11.0-13.6	18.7-23.3	26.3-32.8	7.8-9.4	13.3-16.0	18.7-22.5
210 - 239	13.6-15.0	23.3-25.5	32.8-36.0	9.4-10.0	16.0-17.0	28.7-22.5
240 - 269	15.0-16.2	25.5-27.7	36.0-39.0	10.0-10.5	17.0-17.9	22.5-24.0
270 - 299	16.2-17.4	27.7-29.6	39.0-41.8	10.5-11.0	17.9-18.7	25.3-26.4
300 - 329	17.4-18.5	29.6-31.5	41.8-44.4	11.0-11.4	18.7-19.4	26.4-27.4
330 - 364	18.5-19.6	31.5-33.5	44.4-47.2	11.4-11.8	19.4-20.2	27.4-28.5
365-	19.6	33.5	47.2	11.8	20.2	28.5
365+	19.6	33.5	47.2	11.8	20.2	28.5

Pm - maximum photosynthesis rate in  $\text{kg CH}_2\text{O ha}^{-1} \text{hr}^{-1}$

TABLE A7.2

Total biomass yield potential (Bm) without constraints (mean annual increment in t/ha dry weight) at intermediate level of inputs

Length of growing period (days)	Species without nitrogen fixing ability			Species with nitrogen fixing ability		
	Pm = 7.5	Pm = 15.0	Pm = 25.0	Pm = 7.5	Pm = 15.0	Pm = 25.0
1 - 29	0.0-0.2	0.0-0.3	0.0-0.5	0.0-0.2	0.0-0.3	0.0-0.5
30 - 59	0.2-1.5	0.3-2.5	0.5-3.5	0.2-1.3	0.3-2.2	0.5-3.0
60 - 89	1.5-3.2	2.5-5.3	3.5-7.5	1.3-2.6	2.2-4.4	3.0-6.1
90 - 119	3.2-4.7	5.3-8.0	7.5-11.2	2.6-3.6	4.4-6.2	6.1-8.6
120 - 149	4.7-6.8	8.0-11.6	11.2-16.2	3.6-5.0	6.2-8.5	8.6-12.0
150 - 179	6.8-8.3	11.6-14.0	16.2-19.7	5.0-5.9	8.5-10.0	12.0-14.0
180 - 209	8.3-10.2	14.0-17.5	19.7-24.6	5.9-7.1	10.0-12.0	14.0-16.9
210 - 239	10.2-11.3	17.5-19.1	24.6-27.0	7.1-7.5	12.0-12.8	16.9-18.0
240 - 269	11.3-12.2	19.1-20.8	27.0-29.3	7.5-7.9	12.8-13.4	18.0-19.0
270 - 299	12.2-13.1	20.8-22.2	29.3-31.4	7.9-8.3	13.4-14.0	19.0-19.8
300 - 329	13.1-13.9	22.2-23.6	31.4-33.3	8.3-8.6	14.0-14.6	19.8-20.6
330 - 364	13.9-14.7	23.6-25.1	33.3-35.4	8.6-8.9	14.6-15.2	20.6-21.4
365-	14.7	25.1	35.4	8.9	15.2	21.4
365+	14.7	25.1	35.4	8.9	15.2	21.4

Pm - maximum photosynthesis rate in  $\text{kg CH}_2\text{O ha}^{-1} \text{hr}^{-1}$

**TABLE A7.3**  
Total biomass yield potential (Bm) without constraints (mean annual increment in t/ha dry weight) at low level of inputs

