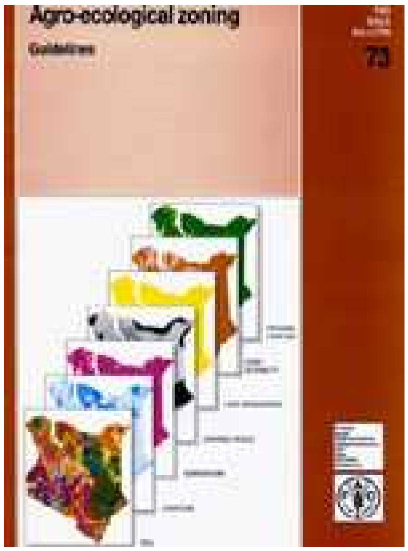
AGRO-ECOLOGICAL ZONING

Guidelines



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Foreword

In most developing countries, the socio-economic needs of rapidly increasing populations are the main driving force in the allocation of land resources to various kinds of uses, with food production as the primary land use. Heavy population pressure and the related increased competition from different types of land users have emphasized the need for more effective land-use planning and management. Rational and sustainable land use is an issue of great concern to governments and land users interested in preserving the land resources for the benefit of present and future populations.

Policy-makers and land users face two basic challenges: the need to reverse trends of land degradation in already-cultivated areas by improving conditions and re-establishing their level of fertility; and prevention of the degradation of land resources in new development areas through appropriate and just allocation and use of these resources to maintain productivity and minimize soil erosion. In both cases an integrated approach to planning and management of land resources is a key factor in a solution which will ensure that land is allocated to uses providing the greatest sustainable benefits. FAO has been promoting the integrated planning and management of land resources in cooperation with regional institutions, individual countries as well as land users.

Over the last two decades, FAO has developed and successfully applied the agro-ecological zones (AEZ) methodology and supporting software packages to analyse solutions to various problems of land resources for planning and management for sustainable agricultural development at regional, national and sub-national levels. The issues addressed include linking land-use outputs with other development goals in such areas as food production, food self sufficiency, cash crop requirements, issues of soil fertility constraints, soil erosion risks and land degradation.

FAO has been assisting various countries such as Mozambique, Kenya, Nigeria, Brazil, China, Bangladesh, Nepal and Grenada in learning, applying and adapting the methodology to local conditions. Several southeast Asian countries such as Thailand, Malaysia and the Philippines have carried out AEZ studies, mainly on their own initiative, which have produced useful applications and results. FAO has organized regional and national workshops in Asia, Africa, Latin America and the Caribbean to discuss AEZ applications and experiences in the various regions and countries. Continuous expansion and refinement of AEZ land resources appraisal procedures and, more recently, linkage to geographic information systems (GIS) have greatly enhanced the power of AEZ land resources databases to implement a wide range of land resources applications. This includes large multilayer databases, linked with various kinds of models, management and decision-support tools and improved interfaces in order to facilitate the use of the systems by non-specialist users. Several variants of the methodology have emerged as it has expanded and been adapted to local conditions. A rich AEZ documentation has been produced which includes numerous detailed technical reports, training materials and workshop proceedings.

Given the expansion of AEZ methods and applications at global, national, district and sub-district levels, a clear need emerged to develop both a terminology and a set of guidelines to relate the scale and scope of agricultural development issues to corresponding levels of resolution in the description of AEZ land resources and facilitate the understanding and use of the voluminous AEZ documentation. These guidelines are supposed to fill this gap. They are intended to guide land resources specialists, land-use planners and other users wishing to design and implement AEZ studies in understanding the essence of the AEZ approach: its concepts and methods, the sequence of activities involved and the tools used, its core and advanced applications. They are also intended to be training material for use in courses and workshops on agro-ecological land resources appraisal.

This publication was prepared under the supervision of Mr. J. Antoine of the Soil Resources, Management and Conservation Service (AGLS) of the Land and Water Development Division. It is the result of material compilation from various sources, but with a focus on the most advanced version of the AEZ methodology as applied in the recent Kenya country study. A first draft was prepared by Mr. J. Van Wambeke and circulated for comment. This draft was revised and expanded by Mr. D. Radcliffe. The publication has also benefitted from comments and inputs from other AGL staff, including Messrs R. Brinkman, L. Jansen, F. Nachtergaele, D. Sims and W. Sombroek.

The procedures described are intended as optional guidelines to assist people throughout the world but particularly in developing countries to improve their own evaluations of their land and water resources and their own decisions on their use. Users' records and annotated experiences with the contents of the guidelines, comments on their usefulness and applicability and suggestions for improvements will be welcome to enable a future re-issue to be upgraded in the light of experience. Comments and suggestions should be sent to:

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ABBREVIATIONS

FAO	Food and Agriculture Organization of the United Nations
IIASA	International Institute for Applied Systems Analysis
ILRI	International Livestock Research Institute
LIS	Land Information System
NGO	Non-governmental Organization
UNFPA	United Nations Fund for Population Activities

Chapter 1 - Introduction

The ability of the world's natural resources to provide the needs of its growing population is a fundamental issue for the international community. World population continues to grow at 1.6% per annum, and at rates exceeding 3% per annum in many of the least developed countries. At the same time, essential natural resources, such as land and water, are declining both in quantity and quality due to such factors as competition with industrial and urban demands, degradation and pollution.

The basic problem is one of mounting pressure on natural resources. Limits to the productive capacity of land resources are set by climate, soil and landform conditions, and by the use and management applied to the land. Sustainable management of land resources requires sound policies and planning based on knowledge of these resources, the demands of the use to which the resources are put, and the interactions between land and land use.

Answers to the following types of questions provide the basis for policy formulation and land-use planning:

· how is land with different potentials and constraints distributed within the country and in component provinces or districts?

· what uses can be recommended on different types of land in different locations?

· how do potential yields vary among locations, years and seasons?

· what is the balance between population demand and land availability in specified areas, and how does this respond to improvements in inputs or management?

Taken within the context of the objectives of governments and those of land users, this information supports the development of land-use policies and enabling strategies in such specific areas as:

· the provision of appropriate, area-specific, extension information and advice;

· the provision of agricultural inputs, or of relief programmes;

· the setting of agricultural research priorities, and the establishment of networks for agro-technology transfer;

· the formulation of legislation or guidelines to regulate and minimize environmental damage, and the establishment of environmental monitoring;

· the identification of particular development programmes or projects.

FAO has devoted considerable attention to the development of techniques for inventory, evaluation and planning of land resources, both at the global level and through its field programme in regions and individual countries. Comple- tion of the Soil Map of the World at 1:5 000 000 scale, together with a standardized soil classification system (FAO, 1974), provided a stimulus to global and comparative assessments of land resource potential. In 1976 the Framework for Land Evaluation (FAO, 1976) established the conceptual approach and methodological orientation to the assessment of land suitability. The Framework is based on evaluating land conditions according to the specific requirements of defined types of land use. This ecological approach marked a radical departure from previous systems of land resource appraisal, and led to a broad range of applications. Guidelines explaining how the Framework can be applied to rainfed and irrigated agriculture, forestry and extensive grazing have been produced (FAO, 1983; 1984a; 1985; 1991).

The original FAO Agro-ecological Zones Project (FAO, 1978) was an early exercise in the application of land evaluation at a continental scale. The methodology used was innovative in that it characterized 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. Agro-ecological zones are defined, which have similar combinations of climate and soil characteristics, and similar physical potentials for agricultural production.

The first series of outputs of the FAO AEZ project were land suitability estimates for 11 crops at three levels of inputs in five regions of the developing world. Subsequently, in cooperation with UNFPA and IIASA, an assessment of potential production and of population support capacity was carried out for the 117 developing nations covered by the project. Following presentation of the findings of this study at the FAO conference in 1983 it was recommended that similar studies be undertaken at national level. Since then, FAO has been assisting various countries, including Mozambique, Kenya, China, Bangladesh, Nepal, Nigeria and Brazil, in learning the methodology, and in applying the results to tackle issues of land, food and people in their component provinces and districts. Still more detailed AEZ investigations have been carried out in selected areas within countries, or on small islands such as Grenada. Some examples of AEZ studies carried out at different scales, and for different purposes, are given in Table 1.

While the AEZ concept is essentially a simple one, the methodology developed by FAO was designed for computers and implemented on them. The nature of the analysis, which involves the combination of layers of spatial information to define zones, lends itself to the application of a geographical information system (GIS). Most advanced AEZ investigations incorporate a series of databases, linked to GIS and dedicated computer models, which have multiple potential applications in natural resource management and land-use planning. Using these techniques, AEZ provides a comprehensive framework for the appraisal and planning of land resources. However, computers are not essential to an AEZ study, and there are many successful examples of application using commercial databases or spreadsheets and conventional cartography.

These guidelines are intended to guide scientists and planners wishing to implement AEZ at the regional, country or sub-national level. Chapter 2 explains the concepts of AEZ and provides definitions of the terms used. Chapter 3 provides a step-wise guide to carrying out an AEZ study, drawing examples from FAO's experience in different environments and different countries, while Chapter 4 discusses computer-assisted techniques, including linkages with GIS. Chapter 5 discusses an alternative, but related, approach to zoning which takes both ecological and economic factors into account.

TABLE 1

Examples of AEZ/GIS studies by scale and application

Planning level	Sample Applications	User
Global and regional 1:5 000 000	Grassland and livestock potential of West Africa	ILRI, Ethiopia
	Population supporting capacity of the developing world	FAO/UNFPA
Regional and large nation 1:1 000 000 to 1:5 000 000	Population supporting capacity, land-use allocation, national resources planning	State Land Administration of China
National and sub-national		
1:2 000 000	Agro-ecological zones of Ethiopia	Ministry of Agriculture and Bureau of Meteorological Services, Ethiopia
1:1 000 000	Agricultural development planning; crops, livestock, fuelwood	Government of Kenya Government of Mozambique
Sub-national and district		
1:500 000	Population supporting capacity	Government of Philippines Government of Malaysia
1:250 000	Land degradation risk assessment in Kaduna State	Federal Land Resources Department, Nigeria
1:125 000	Fertilizer recommendations and technology targeting in districts and thanas	Extension Service, Bangladesh
Small nation and local level		
1:50 000	Decentralized district agricultural development planning	Government of Nepal
1:20 000	Irrigation suitability assessment of northern Ethiopian Rift Valley	Government of Ethiopia
1:15 000	Land evaluation for parish level land use	Government of Grenada
1:10 000	Support to farm planning and development in village communities	Government of Oman

Source: Adapted from FAO (1994a).

Chapter 2 - Concepts and definitions

The purpose of zoning, as carried out for rural land-use planning, is to separate areas with similar sets of potentials and constraints for development. Specific programmes can then be formulated to provide the most effective support to each zone..

Agro-ecalogical zoning (AEZ), as applied in FAO studies, defines zones on the basis of combinations of soil, landform and climatic characteristics. The particu- lar parameters used in the definition focus attention on the climatic and edaphic requirements of crops and on the management systems under which the crops are grown. Each zone has a similar combination of constraints and potentials for land use, and serves as a focus for the targeting of recommendations designed to improve the existing land-use situation, either through increasing production or by limiting land degradation.

When combined with an inventory of land use, expressed as land utilization types and their specific ecological requirements, zoning can then be used as the basis of a methodology for land resource appraisal. The addition of further layers of information, on such factors as land tenure, land availability, nutritional requirements of human and livestock populations, infrastructure and costs and prices, has enabled the development of more advanced applications in natural resource analysis and land-use planning.

AEZ can be regarded as a set of core applications, leading to an assessment of land suitability and potential productivity, and a further set of advanced or peripheral applications, which can be built on the inventories and results of the core AEZ studies (Figure 1). Outputs of core applications include maps showing agro-ecological zones and land suitability, and quantitative estimates on potential crop areas, yields and production. Such information provides the basis for advanced applications such as land degradation assessment, livestock productivity modelling, population support capacity assessment and land-use optimization modelling.

Before applying the procedures of AEZ, the potential user should have a good appreciation of the underlying concepts, so that the potential uses and limita- tions of the methodology are understood. The essential elements of the core applications of AEZ comprise:

· land resource inventory

· inventory of land utilization types and crop requirements

· land suitability evaluation, including:

· potential maximum yield calculation

· matching of constraints and requirements

The methodology and the input variables of AEZ are scale-independent. However, the level of detail to wich such factors as soils, climate and land utilization types are defined may vary according to the map scale and the objectives of the study.

ZONE DEFINITION

Zoning divides the area into smaller units based on distribution of soil, land surface and climate. The level of detail to which a zone is defined depends on the scale of the study, and sometimes on the power of the data processing facilities. The Kenya AEZ study (FAO, 1993a) distinguishes agro-ecological cells (AECs), which are the basic units for land evaluation and data processing, from agro-ecological zones, which are spatial units related to a soil map. While each AEC has a unique combination of soil and climatic characteristics, related to a particular soil type, agro-ecological zones may contain a number of sets of characteristics, relating to different soil types within the same mapping unit. Sometimes, still broader definitions are applied to agro-ecological zones, to encompass several soil mapping units or climatic zones with similar, but not identical, properties. Box 1 gives definitions of terms related to agro-ecological zoning.

BOX 1. KEYWORDS IN AEZ

Agro ecological Zoning Zone and Cell

Agro-ecological Zoning (AEZ)refers to the division of an area of lend into smaller unitis, which have similar characteristics related to land su1tability, potential production and environmental impact.

An Agro-ecological Zone is a land resource mapping unit, defined in terms of climate, landform and soils, and/or land cover, and having a specific range of potentials and constraints for land use.

An Agro-ecological Cell (AEC) is defined by a unique combination of landform, soil and climatic characterist. The AEC is the basic processing unit for physical analysis in an AEZ study.

The essential elements in defining an agro-ecological zone (or cell) are the growing period, temperature regime and soil mapping unit.

Growing period

The concept of the growing period is essential to AEZ, and provides a way of including seasonality in land resource appraisal. In many tropical areas, conditions are too dry during part of the year for crop growth to occur without irrigation, while in temperate climatic regimes crop production in winter is limited by cold temperatures. The growing period defines the period of the year when both moisture and temperature conditions are suitable for crop production.

The growing period provides a framework for summarizing temporally variable elements of climate, which can then be compared with the requirements and estimated responses of the plant. Such parameters as temperature regime, total rainfall and evapotranspiration and the incidence of climatic hazards are more relevant when calculated for the growing period, when they may influence crop growth, rather than averaged over the whole year.

Terminology related to the definition of growing periods and their various components is given in Box 2. The estimation of growing period is based on a water balance model which compares rainfall (P) with potential evapo- transpiration (PET). If the growing period is not limited by temperature, the ratio of P/PET determines the start, end and type of growing period. Figure 2 shows plots of P against PET for the four generalized types of growing period.

The determination of the beginning of the growing period is based on the start of the rainy season. The first rains fall on soil which is generally dry at the surface and which has a large soil moisture deficit in the soil profile. In the absence of soil moisture reserves, seedbed preparation, seed germination and the initial growth of crops are therefore entirely dependent on the amount and frequency distribution of these early rains.

Experimental work indicates that the effectiveness of early rains increases considerably once P is equal to, or exceeds, half ET. The growing period continues beyond the rainy season, when crops often mature on moisture reserves stored in the soil profile. Soil moisture storage must therefore be considered in defining the length of the growing period.

In some areas, particularly those where rainfall does not follow a unimodal pattern, P may exceed ET or ET/2 for two or more distinct periods in the year, resulting in more than one LGP per year. The pattern of the growing period describes the proportional representation of each group of years in the total historical series. Different numbers of growing periods are illustrated in Figure 3. There are obvious differences in plant response depending on whether the growing period is continuous, or whether it is broken into shorter periods of moisture availability separated by dry periods. The number of LGPs is therefore an important consideration in agro-ecological zone definition.

By compiling an inventory of LGPs over a historical sequence of years, the frequency distribution of different annual numbers of LGP can be assessed. Table 2, based on the Kenya AEZ study, identifies 22 occurring LGP patterns..

Most AEZ studies use reference growing periods, which are calculated from Penman ET for a reference grass crop. These provide a generalized basis for zonation but do not account for the differing abilities of crops to extract soil moisture. Following on from the broad scale studies of the original FAO AEZ project, there has also been a tendency to assume standard figures for soil moisture reserves stored towards the end of the growing period, rather than to base calculations on the actual moisture holding capacities of specific soil types. The national study in Bangladesh, however, where soil moisture reserves are particularly important for residual moisture cropping, allows moisture storage to be adjusted in the range 0-250 mm according to soil type. Based on data from Botswana, Table 3 illustrates the comparative duration of the soil moisture reserve period for three mature crops grown on different soil types .

While standardization among crops may be permissible in a regional study where a number of crops are considered, information on soil available water holding capacity (AWC) can usually be inferred from the soil inventory, and its inclusion in the moisture balance would improve the accuracy of LGP prediction. Table 3 clearly shows how stored soil moisture affects the overall LGP. The moisture reserve period on the Vertisol (VRe) is sufficiently long for the growth of a short residual moisture crop and, in wetter environments, such soils are often used for this purpose after the rains have ceased. Residual moisture cropping in Bangladesh and Ethiopia takes place on soils with similarly high AWCs.

LGP analysis is based either on average climatic data, or on historic data for individual years. Most early AEZ studies calculated LGP based on average monthly rainfall and PET. While this approach may be acceptable for broad scale regional studies, it fails to capture the temporal variation in LGP, which is determined mainly by inter-annual variations in rainfall distribution. Assessment of LGP for individual years, based on the use of historical rainfall data, enables quantification of the level of risk as well as the potential production under average climatic conditions. Such an approach greatly improves the utility of the assessment, particularly in areas subject to periodic drought. AEZ national studies in Kenya and Bangladesh (FAO, 1993a; Karim, 1994) have used the LGP pattern, as described above, as a means of capturing inter-annual variation in LGP and consequent land suitability and potential yield. The most recent adaptation of the Kenya study evaluates individual LGPs and land suitability over a historical series of years, enabling the results to be expressed in terms of probabilities.

Thermal regime

The thermal regime is the other basic climatic parameter used to define the agro-ecological zones. The thermal regime refers to the amount of heat available for plant growth and development during the growing period. It is usually defined by the mean daily temperature during the growing period. In regional and national AEZ assessments, thermal zones may be defined based on temperature intervals of 5°C or 2.5°C. A more detailed treatment of thermal regimes is often required in temperate or subtropical areas (Table 10, p. 31).

Soil mapping unit

The soil mapping unit is the basic unit taken from the soil map. On small-scale maps, soil mapping units rarely comprise single soils, but usually consist of a combination of a dominant soil with minor associated soils. 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. An example of the composition of a soil association forming a soil mapping unit is given in Figure 4.

Each soil type occurring in each soil mapping unit is characterized in terms of its land characteristics and qualities (Box 3), which relate to the edaphic requirements of plants or to land-use requirements for management or conservation.

In the publications of FAO describing land evaluation and AEZ the use of the terms soil unit and land unit is not always consistent. Land, according to the FAO definition (Box 3) includes climate, but soil includes properties of the land surface but excludes climate. A soil or land mapping unit is a spatial entity, which is not necessarily uniform in terms of land characteristics. As a soil unit can easily be confused with a soil mapping unit, the term soil type is suggested to refer to a unit with a specific set of soil characteristics.

Land resource inventory

The land resource inventory is essentially an overlay of climatic and soil information. The resulting units are the agro-ecological zones, which have a unique combination, or a specified range, of soil mapping units, growing period regimes, and thermal regimes; and agro-ecological cells, with unique combina- tions of growing period and thermal regimes and soil types. The relevant land characteristics of each AEC are listed under headings related to agro-climatic constraints and soil or land constraints.

Information on land administration, land tenure and present land use, related to potential land availability, may be incorporated in the land resource inventory. Multiple overlay techniques are particularly applicable when GIS is used, and the resulting AECs and zones are more effective planning units when such information is included. Figure 8 (p. 35) presents an example based on the combination of ten layers of information in the Kenya AEZ study.

Land utilization types and crop adaptability

Assessment of land suitability and potential productivity is made in relation to a specific type of land use under certain production conditions. Following the FAO Framework for Land Evaluation (FAO,1976), land use is classified into Land Utilization Types (Box 3). Relevant land utilization types (LUTs), based on existing and potential land use, have to be clearly identified and described before land suitability evaluation.

The reasons for describing land utilization types are:

· to guide the selection of important agro-ecological characteristics to be included in the land inventory which may influence either output level or environmental impact;

· to support the process of defining algorithms and setting thresholds relating agro-ecological characteristics and potential production level, taking intoaccount:

· the impact of "fixed", unmodifiable constraints;

· the extent to which a defined LUT is assumed to be able to modify "non-fixed" constraints, e.g., what level of nutrient application, land improvement and plant care can be assumed?