Length of growing period (days)	Species without nitrogen fixing ability			Species with nitrogen fixing ability		
	Pm = 7.5	Pm = 15.0	Pm = 25.0	Pm = 7.5	Pm = 15.0	Pm = 25.0
1 - 29	0.0-0.2	0.0-0.2	0.0-0.3	0.0-0.1	0.0-0.2	0.0-0.3
30 - 59	0.2-1.0	0.2-1.7	0.3-2.4	0.1-0.9	0.2-1.5	0.3-2.0
60 - 89	1.0-2.1	1.7-3.6	2.4-5.0	0.9-1.7	1.5-2.9	2.0-4.1
90 - 119	2.1-3.1	3.6-5.3	5.0-7.5	1.7-2.4	2.9-4.1	4.1-5.8
120 - 149	3.1-4.5	5.3-7.7	7.5-10.8	2.4-3.3	4.1-5.7	5.8-8.0
150 - 179	4.5-5.5	7.7-9.4	10.8-13.2	3.3-3.9	5.7-6.7	8.0-9.4
180 - 209	5.5-6.8	9.4-11.7	13.2-16.4	3.9-4.7	6.7-8.0	9.4-11.3
210 - 239	6.8-7.5	11.7-12.3	16.4-18.0	4.7-5.0	8.0-8.5	11.3-12.0
240 - 269	7.5-8.1	12.3-13.9	18.0-19.5	5.0-5.3	8.5-9.0	12.0-12.2
270 - 299	8.1-8.7	13.9-14.8	19.5-20.9	5.3-5.5	9.0-9.4	12.2-13.2
300 - 329	8.7-9.3	14.8-15.8	20.9-22.2	5.5-5.7	9.4-9.7	13.2-13.7
330 - 364	9.3-9.8	15.8-16.8	22.2-23.6	5.7-5.9	9.7-10.1	13.7-14.3
365-	9.8	16.8	23.6	5.9	10.1	14.3
365+	9.8	16.8	23.6	5.9	10.1	14.3

Pm - maximum photosynthesis rate in kg CH<sub>2</sub>O ha<sup>-1</sup> hr<sup>-1</sup>

**TABLE A7.4**  
Wood biomass yield potential (Bm) without constraints (mean annual increment in t/ha dry weight) at high level of inputs

Length of growing period (days)	Species without nitrogen fixing ability			Species with nitrogen fixing ability		
	Pm = 7.5	Pm = 15.0	Pm = 25.0	Pm = 7.5	Pm = 15.0	Pm = 25.0
1 - 29	0.0-0.2	0.0-0.3	0.0-0.4	0.0-0.1	0.0-0.2	0.0-0.3
30 - 59	0.2-1.2	0.3-2.0	0.4-2.8	0.1-1.0	0.2-1.7	0.3-2.4
60 - 89	1.2-2.5	2.0-4.3	2.8-6.0	1.0-2.0	1.7-3.5	2.4-4.9
90 - 119	2.5-3.7	4.3-6.3	6.0-8.9	2.0-2.9	3.5-4.9	4.9-6.9
120 - 149	3.7-5.4	6.3-9.2	8.9-13.0	2.9-4.0	4.9-6.8	6.9-9.6
150 - 179	5.4-6.6	9.2-11.2	13.0-15.8	4.0-4.7	6.8-8.0	9.6-11.2
180 - 209	6.6-8.2	11.2-14.0	15.8-19.7	4.7-5.6	8.0-9.6	11.2-13.5
210 - 239	8.2-9.0	14.0-15.3	19.7-21.6	5.6-6.0	9.6-10.2	13.5-14.4
240 - 269	9.0-9.7	15.3-16.6	21.6-23.4	6.0-6.3	10.2-10.8	14.4-15.2
270 - 299	9.7-10.4	16.6-17.8	23.4-25.1	6.3-6.6	10.8-11.2	15.2-15.8
300 - 329	10.4-11.1	17.8-18.9	25.1-26.6	6.6-6.8	11.2-11.7	15.8-16.4
330 - 364	11.1-11.8	18.9-20.1	26.6-28.3	6.8-7.1	11.7-12.1	16.4-17.1
365-	11.8	20.1	28.3	7.1	12.1	17.1
365+	11.8	20.1	28.3	7.1	12.1	17.1

Pm - maximum photosynthesis rate in kg CH<sub>2</sub>O ha<sup>-1</sup> hr<sup>-1</sup>

TABLE A7.5

Wood biomass yield potential (Bm) without constraints (mean annual increment in t/ha dry weight) at intermediate level of inputs