Quantification of the land use requirements of LUTs provides the basis for estimation of potential yields and for land suitability evaluation. Land-use requirements are grouped according to crop climatic and edaphic adaptability, and requirements for management and conservation. The crop climatic inventory lists requirements, for both photosynthesis and phenology, which bear a relationship to yield in quantity and, where necessary, to yield in quality. The rate of crop photosynthesis, growth and yield are directly 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 photosynthesis pathway. Edaphic requirements describe crop responses to soil factors, such as nutrient availability or the presence of toxic substances. Requirements for management and conservation include such factors as soil workability and susceptibility to erosion. Procedures for listing and quantifying the requirements of LUTs are given in the adaptability inventories in Chapter 3.

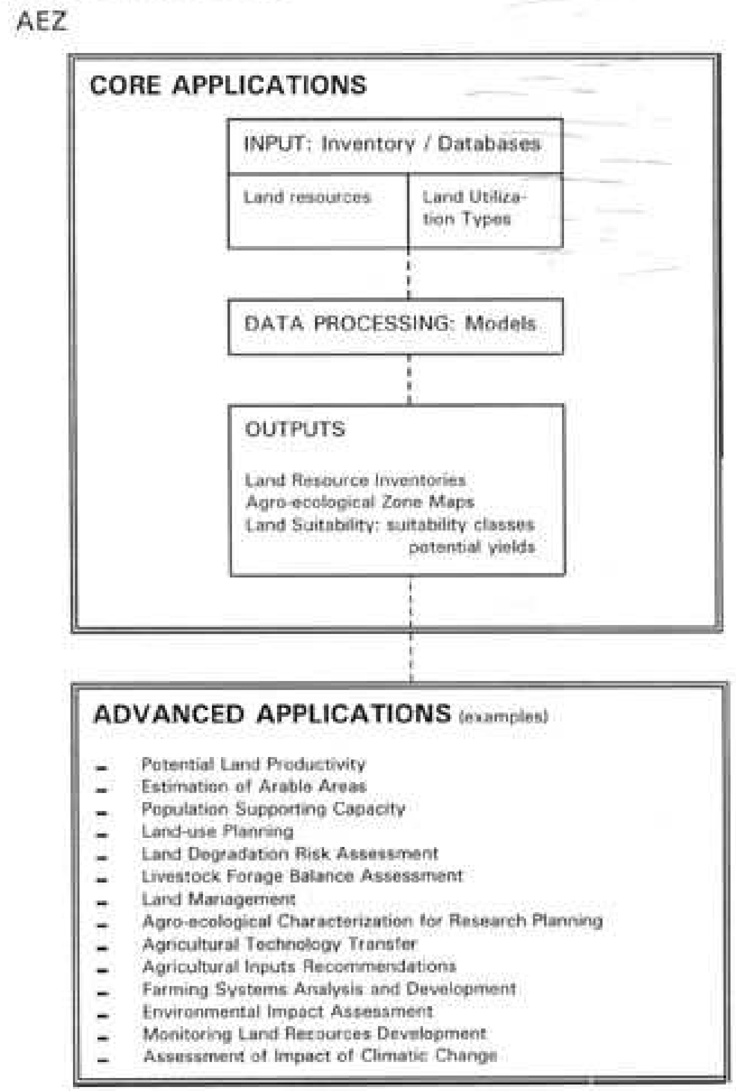
LAND SUITABILITY EVALUATION: POTENTIAL YIELDS AND MATCHING

For estimation of potential productivity, AEZ uses the concept of a maximum attainable total biomass and yield. For a specified LUT, the potential maximum yield is determined by the radiation and temperature characteristics of a particular location, by the photosynthetic efficiency of the crop, and by the fraction of net biomass that the crop can convert to economically useful yield. This potential maximum yield is used as an input to the process of matching of agro-climatic and edaphic requirements with the qualities and characteristics of the land units defined in the inventory.

Potential maximum biomass and yield of crop components of the LUTs are usually calculated using a simple simulation model (FAO, 1978). Correction factors, based on expert knowledge, are used to quantify the yield reductions due to constraints, taking account of levels of management and inputs. The results are a series of estimated agronomically attainable yields for each LUT on each land unit. These estimates are then related to land suitability classes.

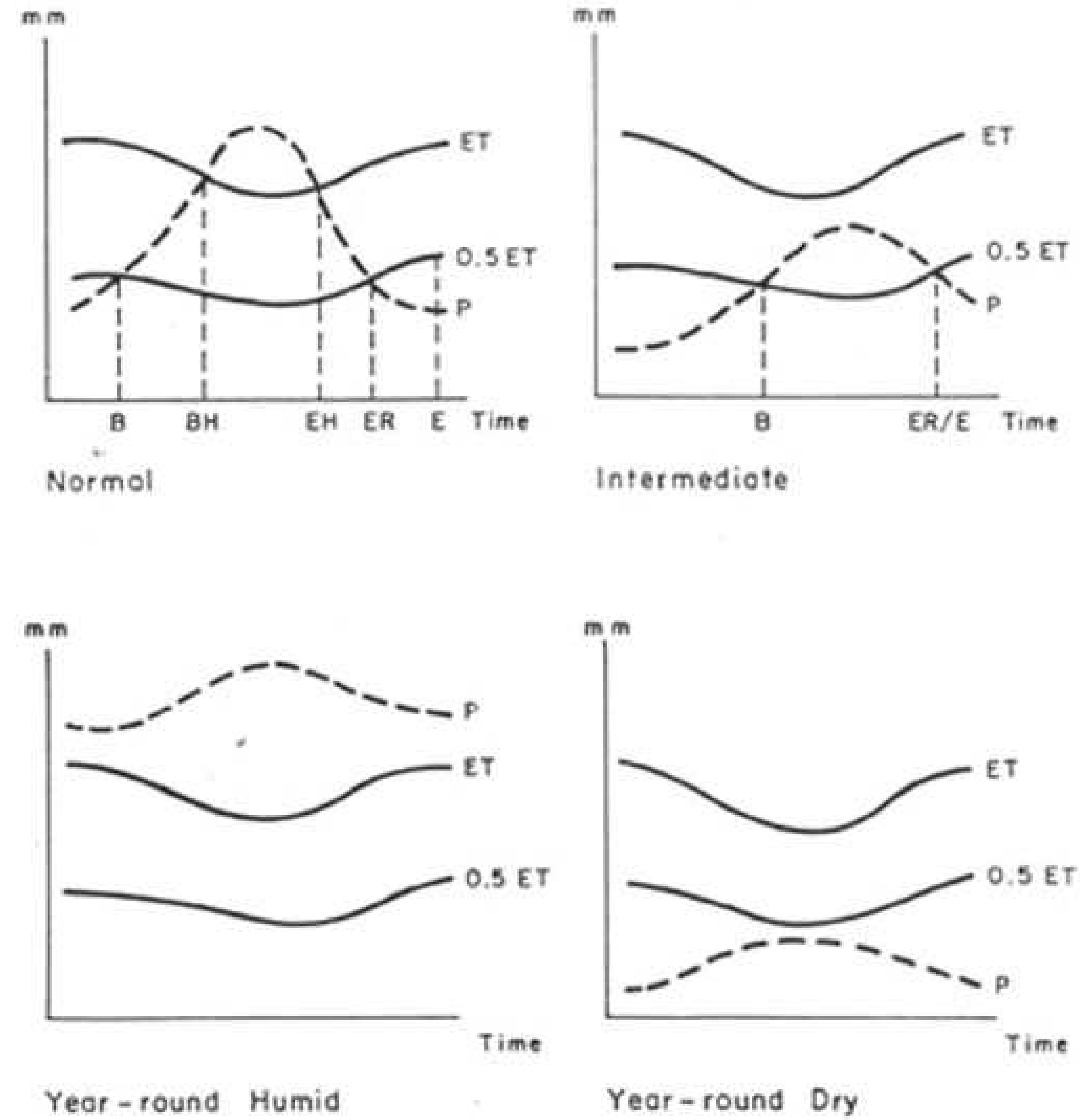
The following chapter describes the procedures required to apply the AEZ methodology for land resource appraisal.

FIGURE 1
Conceptual framework of AEZ



The methodology and the input variables of AEZ are scale-independent. However, the level of detail to which such factors as soils, climate and land utilization types are defined, may vary according to the map scale and the objectives of the study.

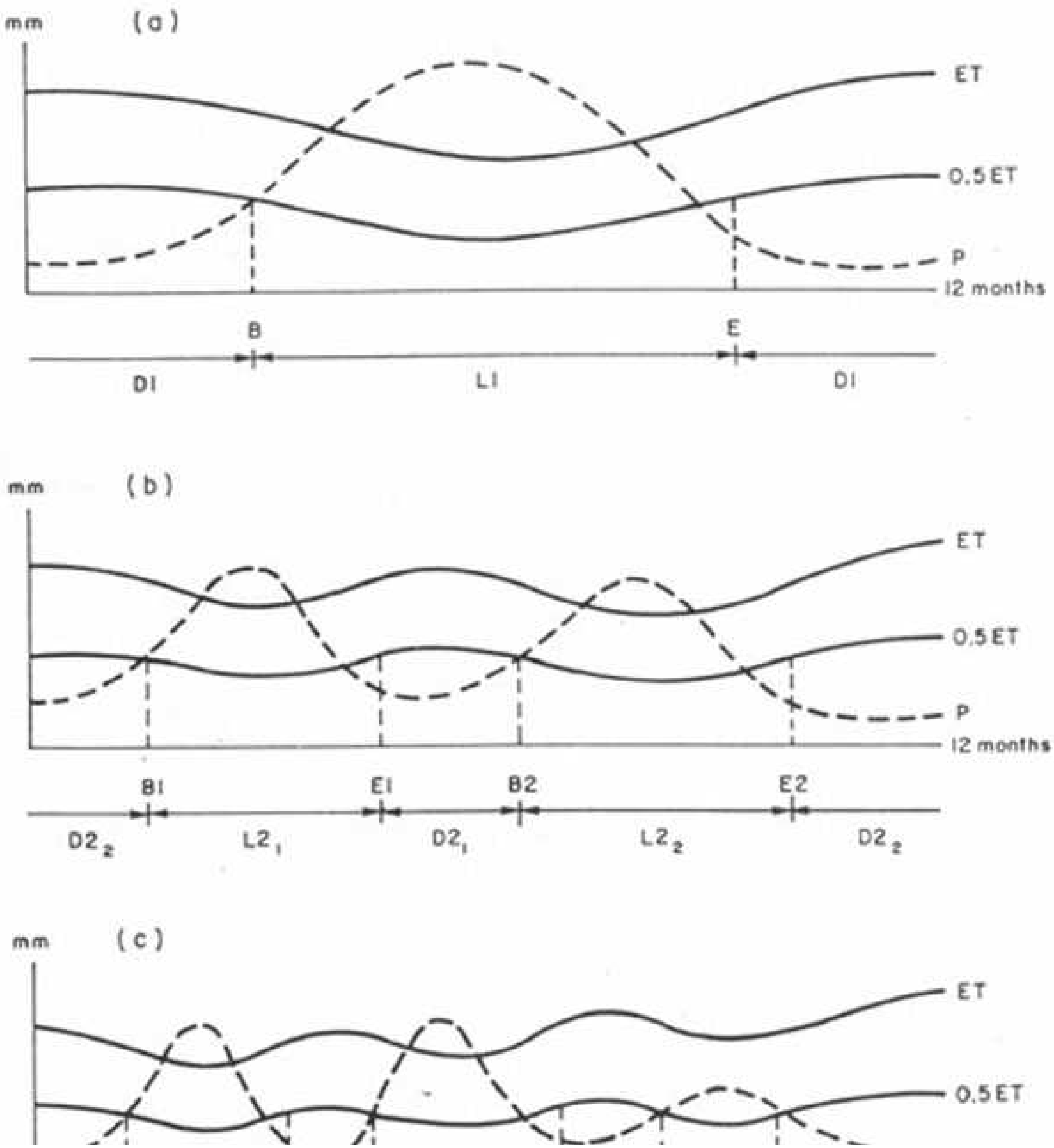
FIGURE 2
Schematic presentation of growing period types

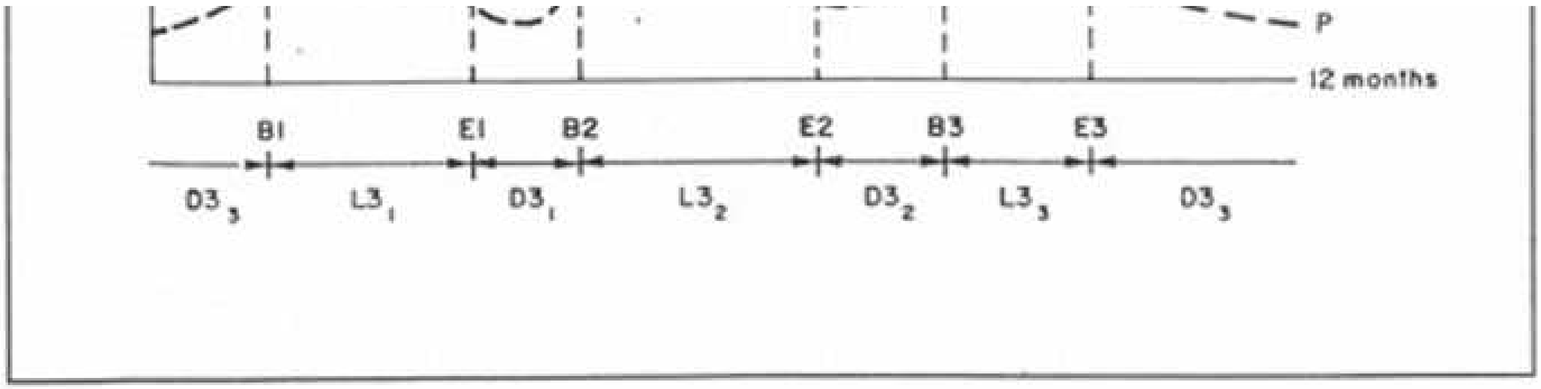


B - Beginning of growing period
BH - Beginning of humid period
EH - End of humid period
ER - End of rainy season
E - End of growing period

P - Precipitation
ET - Potential evapotranspiration

FIGURE 3
Number of growing periods and dry periods per year





BOX 2: REFERENCE LENGTH OF GROWING PERIOD (LGP)

Length of growing period (LGP) is defined as the period during the year when prevailing temperatures are conducive to crop growth (Tmean $\geq$ 5°C) and precipitation + moisture stored in the soil profile exceed half the potential evapotranspiration (PET) (on a daily basis sufficient soil moisture should be accumulated in the soil profile to permit seed germination (model variable set to 50 mm)).

The LGP can be interrupted by (i) a dry break, i.e., water supply from rainfall and soil moisture drops below 0.5 PET (or ETa < 0.5 ETo) and (ii) in analogy with LGPt by a winter break (dormancy or cold break). N.B. A LGP interrupted by a dormancy period is considered as one growing period.

Growing period characteristics

Year-round growing period

In an all year round humid period, P normally exceeds PET for the whole year.

Normal growing period

P exceeds PET for part of the year; it can be distinguished in:

- One Growing Period
- One Growing Period with Dormancy Period
- Two or More Growing Periods
- Two or More Growing Periods of which one with Dormancy Period

Intermediate growing period

In an intermediate growing period, P does not normally exceed PET, but does exceed PET for part of the year; it can distinguished in:

- One Growing Period
- One Growing Period with Dormancy Period
- Two or More Growing Periods
- Two or More Growing Periods of which one with Dormancy Period

No growing period

TABLE 3

Soil moisture reserve period (days) for different soil types and crops

Crop	Soil Type				
	ARo	CMc	LPe	LVf	VRe
Cowpea	25	40	7	52	62
Maize	28	45	7	58	69
Sorghum	24	39	7	51	59

Aro: Ferralitic Arenosols; CMc: Calcaric Cambisols; LPe: Eutric Leptosols; LVf: Ferric Luvisols; VRe: Eutric Vertisols.

Assumptions: *Moisture depleted at steady rate from field capacity based on late season crop coefficients and daily PETs at Gaborone, Botswana, from 1 April. Reduced uptake due to restricted availability at low levels of AWC is not considered.*

TABLE 2

LGP patterns in Kenya

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

Note: *1, 2, 3,* and *4* refer to the number of growing periods in any one year. *H* and *D* refer to years which are completely humid (P>PET) or completely dry (P<PET/2) respectively. The third column shows the proportional distribution of years with the indicated growing period frequency over the range of years analysed.

Source: FAO (1993a).

BOX 3: SOME LAND EVALUATION TERMS

Land. An area of the earth's surface. In the context of land evaluation, land includes all properties of the surface, soil and climate, together with any resident plant and animal communities.

Land Evaluation. The assessment of land performance when used for a specified purpose.

Soil Mapping Unit. An area of land delineated on a map. A soil mapping unit may consist either of a single soil type, or of multiple soil types occurring as a complex or association.

Soil Type. A specific unit of soil with definable ranges of characteristics. May correspond to the lowest hierarchical unit of a soil classification system, including specification of phase.

Land Utilization Type. A use of land defined in terms of a product, or products, the inputs and operations required to produce these products, and the socio-economic setting in which production is carried out.

Land Characteristic. A property of the land that can be measured or estimated.

Land Quality. A complex attribute of land which acts in a distinct way in its influence on the suitability of land for a specified use.

Chapter 3 - AEZ procedures

The core application of AEZ, leading to an assessment of land suitability and productive potential under specified uses, comprises three groups of compound activities:

· inventory of land utilization types and their ecological requirements;

· definition and mapping of agro-ecological zones based on inventories of land resources (including climate, landform and soils);

· evaluation of the land suitability of each agro-ecological zone.

Figure 5 illustrates the relationship of these activities and their component procedures. The final and intermediate outputs can then be applied in a series of more advanced applications which are determined according to the objectives of the study. The present chapter describes how to apply the procedures for the core AEZ application, leading to assessment of land suitability and potential productivity with particular reference to crop-based production systems. Following this description, brief summaries are presented of the following advanced applications:

· land productivity assessment;

· extent of potential arable land;

· land use optimization.

Procedures are described in a step-wise manner, together with the data input requirements and the intermediate output results, and are illustrated by examples drawn from AEZ studies undertaken by FAO. Emphasis is placed on providing the user with an understanding of the procedures so that they can be implemented or adapted according to the objectives of the specific AEZ study and the resources available. Strictly speaking, a computer is not necessary to carry out any of the above procedures (excepting those involved with objective decision making). However, it is assumed that most users will have access to commercially-available database and spreadsheet software, and be familiar with its use. Dedicated software tools, which are available for various groups of procedures, and linkages with GIS, are described in Chapter 4.

The information contained in the land resources inventory is determined to a large extent by the requirements of the land utilization types and their component crops. The procedures for inventory of land utilization types are therefore described first, although the relationship of land-use requirements with the land characteristics contained in the land resource inventory should be noted.

COMPOUND ACTIVITY 1: INVENTORY OF LAND USE TYPES

Selection of Land Utilization Types

A range of LUTs should be selected to reflect current land use and/or land use under a projected improved situation. All subsequent assessments of land suitability and potential productivity carried out as part of the AEZ study will refer to these specific LUTs as practised in defined agro-ecological zones or cells.

LUTs are defined in terms of a product, or a specified range of products, and the management system, including the operations and inputs, used to produce these products. The socio-economic setting is also usually included in the definition. The level of detail to which LUTs are defined is principally determined by the objectives of the study and the data needs of the land suitability assessment. Most AEZ studies have separated LUTs on the basis of crops, or ranges of crops, and level of inputs, as shown in Table 4. Currently available databases, such as the Land Use Database (de Bie, van Leeuwen and Zuidema, 1995) enable a more quantitative characterization of inputs, operations and outputs.

The following factors should be implicit in LUT definition:

· The description of an existing or anticipated agricultural production system in terms of products, production techniques, and expected type and range of inputs and outputs.

· The identification of the important factors which affect the production potential, such as limits to mechanization on sloping lands, and soil requirements for irrigation.

· The production scenarios to be modelled and the level to which production constraints are assumed to be overcome in each scenario.

· The quantification of input levels (labour, materials, capital, etc.) associated with various production scenarios. This is used for:

· estimation of the likely levels of input which correspond to the anticipated outputs;

· estimation of total input demands in relation to actual or anticipated resource availability at country/province level.

Following the definition of LUTs, the next steps involve the inventory of their requirements in relation to the climatic, soil and landform conditions necessary for the component crops and for the management system. These inventories form the basis of a sequential assessment of climatic suitability, edaphic suitability and potential yield calculation.

Compile crop climatic adaptability inventory

A crop climatic inventory is compiled based on crop phenological requirements, thermal ranges and photosynthetic characteristics.

An example of the crop attributes necessary for determination of climatic suitability is given in Table 5. Requirements for day length should also normally be included, but the cultivars considered in this particular case are all day neutral. Similar information regarding other crops is given in FAO (1978) and Kassam (1980).

There are often considerable differences in such factors as the length of crop growth cycle, which are mainly due to the adaptation of different cultivars to different ranges of thermal conditions. Several crop ecotypes are distinguished under days to maturity in Table 5. These ecotypes are treated separately for evaluation of land suitability and potential performance.

Crops should be arranged into climatic adaptability groups based on similar abilities to photosynthesize, assuming their phenological requirements are met. Table 6 summarizes the main characteristics of each group, and gives examples biomass productivity (Step 3.2.1, p. 41).

Compile crop edaphic adaptability inventory

The agricultural exploitation of the climatic potential of crops depends on the properties of soil, and on how the soil is managed. Constraints imposed by landform or by other features of the land surface, such as susceptibility to flooding, must also be taken into account.

Many soils are a result of climatic action and, as a result, climate and soil in many instances have relationships which may have a mutual enhancing effect on crop productivity. The close interrelation of climate and (zonal) soil and natural plant community, to some extent, aids assessments of land suitability.

The basic soil requirements of crop plants may be summarized under the following headings, related to internal and external soil properties.

· Internal requirements:

· soil temperature regime;

· soil moisture regime;

· soil aeration regime;

· natural soil fertility regime;

· effective soil depth;

· soil texture and stoniness;

· soil toxicity;

· other specific properties, e.g. soil tilth.

· External requirements:

· slope/topography;

· occurrence and depth of flooding;

· soil accessibility and trafficability.

From the basic soil requirements of crops, ranges of optimal and marginal conditions can be defined. These are subsequently used for matching with relevant land characteristics in the determination of crop edaphic adaptability inventory is presented in Table 7. Detailed complementary information can be found in numerous FAO publications (FAO, 1976; 1978; 1981; 1983; 1985; 1994a).

Important note: Information on optimal and marginal ranges of edaphic conditions for certain crops, such as that presented in Table 7, may be unavailable or difficult to obtain. In the absence of published information, an educated guess must be made based on parallels with other crop species with similar physiological requirements. These "guesstimates" are important as the models which match crop requirements with soil and climatic characteristics do not allow for missing data. When more reliable local data are obtained, the databases should be updated and the assessment re-run.

COMPOUND ACTIVITY 2: COMPILE LAND RESOURCES INVENTORY

This compound activity comprises the following steps:

2.1 analyse length of growing period (LGP);

2.2 define thermal zones;

2.3 compile climatic resource inventory;

2.4 compile soil and landform resource inventory;

2.5 compile present land use inventory;

2.6 combine above to make land resources inventory based on agro-ecological zones or agro-ecological cells. This inventory also normally includes information on administrative boundaries.

The land resources inventory is based on combining different layers of information to define agro-ecological cells (AECs) with a unique combination of climate, soil and other related land attributes (Figure 5, p.18). Such overlay techniques are most conveniently carried out in a GIS environment. However, alternative methods can be used if a GIS is not available (see step 2.6, p. 33).

Box 4 summarizes the data required to prepare the climatic resources inventory

BOX 4 CLIMATIC DATA REQUIREMENTS

Dataset 1 : Maps

· topographic maps

Dataset 2 : For each climatic station

· location: (coordinates) and elevation

· precipitation

· maximum daily temperature

· mean daily temperature

· minimum daily temperature

· relative proportions of sunshine and cloud cover by time period

· relative humidity

· wind speed

· climatic hazards

Note The time period over which the data is collected depends on the purpose and level of detail of the AEZ study. Where possible, rainfall should be collected for a historical sequence of years

Analyse length of growing period

The growing period is the period of the year when both moisture and temperature conditions are favourable for crop growth (Box 3, p. 13).

In the tropics, where temperature is rarely a limiting factor except at very high altitudes, I GP can be assessed by a simple moisture balance of precipitation (P) and potential evapotranspiration (PET). LGP should be assessed for all valid rainfall stations in the study area with a minimum of 20 years of complete records. Where the synoptic data required for PET calculation are not available, PET can be assessed through locally validated correlations with altitude (e.g. De Pauw, 1987), or, in flatter areas, by linear interpolation from surrounding stations (e.g. Schalk, 1990; Radcliffe, Tersteeg and De Wit, 1992).

Although the original FAO AEZ study at continental scale based LGP calculations on average monthly rainfall and PET data, more detailed studies (e.g. Radcliffe,1981; De Pauw,1987; FAO,1993a) have recognized the value of analysing historical rainfall records and using the results as a basis for statistical analysis of LGP distribution. The approach based on historical data is highly recommended, particularly in semi-arid areas where inter-annual variations in rainfall and resulting LGP are often extreme (FAO, 1993a; Radcliffe, 1993).

Table 8 gives a simple example of LGP calculation over 11 years at Nazreth, Ethiopia, which has a single growing period in most years, determined by moisture availability. This example is taken from a manual intended for field staff who do not necessarily have access to computer facilities. Continuous periods of at least two months when P > PET/2 are taken as the intermediate plus humid phases of the growing period (Figure 2, p. 8). Fifteen days are counted for the first month when rainfall exceeds PET/2, and 30 days are added for each succeeding month with P > PET/2. A further 20 days are added to comprise the soil moisture reserve period.

Statistical analysis of the LGPs in Table 8 gives a dependable growing period, exceeded in 75% of years, of 95 days. The median LGP, exceeded in 50% of years is also 95 days. Assessment of LGP based on average rainfall data gives a value of 155 days, considerably overestimating the actual situation.

The Kenya AEZ study (FAO,1993a) compared PET and moisture balance for historical rainfall records in a way which is similar in principle to the example in Table 8. The computer facilities used in this study enabled a much more detailed analysis of component LGP periods, based on a shorter time period (three days), which is particularly important in areas with multiple growing periods. Based on this analysis, 22 LGP pattern zones, with specified frequencies of occurrence of one, two, three and four growing periods per year (and also of all dry and all humid years), were recognized. These LGP pattern zones are illustrated in Table 2 (p. 11).

The climatic resources inventory listed each individual occurrence of humid, intermediate and dry period and derived statistical correlations, firstly between total lengths of growing period in years with the dominant pattern and years with the associated pattern, and secondly between the lengths of individual component growing periods and the total LGP in years with multiple growing periods. Individual growing periods and total LGP in any one year are used to evaluate the climatic suitability of annual crops and perennial crops respectively (Step 3.2, p. 38).

In temperate regions, temperature is often of equal or greater importance to moisture availability as a determinant of crop growth, and its influence is not adequately catered for by the original AEZ methodology (FAO, 1978). Apart from requiring a more detailed specification of thermal regime (Step 2.2), temperature interacts with moisture availability in determining LGP. Particular modifications to the LGP model developed to deal with the temperate conditions in China are shown in Box 5.

BOX 5: LGP ASSESSMENT FOR TEMPERATE REGIONS

THE CHINESE EXAMPLE

The AEE study in China identifies four components of a temperature related moisture balance in determining LGP:

i. define a temperature growing period, based on the period of the year (in days) when temperature is sufficiently high for crop growth (corresponding to > 0 °C mean temperature in areas where winter crops are grown, but from > 5 °C to < 10 °C in Heilongjiang Province);

ii. different moisture balances are applied to the cold period the transition period and the (temperature defined) growing period (Figure 6),

iii. Penman PET (or PET/2) is replaced by a lower estimate of crop water demand in spring i.e. around the potential start of the moisture-related growing period);

iv. Moisture extraction for soil reserves is adjusted according to ease of availability (soil moisture held at tensions close to permanent wilting paint is more difficult to extract than that held at tensions close to field capacity) A linear quadratic function described by Doorenbos and Kassam (FAO, 1979) is used to calculate water extraction at high tensions.

Source Zheng Zhenyuan, 1994

The China study demonstrates the necessity for adapting elements of the AEZ methodology when it is applied in a different range of environments from those in which it was developed. Modifications to the moisture balance model, however, go beyond what is required to account for the low seasonal tempera- tures, and some of these have potentially broader application. The use of crop coefficients, albeit in a rather generalized way, represents a step towards a more accurate and crop-specific moisture balance modelling, which is a significant development on existing AEZ methodology.

Growing period zones are plotted on a map, and may be based on fixed intervals of mean LGP, or on the dependable LGP exceeded at a given level of probability (0.75 or 0.8). Figure 7 gives an example of growing period zones in Bangladesh (Brammer et al., 1988).

Define thermal zones

Thermal zones describe the temperature regime available for crop growth during the growing period. They are usually defined based on ranges of mean temperature. In tropical highland areas, mean temperature is usually strongly correlated with altitude. Table 9 gives the mean temperature ranges and corresponding altitude for reference thermal zones in Kenya.

TABLE 9

Reference thermal zones in Kenya

Thermal zone code	Mean daily temperature range (°C)	Altitude range (masl)

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**

Such a simplistic treatment of thermal regime may be inadequate in temperate regions. The AEZ study in China (Zheng Zhenyuan,1994) uses a combination of the duration of time and the accumulated degree days above several critical temperature thresholds, and the mean monthly temperatures in January and July in the definition of thermal zones (Table 10).

A recent revision of the thermal regime concepts has led to the following definitions:

· Thermal growing period zones (LGPt)

Period during the year when Tmean $ 5°C. This period is inventoried at 30-day intervals. The winter break (Tmean < 5°C) is defined as (i) dormancy period when hibernating crops can survive, or (ii) cold break when killing tempera- tures for hibernating crops occur (killing temperatures are adjusted according to depth of snow cover (the killing temperature model variable is set at -8°C for 0 cm snow cover, is increasing to -22°C for snow cover heights of 65 cm or more and should not exceed a total duration of 200 days).

· Frost-free period zones

The frost-free period is assumed to coincide with the period Tmean > lO°C. This period is also inventoried at 30-day intervals.

· Reference permafrost zones

The reference permafrost zones refer to climatic conditions assumed to be conducive to the formation and maintenance of permafrost. As an approxima- tion for reference permafrost zones, Tmean < -5°C is assumed for areas with potentially continuous permafrost and Tmean ranging from 0 to -5°C with potentially discontinuous (intermittent) permafrost.

Compile climatic resources inventory

The inventory of climatic resources is prepared as follows:

· plot the individual station data of temperature, LGP-pattern and mean total dominant LGP derived as described above onto a map;

· construct boundaries of thermal zones, LGP pattern zones, growing period zones and isolines of mean total dominant LGPs.

In addition to normal extrapolation techniques, extensive use is usually made of Landsat images, climatic maps, vegetation maps, land-use maps, topographic maps, and soil maps to guide the delineation of boundaries and isolines. If a GIS is used, the inventory maps should be subsequently digitized. Given the necessary base maps, point data and knowledge on the interpolation of climatic variables between these points, the user can prepare climatic maps in the GIS environment.

Compile soil resources inventory

Information on soil type and landform is normally derived from existing soil maps, legends and reports. National soil maps at a scale of 1:1 000 000 or larger are excellent sources from which the required input data can be derived. At more detailed levels of investigation, provincial soil maps may be used or additional data may have to be collected. For purposes of correlation, soils should preferably be classified in the FAO-Unesco Soil Map of the World classification system (FAO,1974; FAO,1990b) although national classification systems can also be used provided the essential characteristics needed for evaluation are included in soil type definitions.

What are the required input data?

On small-scale maps, the mapping unit consists generally of associations of individual soil types occurring within the limits of a mappable physiographic unit (Figure 4, p. 14). The mapping units reflect as precisely as possible the soil pattern of large regions. The information available for each soil type should include those parameters required for matching with land-use requirements. Although it is possible to define a minimum data set necessary for virtually all applications, the range of parameters required may vary according to the geographical region and the level of detail of the investigation. For example, it may be necessary to include such factors as exchangeable aluminium in soil type characterization in humid tropical regions, whereas other factors, such as soluble salt concentrations, are usually more important in arid areas. Box 6 lists the soil parameters required for most AEZ studies.

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. Soil phases are defined in the FAO-Unesco Legend (FAO,1974; 1990b) and can be grouped as follows:

BOX 6 : SOIL DATA REQUIREMENTS

Data Set 1 : Maps

- topographic/geologic/terrain maps
- soil/landform maps + legend + report

Data Set 2 : For each soil/landform mapping unit

- composition of the mapping unit to terms of dominant sod associated soils and inclusions;
- percentage of occurrence of each associated soil within the mapping unit;
- rootable depth and effective water holding capacity, quantity and quality of the organic matter, CEC clay, base saturation, structural stability, stoniness and rockiness, for each identified soil unit groupings in the study area;
- total area extent of individual mapping units;
- dominant slope class;
- texture class of the rooting zone for each associated soil;
- soil phase if any.

· indicating a mechanical hindrance or limitation

  · Rocky, bouldery, stony, gravelly;

· indicating an effective soil depth limitation

  · Lithic, paralithic, petrocalcic, petroferric;

· indicating a physico-chemical limitation

  · Saline, sodic.

The mapping unit composition table

The mapping unit composition table shows the distribution of soil types, and of their key properties, within each soil mapping unit. An example is given in Table 11.

Compile present land use inventory

Present land use and land cover are particularly important when the results of AEZ are applied to land use planning. Classes of land use and land cover should therefore be systematically recorded during the land resource inventory, and can be regarded as attributes of AECs. This inventory is quite distinct from the inventory of land use types (Compound Activity 1), which defines potential land use and lists its requirements for land evaluation.

Compile land resources inventory The land resource inventory is the result of overlaying of thermal zones, LGP zones and soil resources inventories. Additional information on administrative boundaries, land use and other constraints, such as tsetse fly incidence, may also be overlaid as shown in the example in Figure 8. The output of this procedure is a number of agro-ecological cells: approximately 91 000 were defined in the Kenya AEZ study. Table 12 gives an example of land resource mapping units, soil mapping units and AECs in such a land resource inventory.

For the overlay of such large amounts of information a GIS is strongly recommended. If a GIS is not available, however, it is sometimes possible to assign information from one inventory (e.g. climate) to mapping units defined in a separate inventory (e.g. soils), and to use the boundaries of these mapping units as the sole spatial framework for the land resource inventory. For example, the national land suitability assessment of Botswana (Radcliffe et al, 1992) used the 1:1000 000 national soil map (De Wit and Nachtergaele,1990) to define the spatial distribution of units to be evaluated. The boundaries of, these units had been determined by satellite image interpretation and extensive field work and were relatively reliable. The boundaries between climatic zones, based on data collected from a number of reference stations, were not reliable, and in the relatively flat terrain of Botswana, no relationship between altitudinal and climatic factors could be established. Rather than attempting to overlay unreliable climatic boundaries over reliable soil boundaries, each soil mapping unit was assigned a set of climatic information which was used as an input to the land suitability evaluation. This procedure led to 846 land suitability units, which are analogous to AECs.

Even if a GIS is used, digitization of data from different sources may lead to poor coordination of boundaries, and a number of land mapping units may result which do not actually occur in practice. Such problems were encountered in mountainous areas of China (Zheng Zhenyuan,1994), where it was decided to adjust soil association boundaries to boundaries of climatic zones (essentially the reverse of the procedure used in Botswana where climatic zone boundaries were defined by soil mapping units).

Irrespective of whether a random overlay technique is used or whether a single map is used as a spatial framework for the land resources inventory, the AECs must be precisely defined in terms of their land and climatic features. Typical outputs of the land resources inventory are:

total extents of all soil units, broken down by texture class, slope class and phase as they occur in each thermal zone, in each pattern of growing period zone on a country/province basis;

· a tabulated summary of the inventory showing the distribution of individual soil units (combined for all slopes, textures and phases) by length of growing period zone (combined for all thermal zones and pattern of growing period zones);

· a tabulated summary showing the distribution of individual soil units (combined for all slopes, textures and phases) by length of growing period zones for each thermal zone (combined for all pattern of growing period zones);

· a tabulated summary showing the distribution of individual soil units by texture, slope, phase and by length of growing period zones for each thermal zone and each pattern of growing period zone;

· maps and tabulated information on agro-ecological zones.

COMPOUND ACTIVITY 3: ASSESS LAND SUITABILITY

Assessment of land suitability is carried out by a combination of matching constraints with crop requirements, and by modelling of potential biomass production and yield under constraint free conditions. This activity is normally carried out in two main stages, in which firstly the agro-climatic suitability is assessed, and secondly the suitability classes are adjusted according to edaphic or soil constraints. Each stage comprises a number of steps which are listed as follows:

Stage 1: Agro-climatic suitability and agronomically attainable yields

3.1 Matching the attributes of temperature regimes to crop requirements for photosynthesis and phenology as reflected by the crop groups, to determine which crops qualify for further consideration in the evaluation.

3.2 Computation of constraint-free yields of all the qualifying crops taking account of the prevailing temperature and radiation regimes in each LGP zone.

3.3 Computation of agronomically attainable yields by estimating yield reductions due to agro-climatic constraints of moisture stress, pests and diseases, and workability for each crop in each length of growing period zone.

Stage 2: Assessment of agro-edaphic suitability based on soil constraints

3.4 Comparison of the soil requirements of crops with the soil conditions of the soil units described in the soil inventory, at different levels of inputs.

3.5 Modification of the soil unit evaluation by limitations imposed by slope, texture and phase conditions.

Apart from step 3.2, which involves a mechanistic model of biomass production and crop yield, all the above procedures involve the application of rules which are based on the underlying assumptions which relate land suitability classes to each other, and to estimates of potential yields under different input levels. Many of these rules were derived from expert knowledge available when the first FAO AEZ study was undertaken (FAO, 1978), and they should be regarded as flexible rather than rigid. The number of suitability classes, the definition of management and input levels, and the relationships between them can be modified according to increasing availability of information and the scope and objectives of each particular AEZ investigation. Box 7 gives an example of rules applied in the Kenya AEZ study.

Match crops to thermal zones

The initial step in the matching process is comparison of the temperature requirements of individual crops with the identified thermal zones of the climatic resource inventory. This step is essentially a screening exercise which excludes crops which are unsuitable in the specified temperature regimes from further analysis.

An example of matching crop temperature requirements with thermal zone is presented in Table 13. Where requirements are fully met, the zone is rated S1, where requirements are sub-optimal, the zone is rated either S2, S3 or S4, and where the requirements are not met, the zone is rated N (not suitable). Expected yield reductions resulting from sub-optimal conditions are given in Box 7.

Match crops to growing period zones

Matching of crops to growing period zones is according to the following steps:

3.2.1 computation of net biomass and constraint-free crop yield by individual lengths of growing period zones;

3.2.2 inventory of agro-climatic constraints for each length of growing period zone by crop and by input level;

3.2.3 application of the agro-climatic constraints to the constraint-free yields to determine agro-climatically attainable crop yields by individual lengths of growing period zones;

3.2.4 computation of agro-climatically attainable crop yields as affected by year-to-year variability in moisture conditions;

3.2.5 agro-climatic suitability classification of each mean total dominant growing period zone (inventoried) for each crop according to agro-climatically attainable yields by thermal zones and by pattern of growing period zone.

Potential net biomass and yield

FAO AEZ studies have derived figures on potential maximum biomass and crop yield by using a model, the essential features of which are:

1. calculation of gross dry matter production for standard crop;

2. application of correction factor for crop species and temperature;

3. application of correction factor for crop development over time and leaf area;

4. application of correction factor for net dry matter production;

5. application of correction factor for harvested part.

The detailed application of the biomass and yield model is described by Kassam (1977) and FAO (1978). The model is also included in the Agricultural Planning Toolkit (APT) and the AEZ country study (AEZCCS) software developed by FAO (FAO, 1990a; Fischer and Antoine, 1994).

Potential maximum biomass and yield are calculated for all annual crops rated as at least marginally suitable (based on thermal zone) for each individual length of growing period in defined LGP zones. In areas with significant altitudinal variation, the increasing length of crop growth cycle associated with cooler temperatures needs to be accounted for in the assessment. Perennial crops are assessed on the basis of total growing period in areas with more than one LGP per year.

Table 14 gives an example of constraint-free yields based on the effect of the prevailing temperature and radiation regimes on crop photosynthesis and growth within the lengths of growing periods.

Some recent AEZ studies carried out in Asia (FAO, 1994a) have indicated discrepancies between potential maximum yields calculated by the standard AEZ model and best yields achieved on research stations and even on farmers' fields. In some cases this could be attributed to recent advances in plant breeding, particularly of paddy rice, which have made some of the originally published input parameters to the model redundant. Other discrepancies may simply be the result of knowledge gaps in the actual physiological responses of certain crops to environmental variables. In China, maximum yield figures of wheat, maize, rice and soybean obtained from agricultural research sites were used in preference to those calculated by the biomass yield model (Zheng Zhenyuan, 1994).