Length of growing period (days)	Species without nitrogen fixing ability			Species with nitrogen fixing ability		
	Pm = 7.5	Pm = 15.0	Pm = 25.0	Pm = 7.5	Pm = 15.0	Pm = 25.0
1 - 29	0.0-0.2	0.0-0.2	0.0-0.3	0.0-0.1	0.0-0.2	0.0-0.2
30 - 59	0.2-0.9	0.2-1.5	0.3-2.1	0.1-0.8	0.2-1.3	0.2-1.8
60 - 89	0.9-1.9	1.5-3.2	2.1-4.5	0.8-1.5	1.3-2.6	1.8-3.7
90 - 119	1.9-2.8	3.2-4.7	4.5-6.7	1.5-2.2	2.6-3.7	3.7-5.2
120 - 149	2.8-4.1	4.7-6.9	6.7-9.8	2.2-3.0	3.7-5.1	5.2-7.2
150 - 179	4.1-5.0	6.9-8.4	9.8-11.9	3.0-3.5	5.1-6.0	7.2-8.4
180 - 209	5.0-6.2	8.4-10.5	11.9-14.8	3.5-4.2	6.0-7.2	8.4-10.1
210 - 239	6.2-6.8	10.5-11.5	14.8-16.2	4.2-4.5	7.2-7.7	10.1-10.8
240 - 269	6.8-7.3	11.5-12.5	16.2-17.6	4.5-4.7	7.7-8.1	10.8-11.4
270 - 299	7.3-7.6	12.5-13.4	17.6-18.8	4.7-5.0	8.1-8.4	11.4-11.9
300 - 329	7.6-8.3	13.4-14.2	18.8-20.0	5.0-5.1	8.4-8.8	11.9-12.3
330 - 364	8.3-8.9	14.2-15.1	20.0-21.2	5.1-5.3	8.8-9.1	12.3-12.8
365-	8.9	15.1	21.2	5.3	9.1	12.8
365+	8.9	15.1	21.2	5.3	9.1	12.8

Pm - maximum photosynthesis rate in kg CH<sub>2</sub>O ha<sup>-1</sup> hr<sup>-1</sup>

TABLE A7.6

Wood biomass yield potential (Bm) without constraints (mean annual increment in t/ha dry weight) at low level of inputs

Length of growing period (days)	Species without nitrogen fixing ability			Species with nitrogen fixing ability		
	Pm = 7.5	Pm = 15.0	Pm = 25.0	Pm = 7.5	Pm = 15.0	Pm = 25.0
1 - 29	0.0-0.1	0.0-0.2	0.0-0.2	0.0-0.1	0.0-0.1	0.0-0.2
30 - 59	0.1-0.6	0.2-1.0	0.2-1.4	0.1-0.5	0.1-0.9	0.2-1.2
60 - 89	0.6-1.3	1.0-2.2	1.4-3.0	0.5-1.0	0.9-1.8	1.2-2.5
90 - 119	1.3-1.9	2.2-3.2	3.0-4.5	1.0-1.5	1.8-2.5	2.5-3.5
120 - 149	1.9-2.7	3.2-4.6	4.5-6.5	1.5-2.0	2.5-3.4	3.5-4.8
150 - 179	2.7-3.3	4.6-5.6	6.5-7.9	2.0-2.4	3.4-4.0	4.8-5.6
180 - 209	3.3-4.1	5.6-7.0	7.9-9.9	2.4-2.8	4.0-4.8	5.6-6.8
210 - 239	4.1-4.5	7.0-7.7	9.9-10.8	2.8-3.0	4.8-5.1	6.8-7.2
240 - 269	4.5-4.9	7.7-8.3	10.8-11.7	3.0-3.2	5.1-5.4	7.2-7.6
270 - 299	4.9-5.2	8.3-8.9	11.7-12.6	3.2-3.3	5.4-5.6	7.6-7.9
300 - 329	5.2-5.6	8.9-9.5	12.6-13.3	3.3-3.4	5.6-5.9	7.9-8.2
330 - 364	5.6-5.9	9.5-10.1	13.3-14.2	3.4-3.6	5.9-6.1	8.2-8.6
365-	5.9	10.1	14.2	3.6	6.1	8.6
365+	5.9	10.1	14.2	3.6	6.1	8.6

Pm - maximum photosynthesis rate in kg CH<sub>2</sub>O ha<sup>-1</sup> hr<sup>-1</sup>



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