Agro-climatic constraints

In the agro-climatic suitability assessment, yield losses likely to occur due to agro-climatic constraints must be taken into account. Yield losses in a rainfed crop due to agro-climatic constraints are governed by the following major conditions:

· How well the length of the normal growth cycle of the crop in question fits into the available length of the growing period.

· The degree of water stress during the growing period.

· The yield and quality reducing factors of pests, disease and weeds.

· The climatic factors, operating directly or indirectly, that reduce yield and quality of produce mainly through their effects on yield components and their formation.

· Climatic factors which affect the efficiency of farming operations and the cost of production.

All these agro-climatic constraints can be rearranged into a set of four, as follows:

· Constraints resulting from moisture stress during the growing period (e.g. unreliability of rainfall).

· Constraints due to pests, diseases and weeds, directly affecting the physical growth of the crop (e.g. stem-borers, leaf blights and virus diseases).

· Constraints due to various factors affecting yield formation and quality (e.g. cotton stainers, pod borers and silk drying).

· Constraints arising from difficulties of workability and produce handling (e.g. excessive wetness of the land or the produce).

The severity of the four groups of constraints, by crop, length of growing period zone and level of inputs can be presented in a table form as shown in the example in Table 15.

Ratings of 0,1 and 2 correspond to nil, moderate and severe constraints respectively. The agro-climatic constraint-free yields are reduced according to acting constraints in accordance with the rules in Box 6.

Account for year-by-year variability in LGP

This step is only carried out if the LGP has been assessed for individual years. Anticipated yields of annual crops are computed for each crop by each individual component LGP in each thermal zone for each level of inputs.

Each AEC is evaluated with respect to LGP pattern by taking into account all the constituent component lengths of LGP in each pattern. As the frequency of occurrence of numbers of LGPs within LGP patterns is known (Table 2, p.11), a profile of the variability in potential yields over time is constructed. Yields can then be expressed in terms of averages, maxima and minima.

Perennial crops are matched to total LGP, with potential yields being downgraded for LGPs which indicate moisture stress. For example, in total LGPs which include an occurrence of intermediate lengths of growing period in their make-up, yield losses due to such occurrences can be quantified according to yield reduction rules (Box 7).

The results of the above-described computations are the attainable yields for each crop by each mean total length of growing period zone by each pattern of growing period zone and by each thermal zone. These attainable yields form the basis of the agro-climatic suitability classification presented below.

Classify agro-climatic suitability

Classes of agro-climatic suitability are derived by relating the agro-climatic yields (reduced according to the constraints in Table 15) to the potential maximum yield determined from radiation and temperature considerations. Normally between four and six classes of suitability are defined based on different ranges of attainable yield relative to the potential maximum. Rules, such as those in Box 7, are used to establish the limits between suitability classes. Table 16 gives a diagrammatic presentation of potential yields and agro-climatic suitability classes associated with different LGP zones.

Compare crop requirements with soil conditions

The soil unit evaluation is expressed in terms of ratings based on how far the properties of a soil type meet crop requirements under specified level of inputs. Ratings may be made in five basic classes for each crop and level of input, i.e., very suitable (S1), suitable (S2), moderately suitable (S3), marginally suitable (S4), and not suitable (N). These ratings correspond to percentage reductions in potential maximum yield as indicated in Box 6.

Table 7 (p. 24) gives some examples of optimal and marginal ranges of crop edaphic requirements. Suitability ratings are assigned to each combination of crop and soil type by comparing such ranges with the characteristics listed in the soil inventory. Soil type ratings should be based on as much local expertise and knowledge as possible, and site-specific conditions not necessarily reflected in the soil type nomenclature should be taken into account. As an example, soil ratings for selected crops at two levels of input are given in Table 17. These ratings may be further modified according to limitations of soil texture, phase or slope.

Modify c/asses based on texture and phase limitations and slope Limitations imposed by soil texture and phase should be evaluated based on local expertise or expert knowledge. Appropriate rules should be drawn up to account for any additional constraints due to coarse textures or particular phases. An example of such a rule is given in Box 6 (p. 33).

Limitations imposed by slope affect both ease of cultivation and susceptibility to erosion. Table 18 gives an example of slope limits for various cultivation types at specified input levels.

TABLE 18

Slope limits (%) for land use types

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(terracing)	< 30	< 30	< 30

Coffee, tea, fuelwood and pasture, with and without soil conservation measures	**< 45**	**< 30**	**< 45**

Source: FAO (1993a).

If a land utilization type is matched to a land unit with a slope greater than the above limits, the land suitability is rated as N, not suitable.

If sufficiently detailed information is available, projected soil erosion loss can be calculated and related to decreases in productivity. This is regarded as an advanced application of AEZ, which has been developed during the Kenya study. The model is described in outline in the section describing land productivity (p. 51). More detailed accounts of approaches and methodology can be found in Mitchell (1984), Stocking (1984) and FAO (1993a).

The basis of these advanced AEZ applications is a set of GIS-based AEZ land resource inventories of individual districts in Kenya. The AEZ land resource inventories combine digitized map overlays that relate to climatic conditions, soil inventory, administrative units and selected properties of present land use, i.e. cash crop zones, forest areas, irrigation schemes, tsetse infestation areas and game parks. The digitized data were converted to a grid cell or raster database. Each pixel represents one square kilometre (100 ha) (Figure 8). AEZ computer programs are applied to the district land inventories to analyse land suitability. This application builds on the Kenya land productivity assessment which includes cropping patterns, linkage to livestock and forestry production systems and soil erosion considerations. A land productivity database is generated which contains quantified information on the productivity of all feasible land utilization types for each agro-ecological cell in the districts. The land productivity assessment involves 64 types of food and cash crops, pastures, 31 fuelwood species and nine livestock systems which are grouped into 26 production commodities, including 26 crop and ten livestock production commodities. This database provides the input to the Optimal Spatial Resource Allocation Model. It has been developed for integrating crop, livestock and fuelwood production within the framework of AEZ land productivity assessment and its application to various land-use planning scenarios at national and district levels. The model accepts user-specifiable scenario parameters from a control file, reads crop, grassland and fuelwood production potentials by agro- ecological cells from the land productivity database, reads livestock system related data derived from herd structure models, and determines simultaneously land use by agro-ecological cell as well as supported levels of different livestock systems, feed supplies and utilization by livestock zone and season. The model provides a framework for specifying different types of objective functions and kinds of constraints.

The planning scenarios are specified by selecting and quantifying objectives and various constraints related to aspects such as demand preferences, production targets, nutritional requirements, input constraints, cash flow constraints, feed balances, crop-mix constraints and tolerable environmental impacts. Given the potentially large number of agro-ecological cells and number of activities to be taken into consideration, standard linear programming techniques have been used to analyse the multitude of possible solutions and select optimal ones. For instance the linear programming techniques have been used in order to examine alternative regional or district level land-use patterns. Such models suggest feasible land-use allocation patterns that best satisfy specified single develop- ment objectives e.g, target food consumption patterns, population supporting capacities or rural employment levels. One typical application is the determina- tion of potential supporting capacities using various scenarios within defined single or multiple objectives.

Results

The results of the land suitability assessment are a set of land suitability classes for crops grown on different land units or AECs with specified level of inputs. Each land suitability class for each crop under each input level reflects a range of anticipated yields. Knowing the area of each AEC or land unit, estimates of production can be drawn up for more broadly defined agro-ecological zones, or, provided administrative boundaries can be related to AEC or land unit boundaries, by province or' district. Table 19 gives an example of areas suitable for cultivation of specified crops in Chanthaburi Province, Thailand.

Advanced applications

A number of advanced applications of AEZ can be developed from the results of land suitability assessment. These applications are based on sets of rules derived from basic assumptions on the interaction of product yield with the agro-environment, and on the management and conservation requirements of production systems. A conceptually similar set of rules employed in the core application of AEZ is given in Box 7 (p. 38). It must always be borne in mind that rules based on current expert knowledge should be regularly reviewed and updated as more information becomes available.

The need for further analysis of the results on land suitability is determined by the goals and objectives of the AEZ study. The availability of expert knowledge and the reliability of the assumptions on which the analysis is based should be taken into account in applying the results in planning and policy making.

The most extensive set of advanced AEZ applications developed to date is that resulting from the FAO study in Kenya (FAO, 1993a), the prime objective of which was to support land use planning and decision making at district level. Meeting this objective required assessment of the yields and potential productivity of diverse production systems (involving crops, livestock and fuelwood) and the construction of a model to optimize land use, allowing for trade-offs between the benefits of competing production systems. Figure 9 illustrates the overall model used in the Kenya study. Advanced applications which comprise components of this model are described below.

ADVANCED APPLICATION 1: POTENTIAL LAND PRODUCTIVITY

Land suitability assessment enables the selection of single crops to be made for each AEC or land unit according to their yield potential in particular cells. The land productivity is a measure of the potential total annual productivity calculated by fitting the most suitable crops to the available lengths of growing period. Determination of land productivity requires the following steps:

4.1 formulation and quantification of the cropping pattern options;

4.2 formulation and quantification of crop rotations;

4.3 assessment of the impact of soil erosion on productivity.

Formulate cropping pattern options

Under favourable climatic conditions, increased land productivity can be achieved through multiple cropping. Crops may be grown either sequentially or in mixtures, as defined in Box 8. Sequential cropping is only possible when the available growing period (either single or multiple) extends beyond the duration of the growth cycle of a single crop.

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 20). However, because of the cool temperatures in thermal zones T6 and T7 (Table 9, p. 30) sequential cropping is of minor importance because the annual crops that are adapted to the prevailing conditions are generally slow to reach maturity.

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 TS 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 sea- son moisture conditions. In these areas, multiple cropping, both simultaneous and sequential, is practised.

Cropping pattern options are formulated in three steps as follows:

i. fit crop growth cycles into prevailing component LGPs for each AEC;

ii. incorporate the turn-around time between crops, within sequential cropping patterns, needed to harvest the first crop, prepare the land and sow the subsequent crop;

iii. decide for which crops and levels of inputs 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, sugar cane, banana and oil palm.

Formulate crop rotations

This is done by taking account of the restrictions of space and time, and the fallow requirements, of the selected annual cropping pattern options. Restric- tions are imposed by agro-ecological conditions. For example, only mono- cropping is possible in the semi-arid areas.

The fallow requirement is calculated on the basis of maintenance of humus levels (for details see FAO, 1993a; Annex 4, p. 28). This fallow requirement, expressed as the percentage of time the land is under fallow as opposed to cropping, is built into the cropping patterns. At intermediate input levels, when some fertilizer is assumed to be used, fallow requirements are 33% of those at low input level. With high inputs, fallow requirements are 10% of those at low input levels (specific rules apply to Fluvisols and Gleysols).

In the Kenya study, 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.

Crop rotation options are formulated for each agro-ecological cell for each cropping pattern option generated. 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.

Impact of soil erosion on productivity

The impact of soil erosion on productivity is assessed in three stages. Firstly the potential soil erosion is calculated using a modified Universal Soil Loss Equation (USLE), which takes account of rainfall erosivity, soil erodibility, slope gradient and length, crop cover and conservation practices. The net soil loss is then calculated by comparing the calculated soil erosion with an estimate of the rate of soil formation, which is determined by thermal and LGP zone. Thirdly, loss of soil depth is related to productivity loss by adjusting land suitability classes within a critical soil depth range. Such calculations can be used to estimate limits of tolerable soil loss under defined cropping pattern options and to derive specifications for the required soil conservation measures.

The overall land productivity model, as applied in the Kenya study, quantifies productivity potentials of land by AEC for each crop rotation option, selected according to the rules outlined in Steps 4.1 and 4.2, in three stages:

· quantification of sequential crop yields;

· incorporating intercropping yield increments;

· applying production stability constraints and any other constraints as criteria for selecting optimum crop rotations and productivities.

The model can be applied using different sets of assumptions to govern the selection of crop combinations. Table 21 summarizes the aggregated results for Kenya, based on monocropping, including sequential monocropping where and when suitable growing periods occur. Thus the figures refer to total annual productivity for single crops based on addition of figures for individual AECs.

ADVANCED APPLICATION 2: ESTIMATION OF POTENTIAL RAINFED ARABLE LAND

The determination of the extent and quality of arable land is one of the end results of the calculation of land productivity. Table 21 summarizes the extent of arable land in various productivity classes, based on assumption set B.

Assumption set B refers to potential crop productivity on all land which is not indicated as forest zone, game park, or belonging to an irrigation scheme. Whenever possible or appropriate, sequential monocrop combinations of two or three consecutive crops from a crop species have been constructed to ensure highest possible estimates in sub-humid and humid zones.

Six suitability classes have been defined relating average single crop suitability in a cell to maximum attainable yield. The classes C1 to C5 relate to average attainable yields of > 80%, 60-80%, 40-60%, 20-40% and 5-20% of maximum agro-climatic yields. Note that extents in suitability class C5 are usually not considered among the viable crop options, but have been included here to indicate the scope of production in very marginal areas. A sixth suitability class accounts for areas that are entirely unsuitable or allow for only < 5% of maximum yield. Data for this non-suitable class are not included in the results table.

Production potential is calculated from land extents in suitability classes C1 to C4 only. Average, minimum and maximum production potential and yields are determined according to LGP pattern and associated probabilities. The columns are labelled AVG, MIN and MAX respectively. Multiple land use in time, sequential cropping, is indicated by a multi-cropping index (MCI).

Table 21 gives estimates of arable land by productivity class. The algorithm used to determine rainfed arable extents in an AEC works in two stages. Firstly, the crop or monocrop combination which performs best under the worst climatic (according to LGP pattern) is determined. Then all crop combinations which meet the production stability constraint (i.e. fall within a tolerable yield range of the best performing crop) are considered in the final selection. Finally, among all qualifying crops, the combination that maximizes the weighted sum of extents in land suitability classes C1 to C4 is selected as describing the cell's arable land potential. Suitable extents of the primary crop type in the chosen crop combination (i.e. the first crop to be grown in the sequential cropping pattern) are recorded in the relevant totals of arable land resources.

ADVANCED APPLICATION 3: SPATIAL RESOURCE ALLOCATION: OPTIMIZING LAND USE

Population supporting capacity, as defined here, relates to the maximum potential of soil and climatic resources to produce food energy and protein, at a given level of technology. An intermediate level of input/technology is considered in this example (Fischer et al., 1996). The question is simply how much food can be produced on the potentially suitable land under optimal resource use?

An example is given for Bungoma district in Kenya and Figure 10 presents the distribution of harvested area obtained from optimal land allocation to achieve the maximum food production in the district. The scenario used in the optimization specified that all suitable lands are to be considered, including forest and game parks. Since the land resource map of Bungoma district is available in digitized form, a map can also be created showing where in Bungoma what cereals should be grown to achieve the single objective of maximum food production.

The above example shows the application of linear optimization techniques to the analysis of land-use scenarios according to a single objective function which is to maximize food production. Often the specification of a single objective function does not adequately reflect the preferences of decision-makers ,which are of a multi-objective nature in many practical problems of land resources optimization. Multi-objective optimization approaches address problem definitions and solutions in a more realistic way.

In the Kenya study the main issue was to analyse potential population supporting capacity of the district under various land-use scenarios, considering simultaneously several objectives such as maximizing revenues from crop and livestock production, maximizing district self reliance in agricultural produc- tion, minimizing costs of production and environmental damages from erosion. Multi-objective optimization coupled with multi-criteria decision analysis (MCDA) techniques, using the Aspiration Reservation Based Decision Support (ARBDS) approach, was used in the analysis.

The multiple objective programme includes the following objective functions:

1. maximize food output (Food-val) (average yield/production);
2. maximize net revenue (Net_rev);
3. minimize production costs:
4. maximize gross value of output;
5. minimize arable land use (weight of 1 assigned to crop and 0 to grassland) (arable);
6. minimize area harvested;
7. maximize food output (Food-min) (minimum yield in bad years);
8. minimize total erosion (Eros_tot) (sum of all cell erosions);

9. maximize self sufficiency ratio (SSR_v) (minimum of the individual commodity group self sufficiency ratios);

10. minimize maximum erosion (Eros-max) (largest occurring erosion per ha in a cell is small).

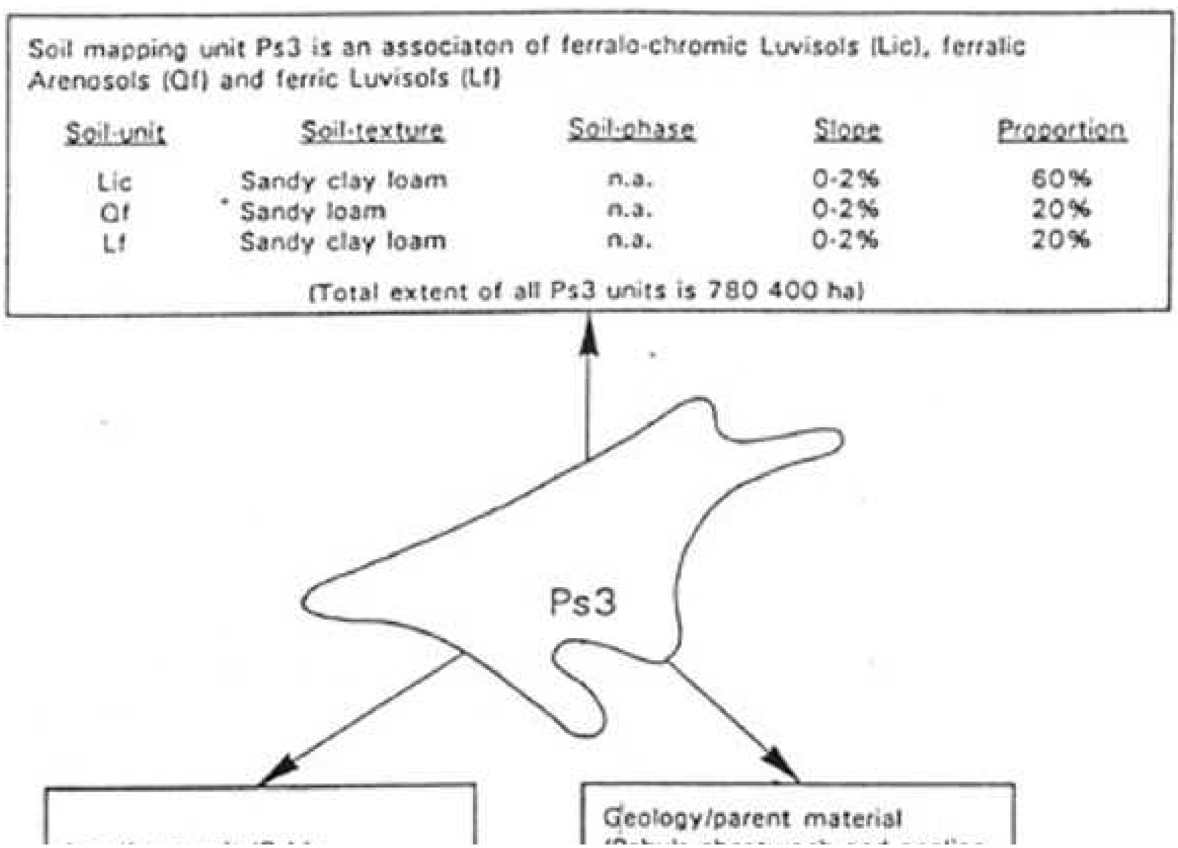
The results of a sample analysis for Bungoma district are given in Table 22. The first seven rows of the table contain the criteria values obtained from solutions for which each criterion is optimized in successive single-criterion optimization runs. The diagonal elements of the matrix represent the Utopia or "best" values for the seven criteria (i.e.1197.2, 1316.6, 96.2, 1010.5, 1164.9,1337.8, 12.2). The Nadir or "worst" values are found by taking the lowest values in the columns of the criteria to be maximized (i.e. Food_val = 742.6, Net_rev = 783.0, Food_min = 548.4, SSR_v=1000.0) and the highest values of the columns of the criteria to be minimized (i.e. Arable = 165.4, Eros_ tot = 3527.0, Eros-max = 227.8).

The last five rows of Table 22 contain the criteria values resulting from a session of interactive multicriteria analysis involving five iterations. The user interacts with the software tool through successive screens displaying graphs of the decision variables, using mouse clicks to make the desired changes in values of decision variables.

The results shows an irregular pattern of variation of the decision variables within the sequence MCD-B ... MCD-E. Generally the increase in arable land use required to achieve higher food production and self sufficiency ratios appears to be associated with increased total erosion; food production, economic return and food security in terms of guaranteed minimum production in bad years and maximum erosion vary within narrow ranges and seem to stabilize.

Given that the solutions produce self sufficiency rates above the 80% minimum limit which was established for the scenarios, the MCD-C solution appears to be a good choice as it represents the relatively "best" optimal combination of values of the decision variables.

FIGURE 4
Example of soil mapping unit composition



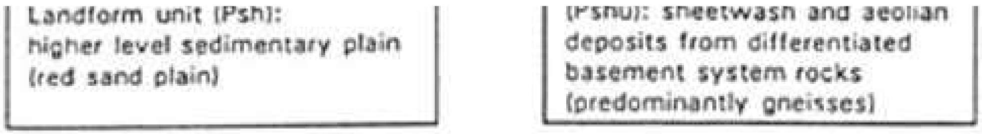
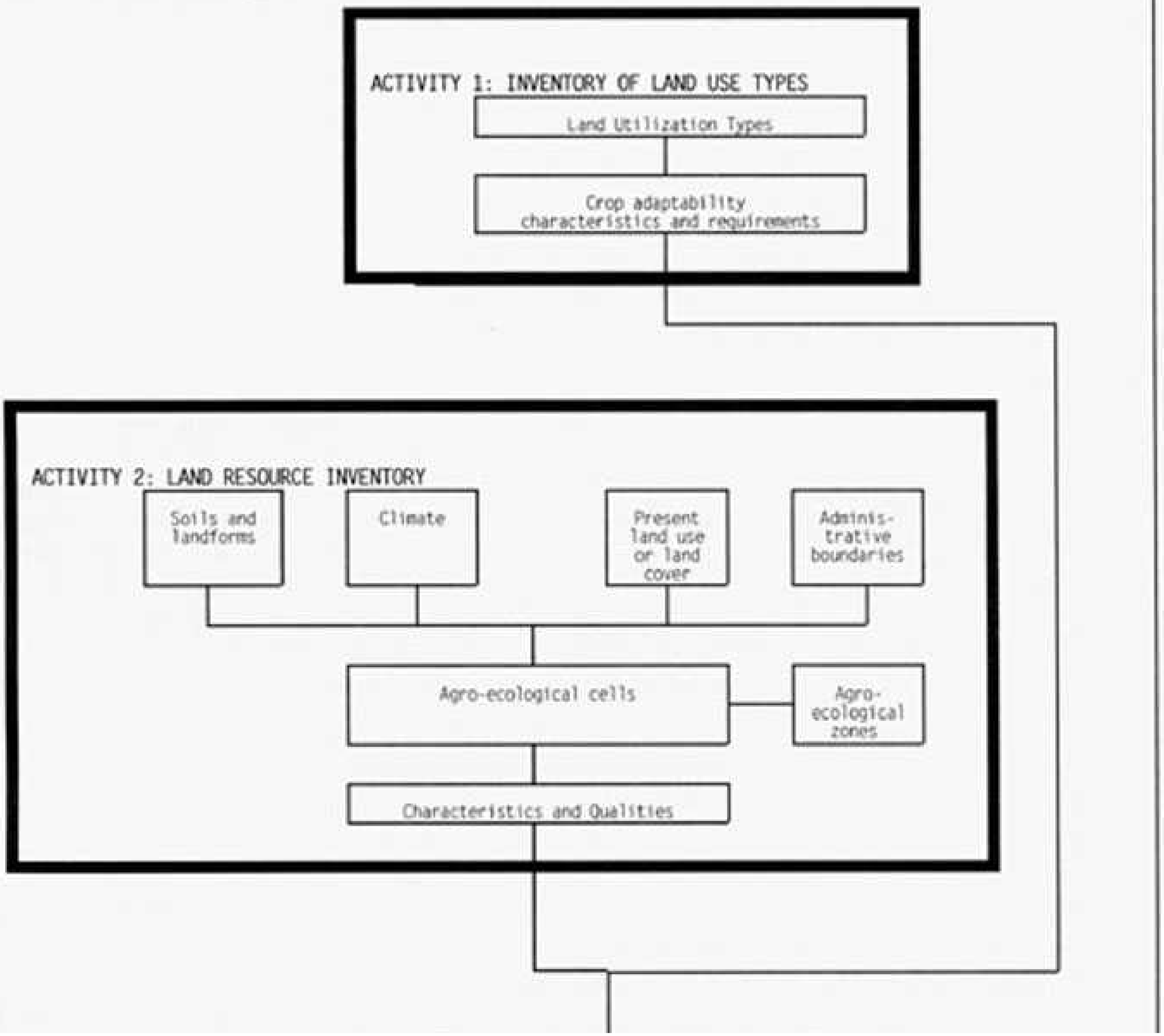


FIGURE 5
AEZ core applications: methodology



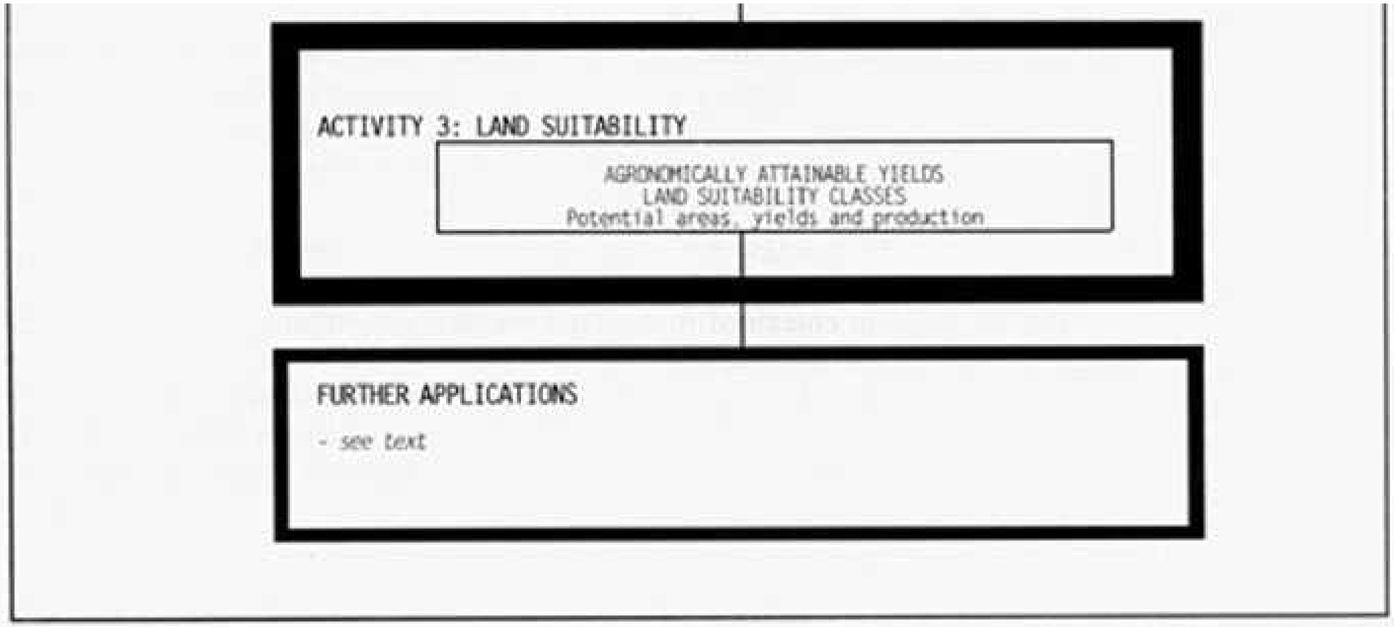

ACTIVITY 3: LAND SUITABILITY
AGRONOMICALLY ATTAINABLE YIELDS
LAND SUITABILITY CLASSES
Potential areas, yields and production
FURTHER APPLICATIONS
- see text

TABLE 4

Example of land utilization types definition

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, *Phaseolus* bean, pigeon pea, soybean, cassava, sweet potato, white potato, banana, oil palm and sugar cane. 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
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 applications of research findings
Land Holding	Small, fragmented	Small, sometimes fragmented	Large, consolidated
Income Level	Low	Moderate	High

Source: FAO (1993a).

TABLE 5

Climatic adaptability attributes of crops

Attributes	Barley	Oat	Cowpea	Green gram	Pigeon pea
Species	*Hordeum vulgare*	*Avena sativa*	*Vigna unguiculata*	*Vigna radiata*	*Cajanus cajan*
Photosynthetic pathway	C3	C3	C3	C3	C3
Crop adaptability group	I	I	II	II	II
Days to maturity	90-120 (1) 120-150 (2) 150-180 (3)	90-120 (1) 120-150 (2) 150-180 (3)	80-100 (4) 100-140 (4)	60-80 (4) 80-100 (4)	130-150 (4) 150-170 (4) 170-190 (4)
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 - Cultivated	 Annual Annual	 Annual Annual	 Annual Annual	 Annual Annual	 Short-term perennial 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

(1) thermal zones 3 & 4
(2) thermal zone 5
(3) thermal zones 6 & 7
(4) thermal zones 1, 2 & 3

Source: FAO (1993a).

TABLE 6

Photosynthetic characteristics of crop climatic adaptability groups

Characteristics	Crop Adaptability Group			
	I	II	III	IV
Photosynthetic pathway	C_3	C_3	C_4	C_4
Rate of photosynthesis at light saturation at optimum temperature (mg CO_2 $dm^{-2}h^{-1}$)	20-30	40-50	>70	>70
Optimum temperature (°C)	15-20	25-30	30-35	20-30
Radiation intensity of maximum photosynthesis (cal $cm^{-2}min^{-1}$)	0.2-0.6	0.3-0.8	>1.0	>1.0
Crops (examples)	Barley Oat Wheat *Phaeseolus* bean Potato	Cowpea Green gram Pigeon pea *Phaeseolus* bean Rice Soybean Groundnut Sweet potato Cassava Banana Oil palm	Pearl millet Sorghum Maize Sugar cane	Sorghum Maize

Source: FAO (1993a).

TABLE 7

Crop edaphic adaptability inventory for selected crops

Crop	Slope (percent)				Drainage	
	High Inputs		Low & Int. inputs		All Inputs	
	Optimum	Marginal	Optimum	Marginal	Optimum	Marginal
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	Fo	F1	L-MCs	SL-MCs	L-SC	SL-KC
Oat	Fo	F1	L-C	SL-MCs	L-SC	SL-KC
Cowpea	Fo	F1	SL-SCL	LS-KC	SL-SCL	LS-KC
Green gram	Fo	F1	L-CL	SL-KC	L-CL	LS-KC
Pigeon pea .	Fo	F1	SL-SCL	LS-KC	SL-SCL	LS-KC

Flooding classes: Fo = no floods; F1 = 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)		CaCO3 (%)		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

Source: FAO (1993a).

TABLE 8

Example of LGP calculation based on historical monthly rainfall

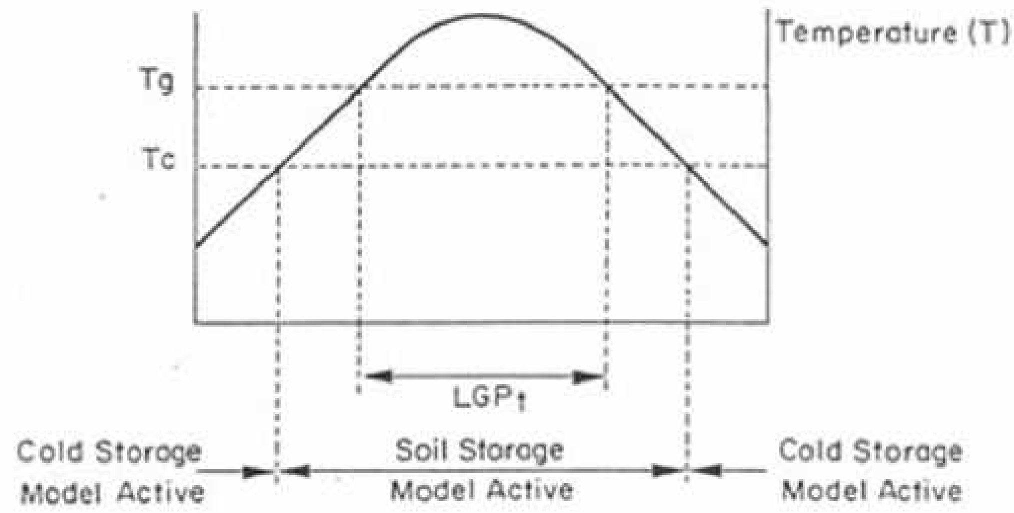
Station: Nazreth 8°33'N; 39°17'E; 1622m

PET or Rainfall (mm)	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.	Ann.	LGP (days)
PET (mean)	139	137	161	149	147	134	121	123	120	138	131	132	1631	
PET/2 (mean)	70	68	80	75	73	67	60	62	60	69	66	66	816	
Rainfall by year														
1975	2	8	1	101	42	202	470	168	90	72	0	8	1164	155
1976	0	33	67	64	96	48	190	213	109	0	30	6	856	95
1977	59	11	59	133	66	140	225	172	83	163	64	0	1175	155
1978	3	99	3	16	15	59	96	200	83	68	14	6	662	95
1979	115	21	60	9	126	115	91	120	21	17	14	5	714	125
1980	data incomplete													
1981	0	40	89	57	95	3	246	311	138	5	0	0	984	95
1982	9	41	35	29	79	32	127	260	48	105	31	11	807	65
1983	21	34	34	79	188	25	215	231	72	14	0	0	913	95 + 65
1984	0	0	4	0	171	85	203	148	67	0	0	20	698	155
1985	3	33	23	184	67	8	405	327	169	0	0	0	1219	95
Mean	21	32	38	67	95	72	227	215	88	44	15	6	919	155

Source: Adapted from Radcliffe (1989).

FIGURE 6

LGP and moisture balance models in China AEZ study



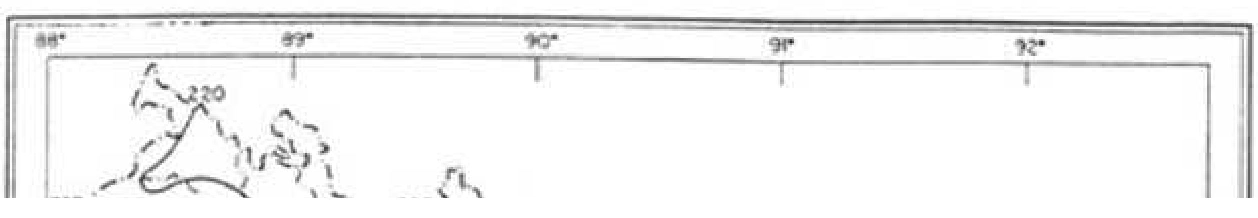
Three possible regimes:

Growing Period	T > Tg	Soil Model
Transition Period	Tg ≥ T ≥ Tc	Soil Model
Cold Period	T < Tc	Winter Model

where: Tg = growing period cutoff temperature
Tc = cold period cutoff temperature

FIGURE 7

Generalized map of moisture resources of Bangladesh



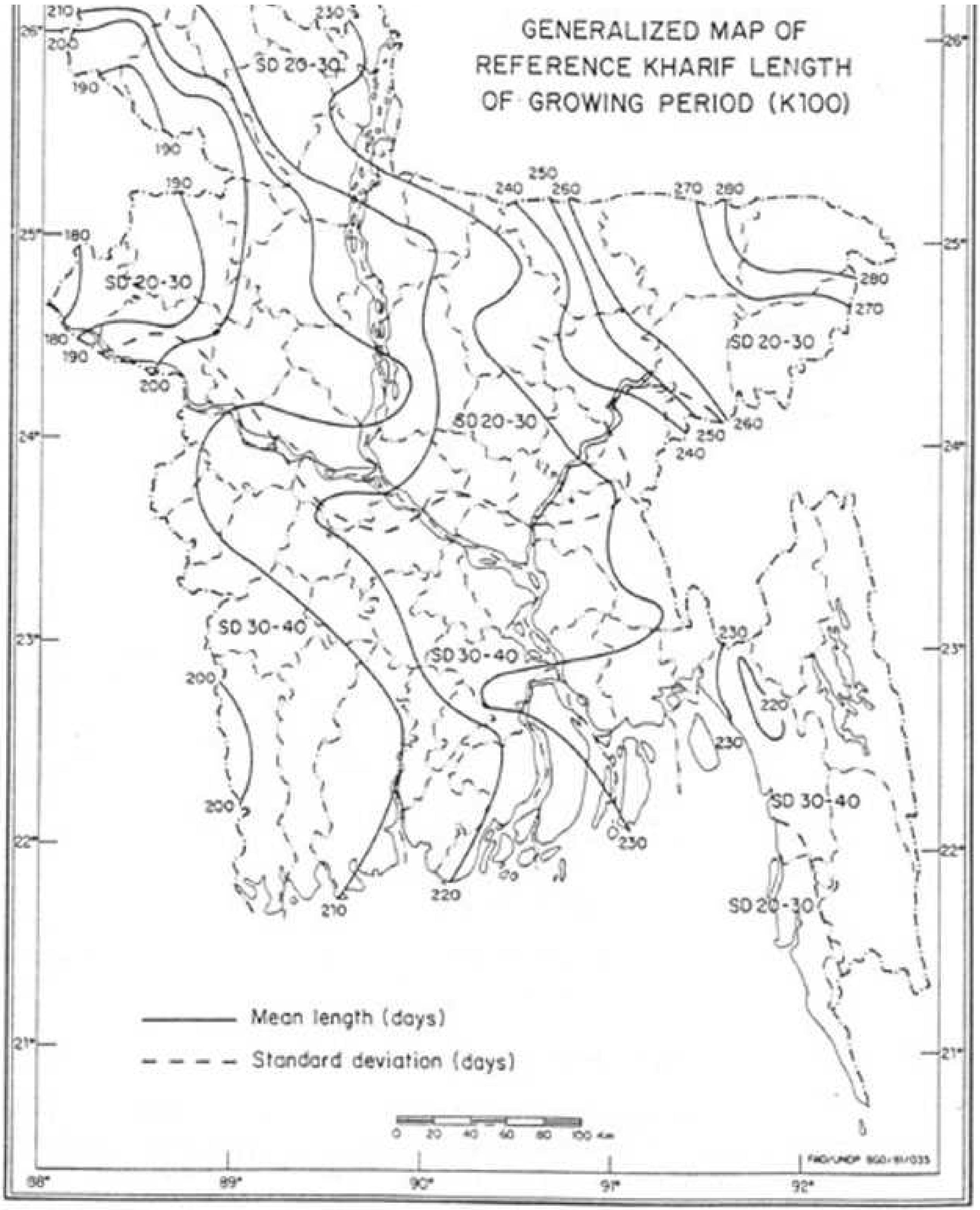

GENERALIZED MAP OF
REFERENCE KHARIF LENGTH
OF GROWING PERIOD (K100)
210
200
190
230
SD 20-30
250
240
260
270
280
180
SD 20-30
SD 20-30
200
SD 20-30
250
240
SD 30-40
SD 30-40
220
SD 30-40
210
220
230
SD 20-30
Mean length (days)
Standard deviation (days)
0 20 40 60 80 100 Km
88°
89°
90°
91°
92°
26°
25°
24°
23°
22°
21°

TABLE 11

Mapping unit composition table of Region III (Nicaragua)

Symbol/km^2	Soil Unit	%	Texture	Slope	Phase	Extent (km^2)
1/145	Eutric Regosol	100	2	3	Lithic	145
2/225	Pellic Vertisol	85	3	1	No phase	191.2
	Chromic Vertisol	10	3	1	No phase	22.5
	Eutric Fluvisol	5	3	1	No phase	11.3
3/450	Mollic Andosol	90	2	1	No phase	405.0
	Vitric Andosol	6	2	1	No phase	27.0
	Pellic Vertisol	4	3	1	No phase	18.0
4/825	Vitric Andosol	92	2	1	No phase	759.0
	Mollic Andosol	5	2	1	No phase	41.2
	Luvic Phaeozems	3	2	1	No phase	24.8
5/1550	Eutric Cambisol	70	2	3	Stony	1085.0
	Eutric Regosol	20	2	3	Lithic	310.0
	Eutric Fluvisol	10	2	1	No phase	155.0
6/735	Luvic Phaeozem	80	2	2	No phase	588.0
	Pellic Vertisol	15	3	1	No phase	110.2
	Eutric Regosol	5	2	1	No phase	36.8
8/950	Eutric Cambisol	60	2	2	No phase	570.0
	Pellic Vertisol	30	3	1	No phase	285.0
	Luvic Phaeozem	10	2	2	No phase	95.0
9/620	Haplic Phaeozem	80	2	2	No phase	496.0
	Eutric Regosol	15	2	2	No phase	93.0
	Mollic Andosol	5	2	2	No phase	31.0

Source: Van Wambeke (1991).

TABLE 12

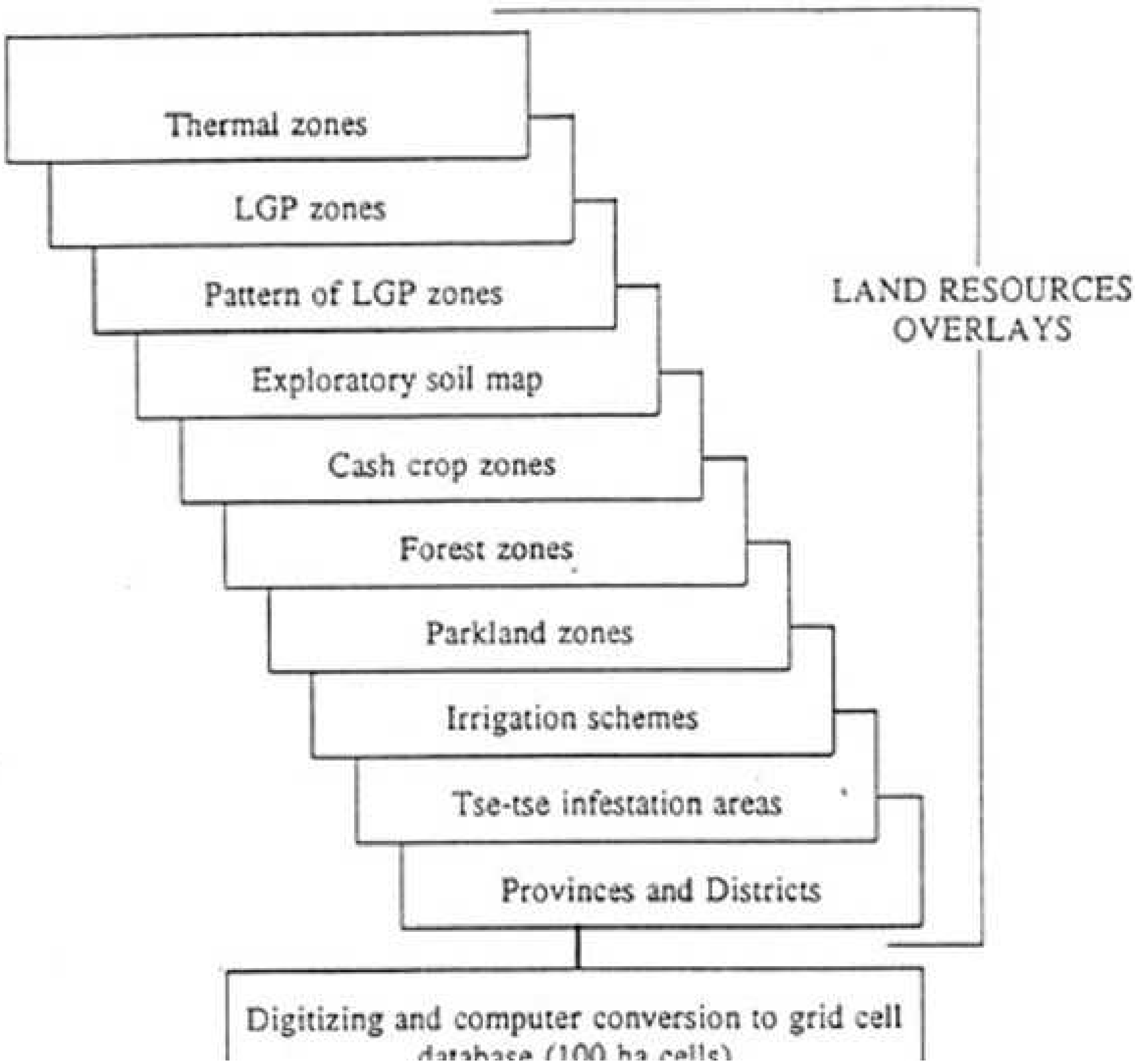
Computerized land resources inventory: agro-ecological cells

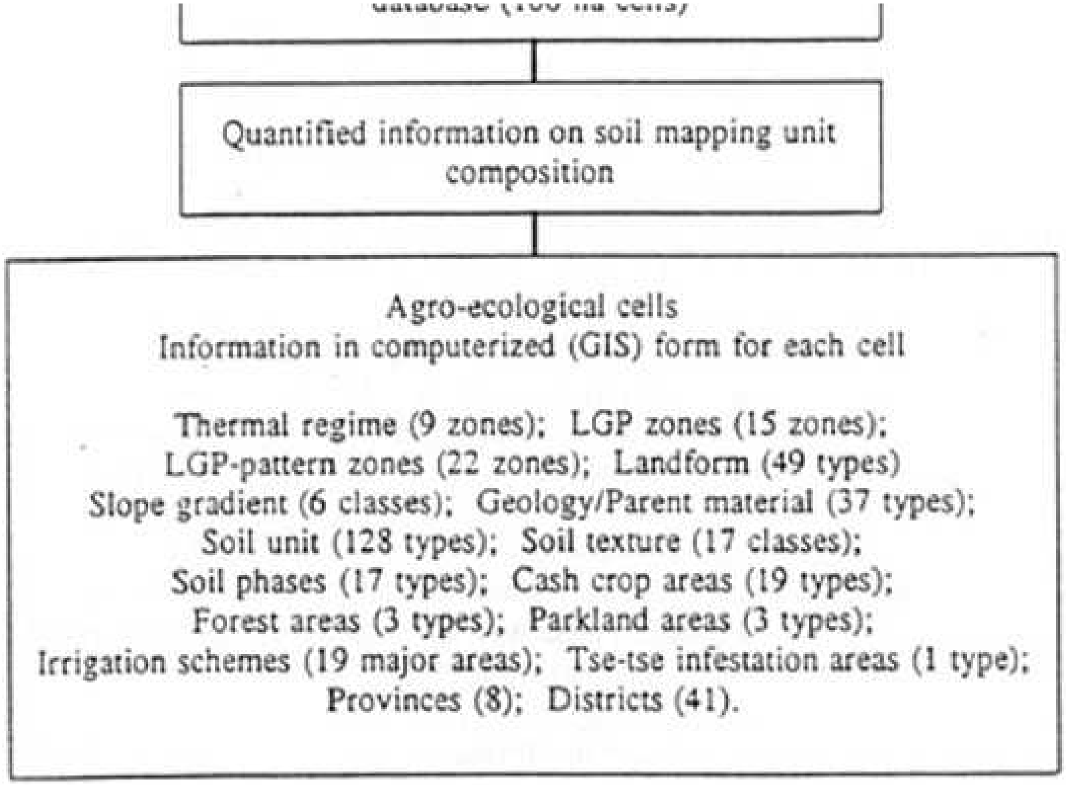
LRI MAPPING UNIT	Thermal zone	LGP code	LGP pattern code	Soil inventory mapping unit	Extent (km^2)
7	IV	5	7	193	880

SRI MAPPING UNIT	Soil type	Texture class	Slope class	Phase code	%
193	Yh	2	1	20	60
	Xk	2	1	20	40

AEZ CELLS	Thermal zone	LGP code	LGP pattern code	Soil type	Texture class	Slope class	Phase	Extent (km^2)
I	IV	5	7	Yh	2	1	20	528
II	IV	5	7	Xk	2	1	20	352

FIGURE 8
Structure of Kenya land resources database for definition of agro-ecological cells




Quantified information on soil mapping unit composition
Agro-ecological cells
Information in computerized (GIS) form for each cell
Thermal regime (9 zones); LGP zones (15 zones);
LGP-pattern zones (22 zones); Landform (49 types)
Slope gradient (6 classes); Geology/Parent material (37 types);
Soil unit (128 types); Soil texture (17 classes);
Soil phases (17 types); Cash crop areas (19 types);
Forest areas (3 types); Parkland areas (3 types);
Irrigation schemes (19 major areas); Tse-tse infestation areas (1 type);
Provinces (8); Districts (41).

BOX 7: EXAMPLES OF AEZ LAND SUITABILITY RULES

1. Potential yield under low inputs = 25% of that under high inputs.
   Potential yield under intermediate inputs = 62.5% high input yield.

2. S2, S3, and S4 ratings of thermal zone against crop requirements imply 25%, 50%, and 75% reductions in yield potential respectively (*Step 3.1*).

3. The potential yield in an intermediate growing period is 50% of that in a normal growing period (Fluvisols and Gleysols excepted) (*Step 3.2*).

4. *Moderate* and *severe* agro-climatic constraints result in 25% and 50% of potential yield loss respectively (*Step 3.3*).

5. Classes of agro-climatic suitability (*Step 3.3*), and land suitability (*Step 3.5*) correspond to the following ranges of attainable yield (expressed as percentages of the potential maximum yield):

VS (S1)	Very suitable	80-100
S (S2)	Suitable	60- 80
MS (S3)	Moderately suitable	40- 60
mS (S4)	Marginally suitable	20- 40
Vms	Very marginally suitable	5- 20
NS (N)	Not suitable	0- 5

6. S2, S3, and S4 ratings of selected soil parameters against crop requirements imply 25%, 50%, and 75% reductions in yield potential respectively (*Step 3.4*).

7. Coarse textured soils (sands and loamy sands) result in a further 25% reduction of yield for all crops except groundnuts and potatoes.

TABLE 13
Land suitability ratings of crops in thermal zones

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		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

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
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

Source: FAO (1993a).

TABLE 14

Potential net biomass (Bn) and marketable yield (By) based on radiation and temperature for different LGP zones

Unit : ton/ha

Crop name		Dominant length of growing period (days): <135	135-149	160-164	165-179	180-194	195-209	210-224	225-239	240-254	255-269	270-284	285-299	>300
Maize	Bn	22.30	22.30	19.30-19.90	16.30-21.60	16.30-22.20	18.60-20.90	18.30-20.90	18.00-20.80	18.00	19.00-19.70	18.50-19.70	18.50-19.70	18.90-19.20
	By	8.90	8.90	7.70-8.00	6.50-8.60	6.50-8.90	7.40-8.40	7.30-8.30	7.20-8.30	7.20	7.60-7.90	7.40-7.80	7.40-7.80	7.60-7.70
Paddy rice	Bn	13.60	13.60	12.10-13.30	10.50-13.30	10.50-13.60	11.50-13.00	11.50-13.00	11.40-12.70	11.40	12.10-12.30	11.70-12.30	11.70-12.00	11.90-12.10
	By	4.10	4.10	3.60-4.00	3.10-4.00	3.10-4.10	3.50-3.90	3.50-3.90	3.40-3.80	3.40	3.60-3.70	3.50-3.70	3.50-3.60	3.60-3.60
Groundnut	Bn	10.00	10.00	8.90-9.90	7.70-9.90	7.70-10.20	8.60-9.90	8.60-10.10	8.50-10.10	8.50	9.00-9.10	8.80-9.40	8.80-9.10	8.90-9.10
	By	3.00	3.00	2.70-3.00	2.30-3.00	2.30-3.10	2.60-3.00	2.60-3.00	2.60-3.00	2.60	2.70-2.70	2.60-2.80	2.70-2.70	2.70-2.70
Soybean	Bn	10.00	10.00	8.90-9.90	7.70-9.90	7.70-10.20	8.60-9.90	8.60-10.10	8.50-10.10	8.50	9.00-9.10	8.80-9.40	8.80-9.10	8.90-9.10
	By	3.00	3.00	2.70-3.00	2.30-3.00	2.30-3.10	2.60-3.00	2.60-3.00	2.60-3.00	2.60	2.70-2.70	2.60-2.80	2.70-2.70	2.70-2.70
Sorghum	Bn	20.10	20.10	17.40-19.50	14.70-19.40	14.70-20.00	16.50-18.80	16.50-18.80	16.20-18.80	16.20	17.10-17.80	16.60-17.00	17.00-17.30	16.60-17.30
	By	5.00	5.00	4.30-4.90	3.70-4.90	3.70-5.00	4.10-4.70	4.10-4.70	4.10-4.70	4.10	4.30-4.40	4.20-4.30	4.30-4.30	4.20-4.30
Cassava	Bn	31.60	31.60	28.00-29.30	24.30-31.30	28.20-32.00	27.10-31.30	27.10-32.00	26.80-32.00	26.90	28.50-28.60	27.50-29.50	27.50-28.50	27.90-28.70
	By	17.40	17.40	15.40-16.10	13.40-17.20	15.20-17.60	14.90-17.20	14.90-17.60	14.80-17.60	14.80	15.70-15.70	15.20-16.20	15.20-15.70	15.40-15.80
Cotton	Bn	16.90	16.90	15.00-16.50	13.10-16.50	13.10-16.90	14.50-16.30	14.40-16.00	14.20-16.30	14.30	15.00-15.30	14.60-15.40	14.60-15.00	14.80-15.10
	By	1.18	1.18	1.05-1.16	0.91-1.16	0.91-1.18	1.02-1.14	1.01-1.12	1.00-1.14	1.00	1.05-1.07	1.02-1.08	1.02-1.05	1.04-1.05
Sugar cane	Bn	46.70	46.70	40.40-46.70	33.90-45.90	33.90-47.20	38.60-45.90	38.60-46.40	38.10-46.40	42.00	40.80-41.30	39.30-42.50	40.00-40.80	40.00-40.00
	By	11.70	11.70	10.10-11.70	8.50-11.50	8.50-11.80	8.50-11.50	9.60-11.60	9.50-11.60	10.50	10.20-10.30	9.80-10.60	10.00-10.20	10.00-10.00

Source: FAO (1994a).

TABLE 15

Extract of an agro-climatic constraints inventory

AGRO-CLIMATIC CONSTRAINTS BY CROPS
GROUPS II AND III CROPS IN TROPICAL AND SUBTROPICAL (SUMMER RAINFALL) AREAS

Length of growing period (days)	Constraints			Constraints			Constraints			Constraints		
	Ratings Inputs		Examples	Ratings Inputs		Examples	Ratings Inputs		Examples	Ratings Inputs		Examples
	Low abcd	High abcd		Low abcd	High abcd		Low abcd	High abcd		Low abcd	High abcd	
	Millet			**Sorghum**			**Maize**			**Soybean**		
75-89	2010	2010	Rainfall variability	2110	2010	Rainfall variability	2120	2020	Rainfall variability	2020	2020	Rainfall variability
90-119	1000	1000	Quelea	2100	2000	Quelea Striga	2110	2010	Silk drying	2010	2010	
120-149	0000	0000		1100	1000		1100	1000		1000	1000	
150-179	0000	0000		0000	0000		0000	0000		0000	0000	
180-209	0100	0100		0000	0000		0000	0000		0100	0000	
210-239	0110	0111		0110	0011		0100	0001		0110	0001	

240-269	0221	0222	Downy mildew	0121	0022	Downy mildew	0101	0002		0110	0002	Leaf spot
270-299	0221	0222	Borer	0221	0122	Borer Shoot fly	0101	0102	Borer	0111	0102	Leaf hoppers
300-330	0221	022	Midge Ergot	0221	0222	Head moulds	0101	0102	Leaf spot Leaf blight	0211	0112	Pod borers
330-364	0222	0222	Grain smuts	0222	0222	Smuts Midge	0112	0112	Streak virus Wet produce	0222	0122	Wet produce
365	0222	0222	Workability	0222	0222	Workability	0222	0222	Workability	0222	0222	Workability
	Phaseolus bean			Cotton			Sweet potato			Cassava		
75-89	2020	2020	Rainfall variability	2000	2000	Rainfall variability	2010	2010	Rainfall variability	2010	2010	Rainfall variability
90-119	2010	2010	Poor pod set/grain quality	2110	2000		2010	2010	Dry/compact lifting conditions	2010	2010	Dry/compact lifting conditions
120-149	1000	1000		1110	1000		1001	1001		1011	1011	
150-179	0000	0000		0110	0000		0000	0000		1101	1001	
180-209	0100	0000		0110	0000		0000	0000		0100	0000	
210-239	0110	0001		0110	0110	Stainer	0000	0000		0100	0000	
240-269	0210	0002	Leaf spot	0110	0111	Bollworm	0010	0000		0100	0000	
270-299	0211	0102	White flies	0121	0121	Leaf curl Sucking bugs	0010	0001		0100	0000	
300-330	0211	0112	Virus diseases	0221	0122	Wilt	0020	0012	Soft rot Dry rot	0100	0000	Leaf mosaic Blight
330-364	0222	0122	Leaf hoppers	0222	0222	High night temperatures	0020	0012	Root weevil Black rot	0110	0011	White flies Nematodes
365	0222	0222	Workability	0222	0222	Workability	0021	0022	Workability	0111	0012	Workability

Notes:
0 No or slight constraints.
1 Moderate constraints.
2 Severe constraints.
Column a Yield losses due to water stress constraints on crop growth.
Column b Yield losses due to the effects of pests, diseases and weeds constraints on crop growth.
Column c Yield losses due to water stress, pests and diseases, and climatic constraints on crop yield potential components, yield formation and quality of produce.
Column d Yield losses due to workability constraints (all cultural operations including produce handling).

Source: FAO (1978).

TABLE 16
Agro-climatic suitability classification

Crops	Input Level	Growing period (days)	75–89	90–119	120–149	150–179	180–209	210–239	240–269	270–299	300–329	330–364	365
PEARL MILLET	High	Yield	1.1–1.6	2.2–3.1	2.2–3.0	2.8–3.9	2.0–2.8	1.1–1.6	0.3–0.5	0.3–0.5	0.3–0.4	0.3–0.4	0.3–0.4
		% of maximum 1/	28 41	57 79	79	100	73	41	12	12	10	10	10
		Suitability 2/	MS	S	S / VS	VS	S	S / MS	NS	NS	NS	NS	NS
	Low	Yield	0.3–0.4	0.5–0.8	0.5–0.8	0.7–1.0	0.5–0.7	0.4–0.5	0.2–0.2	0.1–0.2	0.1–0.2	0.1–0.2	0.1–0.2
		% of maximum	29 40	56 78	79	100	73	55	19	17	17	17	17
		Suitability	MS	S	S / VS	VS	S	S	MS / NS	NS	NS	NS	NS
SORGHUM	High	Yield	0.5–1.3	1.8–2.6	2.7–3.8	3.5–5.1	3.4–5.0	1.8–2.7	0.8–1.2	0.6–0.9	0.4–0.6	0.4–0.6	0.4–0.6
		% of maximum	10 25	35 51	53 74	100	98	53	23	18	12	12	12
		Suitability	NS / MS	MS	S	VS	VS	S	MS	NS	NS	NS	NS
	Low	Yield	0.1–0.2	0.3–0.5	0.5–0.7	0.9–1.3	0.9–1.3	0.5–0.7	0.2–0.3	0.1–0.2	0.1–0.2	0.1–0.2	0.1–0.2
		% of maximum	7 19	27 39	40 56	100	98	54	27	17	17	17	16
		Suitability	NS	MS	S	VS	VS	S	MS	NS	NS	NS	NS
MAIZE	High	Yield	0.5–1.2	1.9–2.7	3.7–5.4	4.9–7.1	4.8–7.0	3.4–5.1	2.3–3.4	1.7–2.5	1.6–2.4	1.2–1.8	0.5–0.8
		% of maximum	7 17	27 38	52 76	100	98	72	48	35	34	25	11
		Suitability	NS	MS	S	VS	VS	VS / S	S	S / MS	MS	MS	NS
	Low	Yield	0.1–0.2	0.4–0.5	0.7–1.0	1.2–1.8	1.2–1.7	0.9–1.3	0.7–1.0	0.7–0.9	0.6–0.9	0.5–0.7	0.2–0.3
		% of maximum	5 13	20 29	39 57	100	99	72	54	52	51	38	17
		Suitability	NS	NS / MS	S	VS	VS	VS / S	S	S	S	S / MS	NS

Source: FAO (1978).

TABLE 17

Extract of soil type evaluation for selected crops

Soil	Crop	Maize		Sorghum		Pearl millet		Spring wheat		Soybean		Groundnut		Cassava		Cotton	
	Level of inputs	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High
Af	Ferric Acrisols	S3	S2	S3	S1	S3	S1	S3	S2	S3	S2	S3	S2	S3	S1	S3	S2
Bc	Chromic Cambisols	S1	S1	S1	S1	S1	S1	S1	S1	S1	S1	S1	S1	S1	S1	S1	S1
F	Ferralsols	S3	S3	S3	S2	S3	S2	S3	S3	S3	S3	S3	S3	S3	S2	S3	S3
Fo	Orthic Ferralsols	S3	S3	S3	S2	S3	S2	S3	S3	S3	S3	S3	S3	S3	S2	S3	S3
Fx	Xanthic Ferralsols	S3	S3	S3	S2	S3	S2	S3	S3	S3	S3	S3	S3	S3	S2	S3	S3
Fr	Rodic Ferralsols	S3	S2	S3	S1	S3	S1	S3	S2	S3	S2	S3	S2	S3	S1	S3	S2
Fh	Humic Acrisols	S3	S2	S3	S1	S3	S1	S3	S2	S3	S2	S3	S2	S3	S1	S3	S2
Ge	Eutric Gleysols	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Gh	Humic Gleysols	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Gp	Pellic Gleysols	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
I	Lithosols	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Je	Eutric Fluvisols	S1	S1	S1	S1	S1	S1	S1	S1	S1	S1	S1	S1	S1	S1	S1	S1
Jt	Thionic Fluvisols	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Lo	Orthic Luvisols	S1	S1	S1	S1	S1	S1	S1	S1	S1	S1	S1	S1	S1	S1	S1	S1
Lc	Chromic Luvisols	S1	S1	S1	S1	S1	S1	S1	S1	S1	S1	S1	S1	S1	S1	S1	S1
Lf	Ferric Luvisols	S3	S2	S3	S2	S3	S1	S3	S2	S3	S2	S3	S1	S3	S3	S3	S2
Lg	Gleyic Luvisols	S4	S4	S4	S4	S4	S4	S4	S4	S4	S4	N	N	N	N	N	N
Ne	Eutric Nitisols	S1	S1	S1	S1	S1	S1	S1	S1	S1	S1	S1	S1	S1	S1	S1	S1
Nd	Distric Nitisols	S3	S1	S3	S1	S3	S1	S3	S1	S3	S1	S3	S1	S3	S1	S3	S1
Nh	Humic Nitisols	S3	S1	S3	S1	S3	S1	S3	S1	S3	S1	S3	S1	S3	S1	S3	S1
Oe	Eutric Histosols	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Qc	Cambic Arenosols	N	S3	S3	S2	S3	S1	N	S4	S3	S3	S3	S1	S3	S3	S4	S4
Ql	Luvic Arenosols	N	S3	S3	S2	S3	S1	N	S4	S3	S3	S3	S1	S3	S3	S4	S4
Qf	Ferralic Arenosols	N	S4	S4	S4	S3	S4	N	N	S4	S4	S3	S4	S3	S4	N	N
Qa	Albic Arenosols	N	N	N	N	S4	S4	N	N	N	N	S4	S4	S4	S4	N	N
Re	Eutric Regosols	S1	S1	S1	S1	S1	S1	S1	S1	S1	S1	S1	S1	S1	S1	S1	S1
So	Orthic Solonetz	N	S1	N	N	N	N	N	N	N	N	N	N	N	N	N	N
V	Vertisols	S4	N	S4	S1	S4	S3	S4	S1	S4	S2	N	S3	N	S3	S3	S1
Vp	Pellic Vertisols	S4	S1	S4	S1	S4	S3	S4	S1	S4	S2	N	S3	N	S3	S3	S1
We	Humic Planosols	S3	S3	S3	S3	S1	S3	S3	S3	S3	S3	S3	S3	S4	S4	S3	S3
Ws	Solodic Planosols	N	N	N	N	N	N	N	N	N	N	N	N	N	N	S4	S4
X	Xerosols	S1	S1	S1	S1	S1	S1	S1	S1	S3	S3	S1	S1	NA		NA	
Zo	Orthic Solonchaks	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Zg	Gleyic Solonchaks	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N

TABLE 19

Example of AEZ tabulated suitability results (by area)

Country : Thailand

Province : Chanthaburi

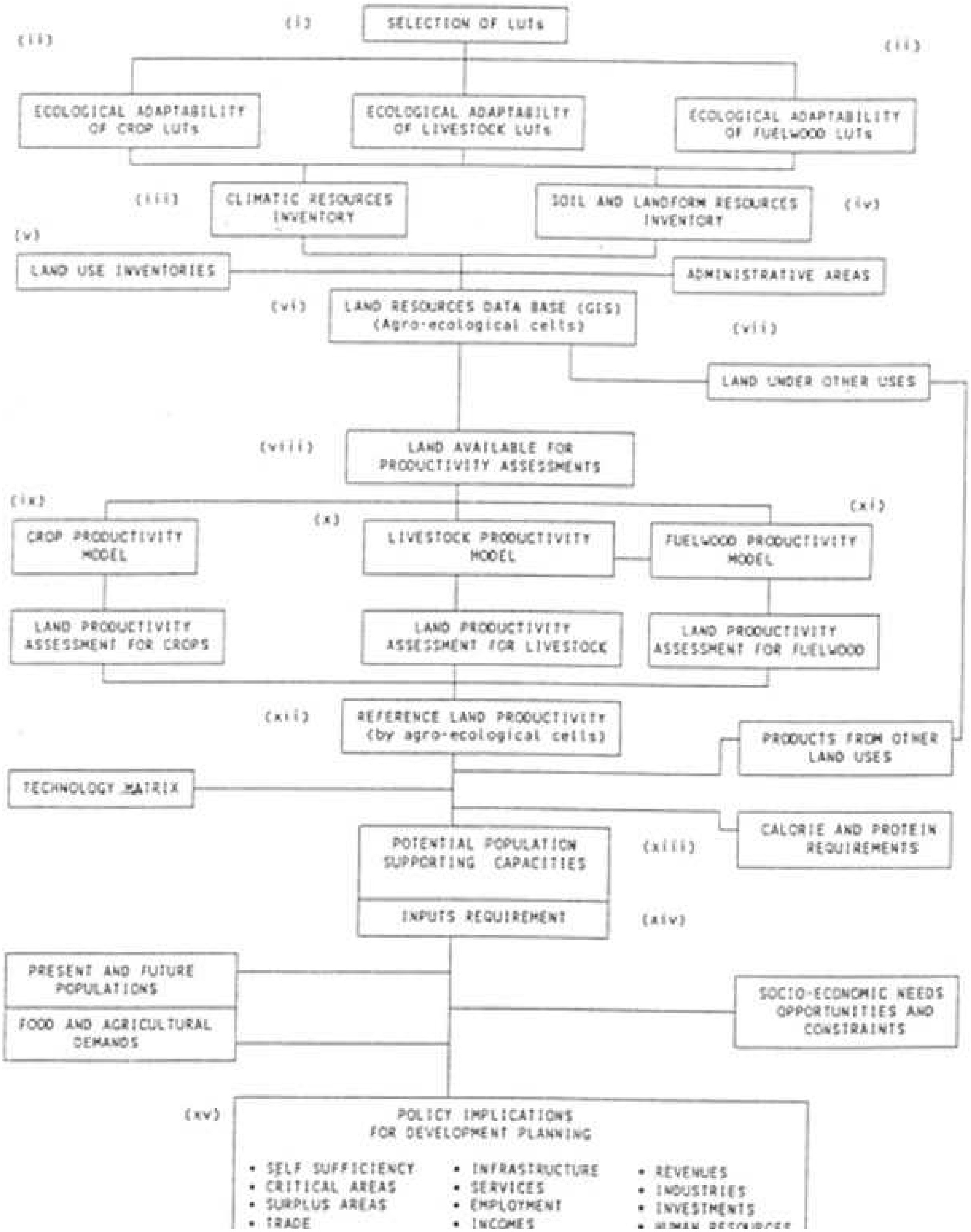
Length of growing period	Extents of land variously suited to production (km^2)																	
	Maize						Cassava						Paddy rice					
	VS	S	MS	mS	NS	Total	VS	S	MS	mS	NS	Total	VS	S	MS	mS	NS	Total
High input:																		
120-134	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
135-149	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
150-164	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
165-179	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
180-194	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
195-209	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
210-224	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
225-239	0	13	12	0	575	600	0	25	0	0	575	600	0	0	0	25	575	600
240-254	0	888	12475	0	4774	18137	888	12475	0	0	4774	18137	0	875	0	7884	9378	18137
255-269	0	90	12627	12520	19793	45030	717	24518	0	0	19795	45030	372	2480	2108	7599	32471	45030
270-284	0	0	0	270	1162	1432	0	136	134	0	1162	1432	0	0	25	0	1407	1432
285-299	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
300-360	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Totals	0	991	25114	12790	26304	65199	1605	37154	134	0	26306	65199	372	3355	2133	15508	43831	65199
Low input:																		
120-134	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
135-149	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
150-164	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
165-179	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
180-194	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
195-209	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
210-224	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
225-239	0	0	0	25	575	600	0	0	25	0	575	600	0	0	0	0	600	600
240-254	0	438	455	3961	13283	18137	0	899	7896	4591	4751	18137	0	0	438	437	17262	18137
255-269	0	0	0	230	44800	45030	0	230	19442	4941	20417	45030	0	741	0	4219	40070	45030
270-284	0	0	0	0	1432	1432	0	0	136	134	1162	1432	0	0	0	13	1419	1432
285-299	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
300-360	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Totals	0	438	455	4216	60090	65199	0	1129	27499	9666	26905	65199	0	741	438	4669	59351	65199

Note: VS-Very suitable (80-100% attainable yield); S-Suitable (60-80%); MS-Moderately suitable (40-60%); mS-Marginally suitable (20-40%); NS-Not suitable (<20%).

Source: FAO (1994a).

FIGURE 9

Schematic presentation of overall model used in Kenya study



(i)
SELECTION OF LUTs
(ii)
ECOLOGICAL ADAPTABILITY OF CROP LUTs
ECOLOGICAL ADAPTABILITY OF LIVESTOCK LUTs
ECOLOGICAL ADAPTABILITY OF FUELWOOD LUTs
(iii)
CLIMATIC RESOURCES INVENTORY
SOIL AND LANDFORM RESOURCES INVENTORY
(iv)
(v)
LAND USE INVENTORIES
ADMINISTRATIVE AREAS
(vi)
LAND RESOURCES DATA BASE (GIS) (Agro-ecological cells)
(vii)
LAND UNDER OTHER USES
(viii)
LAND AVAILABLE FOR PRODUCTIVITY ASSESSMENTS
(ix)
CROP PRODUCTIVITY MODEL
(x)
LIVESTOCK PRODUCTIVITY MODEL
(xi)
FUELWOOD PRODUCTIVITY MODEL
LAND PRODUCTIVITY ASSESSMENT FOR CROPS
LAND PRODUCTIVITY ASSESSMENT FOR LIVESTOCK
LAND PRODUCTIVITY ASSESSMENT FOR FUELWOOD
(xii)
REFERENCE LAND PRODUCTIVITY (by agro-ecological cells)
PRODUCTS FROM OTHER LAND USES
TECHNOLOGY MATRIX
CALORIE AND PROTEIN REQUIREMENTS
POTENTIAL POPULATION SUPPORTING CAPACITIES
(xiii)
INPUTS REQUIREMENT
(xiv)
PRESENT AND FUTURE POPULATIONS
FOOD AND AGRICULTURAL DEMANDS
SOCIO-ECONOMIC NEEDS OPPORTUNITIES AND CONSTRAINTS
(xv)
POLICY IMPLICATIONS FOR DEVELOPMENT PLANNING
• SELF SUFFICIENCY
• CRITICAL AREAS
• SURPLUS AREAS
• TRADE
• INFRASTRUCTURE
• SERVICES
• EMPLOYMENT
• INCOMES
• REVENUES
• INDUSTRIES
• INVESTMENTS

BOX 8: DEFINITIONS OF MULTIPLE CROPPING PATTERNS (FAO, 1993)

Multiple cropping	The intensification of cropping in space and time dimensions. Growing of two or more crops on the same field in a year.
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 and there is no intercrop competition. Farmers manage only one crop at a time in the field.
Intercropping	Growing two or more crops simultaneously in the same field. Crop intensification is in both space and time dimensions. There is intercrop competition during all or part of crop growth. Farmers manage more than one crop at a time in the field.

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Chapter 4
Software tools and geographic information systems

AEZ entails the linking of a number of logical procedures to arrive at a quantitative estimate of yield or production for a particular agro-ecological zone or agro-ecological cell. Such a methodology is particularly suited to computer- ization, and mainframe computers were used in the early FAO continental scale studies (FAO,1978) because of the large amounts of data involved. Subsequent- ly the methodology has been implemented on minicomputers, and most recently on microcomputers. Most advanced AEZ investigations incorporate a series of databases, linked to GIS and dedicated computer models, which have multiple potential applications to natural resource management and land-use planning.

Software tools can be grouped into databases, geographical information systems, models, and integrated packages.

Databases

In the compilation of inventories of land and land use, AEZ studies normally use large quantities of data. For direct viewing of information and for access by models for land suitability and productivity assessment, these data are most conveniently stored in databases. Databases can either be constructed using commercially-available software, or dedicated pre-programmed packages can be used. Relevant databases available from FAO are:

· multilingual soil database (FAO/ISRIC/CSIC, 1995)

· crop environmental requirements database (FAO, 1994b)

· land use database (de Bie, van Leeuwen and Zuidema, 1995).

Most recent FAO AEZ studies have used databases incorporated into shell programmes such as the Agricultural Planning Toolkit (APT), which is described under the heading of Integrated Packages (p. 61).

Models

Once the essential data are stored in the databases, AEZ uses models to derive quantitative outputs describing productivity and land suitability. Models represent a simplification of a more complex reality and the level of detail of the model should be consistent with the objectives of the study, the availability of data, and the knowledge base from which inferences can be drawn. Summary mechanistic models, based on relationships between external variables and the intermediate or ultimate products are particularly suited to land evaluation (Dumanski and Onofrei,1989). As plants obey similar physiological rules, sets of parameters can be input for individual crops, and for inputs and operations which describe the production system, and the results can be directly compared for different production systems and different land units or AECs.

A number of suitable models are available for use in AEZ studies. CYPPAC (De Baveye,1988), and CYSLAMB (crop yield simulation and land assessment model for Botswana) (Tersteeg, 1994) have been developed in the course of FAO projects. An updated version of the former program is incorporated in the APT shell. Most national AEZ studies use simpler models for crop productivity estimation in which the crop water balance is not crop specific. Further models are used to assess erosion induced production loss, and to estimate livestock and fuelwood productivity.

GIS

Geographic information systems have emerged as powerful tools in the management and analysis of the large amount of basic data and information, statistical, spatial and temporal, needed to generate in a flexible, versatile and integrated manner, information products in the form of maps as well as tabular and textual reports for land use decisions. In recent years FAO has been developing GIS in linkage with its agro-ecological zoning and similar models, applying these to tackle issues of land, food and people at global, national and sub-national levels. So far the applications have mainly addressed issues linking land-use outputs with other development goals in such areas as food production, food self sufficiency, cash crop requirements, population supporting capacity, taking into account soil fertility constraints, soil salinity, soil erosion risks and land degradation hazards. Good progress has been made in developing GIS- based tools for land resources planning, management and monitoring at different scales.

The development of these and other related applications involve the analysis and interpretation of large quantities of biophysical and socio-economic data, statistical, spatial and temporal, in order to produce the diverse kinds of information products required in the form of images, maps and both tabular and textual reports for decision making at the various application scales of interest. Up-to-date computing tools of spatial analysis allowing easy access to data and information and their manipulation are necessary to produce these.

Rapid development in information technology in the last decade has created a unique opportunity for the development of such a tool in the form of a multi- purpose land resource information system (LRIS) which can be used to generate quickly and efficiently various kinds of information according to the require- ments of different users. The LRIS contains computerized databases, models, decision-support tools and a user interface to facilitate its operation.

A GIS is the central element in the configuration of a LRIS. GIS's utility derives from a capacity for dynamic functionality based on the following three main qualities:

1. the physical computing capacity to manipulate data, including overlay, join, disaggregate;

2. the related capacity to query the data by formulating hypotheses for testing assumptions, defining potential relationships and developing theoretical constructs;

3. the capacity to relate two-dimensional and three-dimensional location of earth features, including atmosphere, lithosphere/hydrosphere/ecosphere, along with dynamic (space/time) four-dimensional processes, such as represented by functional operations of systems of land resources appraisal, planning, management and monitoring.

GIS/LRIS is a multidisciplinary undertaking which integrates databases of various kinds and sources, models for data analysis, decision-support tools, computer hard and software and the human resources and institutional framework to operate the system. Remote sensing provides data and maps on land cover and land use and enables rapid and efficient monitoring of land use change, which is an essential element of land degradation assessments and a determinant of land use sustainability.

Integrated packages: linking databases, GIS and models

The integration of AEZ and GIS, in combination with procedures and expert guidance, enables AEZ analysis to be performed more efficiently, and allows a flexible presentation of results according to user needs. The FAO AEZ study in Kenya (FAO,1993a) developed an integrated software package which could be adapted for use elsewhere, provided the expertise is available to reset the parameters. Alternatively, APT is a package which integrates databases and models, but the results require separate importation into GIS.

The integrated systems used in the Kenya AEZ study have two principal components :

· a computerized land resource database;

· a set of (mainly empirical and heuristic) models in the form of computer programs.

The land resource database is obtained by combining various data layers (map and tabular data) on the physical aspects of agricultural environments such as soil, landform and climate. The models are used to create the land resource database, calculate land suitabilities and land productivity, and to determine optimum land resources allocations (Figure 8). Various outputs are generated in both tabular and map form. The power of the AEZ methodology is based on the multipurpose integrated resources database it creates.

The linkages between GIS and AEZ models can be called ad hoc and partial. GIS and models are developed separately. Map input/overlay and map output capabilities of the GIS are used for preparation of the land resources database required by the models. Model processing is outside the GIS. Data flow from the GIS-created databases into the AEZ model and vice versa. Modelling results are transferred to GIS for further processing and presentation.

The software package used in the detailed country AEZ methodology consists of five computer programs to implement the AEZ models and a number of utility programs of various kinds related to database management, statistical analysis and display of results. The AEZ programs analyse land suitability and land productivity including cropping patterns, linkage to livestock and forestry production systems and soil erosion considerations. A linear programming program for land-use optimization at cell and district levels is incorporated in the package.

Linear programming for multiple goal decision making

One major area of development has been in applying optimization models to sets of AEZ/GIS outputs in order to examine alternative regional or district level land-use patterns. Such models suggest feasible land-use allocation patterns that best satisfy specified development objectives, e.g., target food consumption patterns, population supporting capacities or rural employment levels. A mathematical programming approach is taken as there are many feasible land- use allocations e.g., maximize population supporting capacity (production of calories and proteins and the cell level), subject to a district level crop mix constraint, and a district level limit on the use of fertilizer.

Future development of AEZ and GIS

The continued development of AEZ/GIS has also served to expand the spatial ranges, or scales, of its application. While the underlying concepts of AEZ are valid at any scale, the specific methods and tools of implementation must often differ in order to reflect the changing nature and complexity of decision making at national, district, farm and even plot level.

AEZ/GIS approaches are suited to any application in which the relationship between land resources and land uses needs to be explored - either in the context of assessing the suitability of land resources for specific uses, or of assessing the likely impact of those uses on the land resources themselves. Furthermore, the ways in which these relationships can be explored are constantly being enriched. Other applications in the policy analysis and planning areas pose "what if ....?" questions. The two main types of questions are: (1) what if I could modify one or more land resource characteristics? (e.g., by terracing, drainage, fertilizer application, liming) or (2) what if I could modify current or proposed land-use characteristics? (e.g., by the use of genetic materials that are more drought resistant, or that have a shorter growth cycle, or by the use of more machinery and less labour, or by the use of crop residues for feed and not for mulching). AEZ/GIS can estimate the changes either in land-use suitability or in environmental degradation hazard that arise from the "what if .... ?" scenario being tested. The broader socio-economic costs and benefits of proposed modifications can then be evaluated. For this type of application a GIS and model are developed in close interaction. The model is implemented using exclusively input, processing and output functions of the GIS.

This methodology continues to develop, and the further recent enhancements include the following:

· Improved model of climatic data analysis to take into account the effects of cold temperatures in LGP calculation.

· Refined models of crop suitability to:

· take into account CO_2 enrichment and its effects on rate of photosynthesis and crop water use efficiency in the biomass calculation model depending on crop cycle length;

· better evaluate agro-climatic constraints and quantify soil moisture deficit at various stages of crop growth;

· enable artificial increments in temperature and precipitation under existing and evaluated CO_2 concentrations to test the sensitivity of the AEZ models to climatic variations;

· enable inclusion of sustainability considerations in the formulation of the planning scenarios;

· fully integrate potential evapotranspiration (PET) calculation, length of growing period (LGP) determination (water balance model), biomass and yield calculation into suitability/productivity assessment.

The latest version of the integrated GIS/AEZ system is shown in Figure 12.

FAO is preparing an improved tool, which incorporates these upgraded AEZ models and multi-criteria decision support techniques for a more generalized use in different agro-ecological and socio-economic settings to provide more effective assistance to various stakeholders in their land-use decision making and land use-negotiations. The software will be able to run on PC computers which are readily available in developing countries.

TABLE 20
Important rainfed cropping patterns generalized according to thermal zones and LGP zones

LGP	Thermal zone		
(days)	T1, T2, T3	T4, T5	T6, T7
< 120	SC_{as} (I_a)	SC_{as} (I_a)	SC_{as}
120-210	SC_{as} I_a + I_d (S_{mo} + S_{mu})	SC_{as} I_a + I_d	SC_{as} I_a
210-270	SC_{a1} I_a + I_d S_{mo} + S_{mu}	SC_{a1} I_a + I_d (S_{mo} + S_{mu})	SC_{a1} I_a + (I_d)
270-365	SC_{a1} + SC_p I_d + I_a S_{mo} + S_{mu}	SC_{a1} + SC_p I_d + I_a (S_{mo} + S_{mu})	SC_{a1} + SC_p I_a + I_d (S_{mo} + S_{mu})

Note: Brackets indicate minor status.

Key: SC_{as} — Sole cropping of annual short-duration crops; SC_{a1} — Sole cropping of annual long-duration crops; SC_p — Sole cropping of perennial crops; I_a — Intercropping with crops of similar lengths of maturity; I_d — Intercropping with crops of different lengths of maturity; S_{mo} — Sequential monoculture; S_{mu} — Sequential multiculture.

TABLE 21
Results of crop productivity assessment - assumption set B

NATIONAL TOTAL: KENYA (Assumption Set B)

Arable land by productivity classes (100 ha):

No.	Zone	C1 >80	C2 60-80	C3 40-60	C4 20-40	Total C1-C4	C5 5-20	Total C1-C5	Total extent	C1-C4 % of zone
1	Arid	0	287	2204	3108	5598	19084	24682	423321	1.3
2	Semi-arid	993	2327	6988	8010	18318	14146	32464	67536	27.1
3	Sub-humid	3434	4660	5658	5319	19072	4767	23839	37538	50.8
4	Humid	3532	7756	6606	7550	25444	4736	30180	46427	54.8
	Total	7959	15030	21456	23988	68433	42733	111165	574823	11.9

Potential crop production:

No	Crop	Land by productivity class (100 ha)						Class C1-C4			Class C1-C4			
		C1 >80	C2 60-80	C3 40-60	C4 20-40	Total C1-C4	C5 5-20	Production (1000 mt)			Yields (kg/ha)			
								Min	Avg	Max	Min	Avg	Max	MCI
1	Barley	3902	5984	6009	14348	30243	16004	2390	5239	7675	790	1732	2538	1.53
2	Maize	3755	5213	10076	20603	39648	39540	5431	10247	14614	1370	2584	3686	1.69
3	Oats	1109	3475	8568	10364	23517	19351	1381	3248	4830	587	1381	2054	1.38
4	Millet	1528	4010	9776	20603	35916	31275	2160	3703	4530	602	1031	1261	1.53
5	Rice	95	740	1554	8574	10964	18741	1130	1899	2602	1031	1732	2373	1.94
6	Sorghum	3339	6133	8615	20665	38752	45419	3035	6312	9111	783	1629	2351	1.69

7	Wheat	2266	5175	4699	12620	24759	17359	1713	4277	6786	692	1727	2741	1.41
8	Cowpea	674	647	2931	8527	12779	13277	599	1084	1527	469	849	1195	1.77
9	Gram	173	1609	3659	6781	12222	35156	501	954	1341	410	781	1097	1.80
10	Grndnt	672	696	2937	8777	13081	12800	957	1727	2446	732	1320	1870	1.68
11	Beans	4262	5819	7000	12193	29274	16711	1699	3149	4505	580	1076	1539	1.72
12	Pigpea	2048	1168	3781	9159	16155	8790	927	1847	2521	574	1143	1561	1.49
13	Soybean	732	906	2569	8657	12864	13621	564	1103	1593	439	857	1238	1.66
14	Cassava	884	2285	3087	7385	13641	17312	12780	14270	14862	9369	10461	10895	1.00
15	Sw.pot	896	1280	2253	6365	10795	13670	5213	9184	12245	4829	8508	11344	1.59
16	Wh.pot	1832	4202	7115	9917	23066	18096	10976	23949	36506	4758	10383	15827	1.81
17	Banana	0	149	635	5109	5892	5003	3957	4263	5047	6715	7234	8565	1.00
18	Oilpalm	0	24	71	419	514	609	31	59	67	601	1143	1311	1.00
19	Sugcane	75	593	2024	6471	9163	11867	21470	23973	24991	23430	26162	27273	1.00
20	Coffee	1903	3571	3094	7217	15784	11290							
21	Cotton	53	185	1102	3911	5251	4828							
22	Pineapp	117	463	2069	2066	4716	144							
23	Pyreth	1689	5958	7719	9186	24552	3337							
24	Sisal	535	2051	5010	9363	16958	19501							
25	Tea	1646	6279	7376	8571	23871	7161							
26	Fuelw1	3974	26315	22786	37923	90997	50669	36283	40185	42050	3987	4416	4621	1.00
27	Fuelw2	8040	21608	19881	24639	74167	61648	69480	74856	77619	9368	10093	10465	1.00
28	Grass	12138	18715	13178	34039	78070	164781	38113	42737	44422	4882	5474	5690	1.00

Source: FAO (1993b).

FIGURE 10
Harvested area under maximum food production, Bungoma District

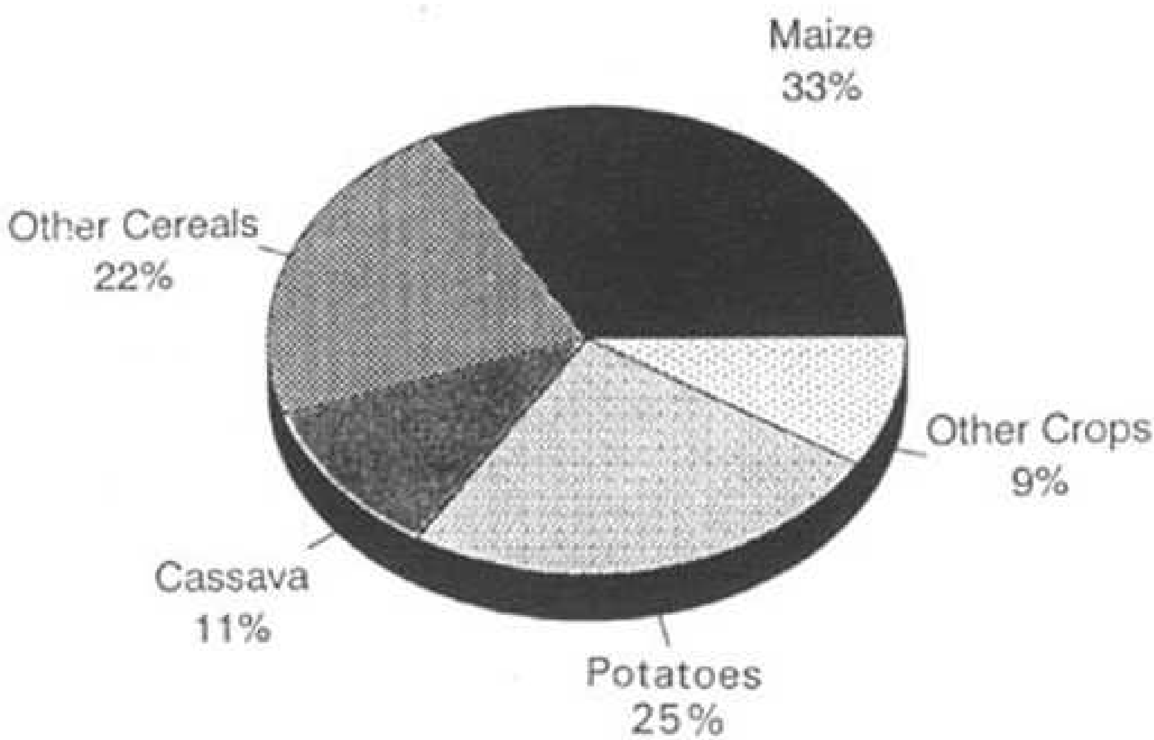


TABLE 22

Results of ALDS analysis for Bungoma District

Bungoma	Food_val	Net_rev	Arable	Food_min	Eros_tot	SSR_v	Eros_max	SSR
Food_val	1197.2	1082.6	165.4	969.7	3206.9	1204.0	112.8	96
Net_rev	931.1	1316.6	126.4	717.9	2622.1	1000.0	85.4	80
Arable	742.6	789.2	96.2	548.4	1875.3	1000.0	85.4	80
Food_min	1139.3	1071.2	161.1	1010.5	3256.5	1066.7	148.4	85
Eros_tot	773.0	792.5	105.8	598.6	1164.9	1000.0	29.1	80
SSR_v	905.6	1044.5	157.3	654.3	3527.0	1337.8	227.8	107
Eros_max	746.8	783.0	121.0	574.9	1837.6	1000.0	12.2	80
MCD-A	1027.1	1075.5	127.5	813.6	2232.1	1184.7	73.8	95
MCD-B	1074.6	1007.7	150.9	857.3	2549.0	1234.5	32.5	99
MCD-C	1090.5	1054.7	161.4	875.7	2810.2	1229.9	30.0	98
MCD-D	1066.1	1038.9	161.9	846.8	3074.1	1250.8	33.9	100
MCD-E	1082.4	1041.8	163.1	865.5	2991.7	1239.9	31.3	99

Source: Fischer *et al.* (1996).

FIGURE 11
Example of AEZ/GIS output

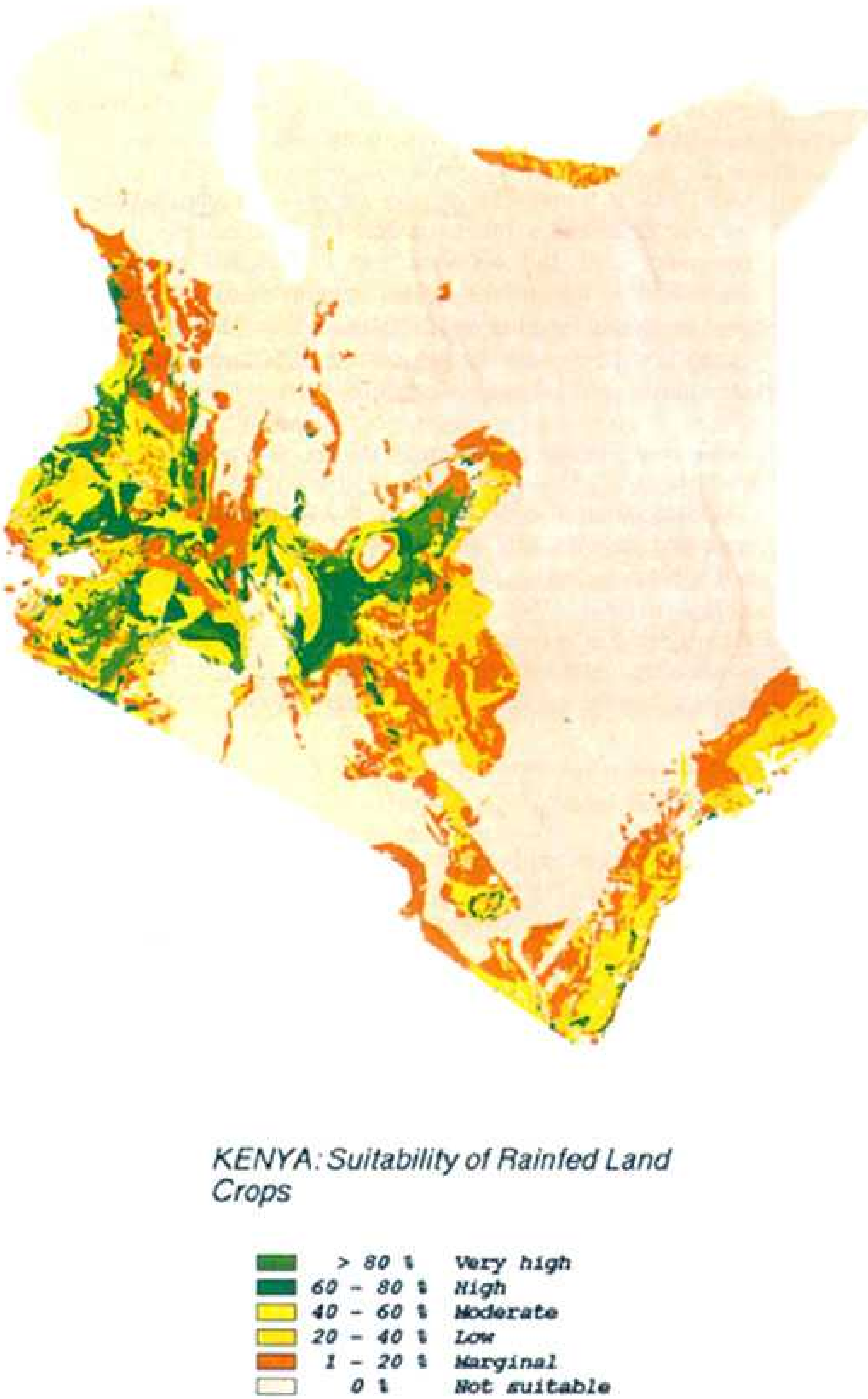
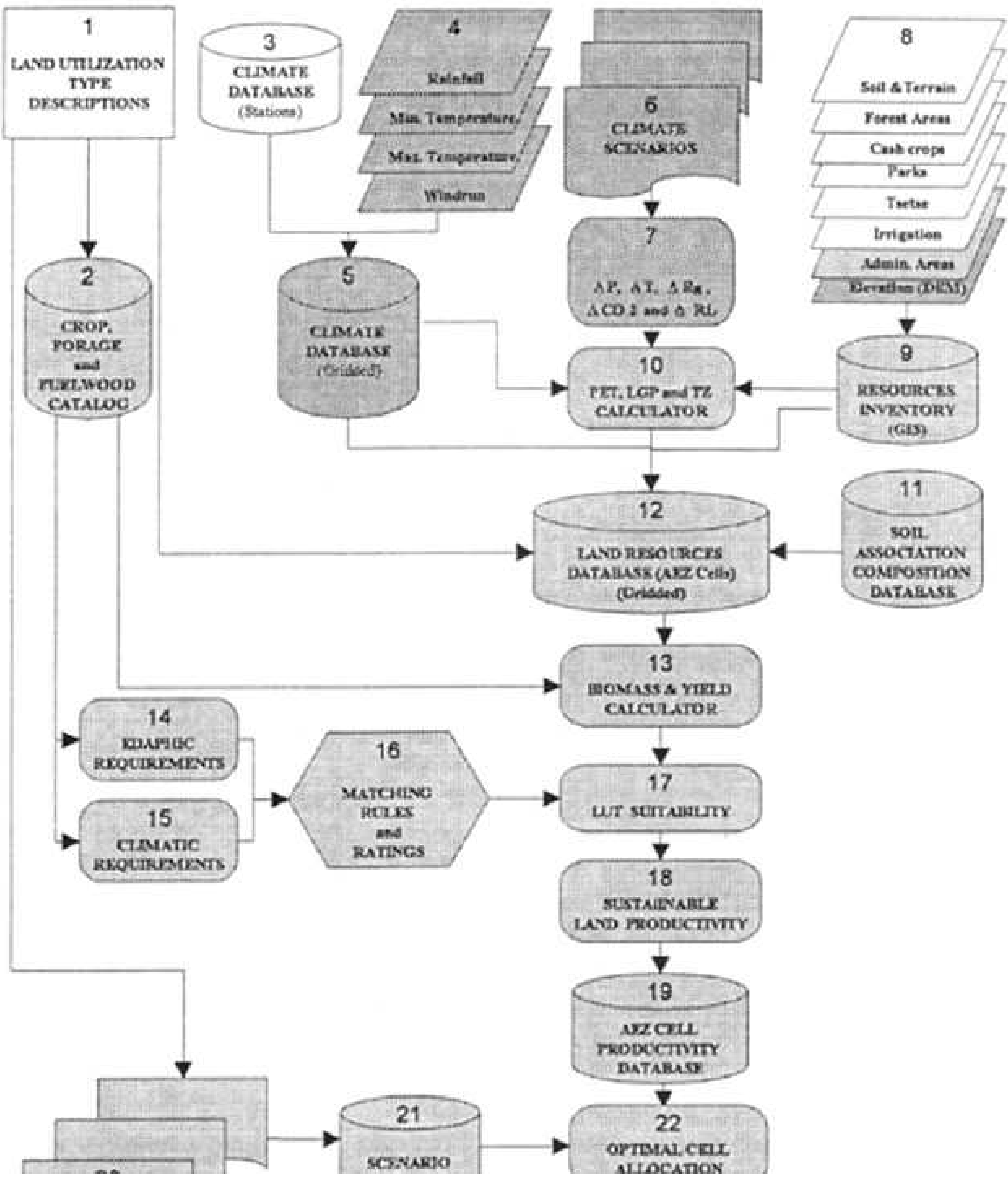
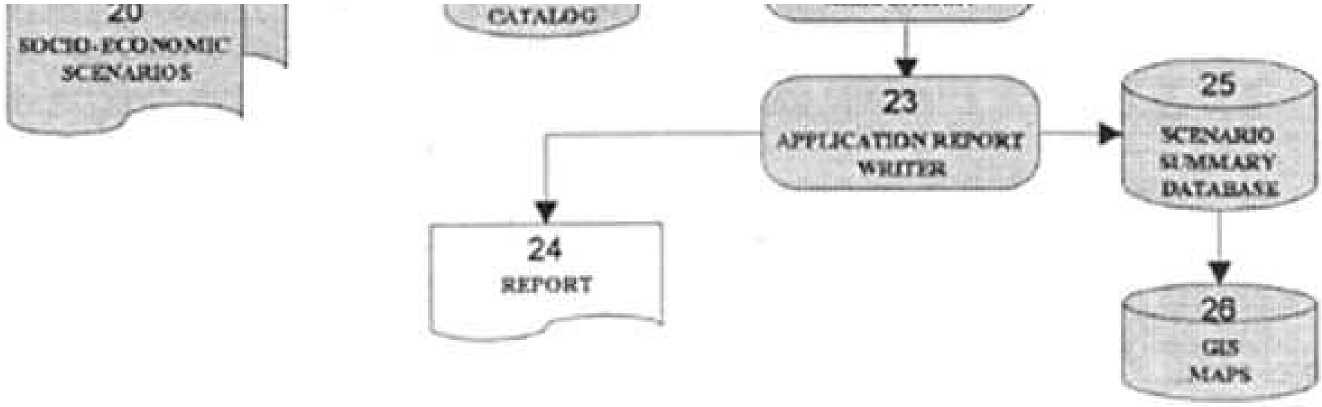


FIGURE 12
AEZ climatic change application: information flow and integration

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Chapter 5
Ecological- economic zoning

Ecological-economic zoning (EEZ) is an alternative approach to zoning which aims to correct the emphasis on physical factors and crop production in AEZ by including socio-economic factors and a wider range of land uses in zone definition. In principle, EEZ deals with both land and with people and their social organization. These people comprise the actual or potential land users, which may consist of individuals, communities or governments that have a traditional, current or future right to co-decide on the future of the land.

Through a process of dialogue with the various stakeholders involved in land- use decisions, the EEZ specialist assists these target groups to make the best decisions for themselves and for the community at large.

The principal aims of EEZ are as follows (Sombroek, 1994):

· to identify areas where particular uses may be encouraged through development programmes, services, financial incentives, etc.;

· to identify areas with special needs and problems, as well as areas which require protection or conservation;

· to provide a basis for infrastructural development.

EEZ is in fact a form of land use planning that takes into account all elements of the physico-biotic environment on the one hand and the socio-economic environment on the other. It then matches both of them through multiple goal analysis, thereby providing a neutral tool for the various stakeholders (land users) to arrive at a consensus on the optimal use or non-use of the land - to be subsequently executed through legislative, administrative and institutional action on demarcated spatial units.

EEZ is in principle applicable to all geographic scales and for lands of any intensity of use. In practice, it is mostly used for large tracts of land such as major river catchments and physiographic regions that have as yet a sparse human population. An essential element of EEZ is its dynamic character; it can and should be repeated or adjusted in relation to changing socio-economic conditions of the region concerned and outside influences, such as world market trends.

EEZ has no a priori bias towards high-input and high-producing agricultural land use but considers a wide range of uses which may satisfy the objectives of the stakeholders. These objectives may be incompatible to a greater or lesser extent and they may change over time. The use of "multiple-goal analysis" and subsequent optimization enables the ranking and periodic reassessment of objectives to select the optimum use (or non-use) of the defined area.

The potential benefits of conscientiously executed EEZ are the following:

· the avoidance of haphazard occupation of the land under consideration, which may lead to social conflicts and irreparable damage to the quality of the natural resources system;

· the better understanding of the objectives, priorities and requirements of the different stakeholders, thereby facilitating an eventual consensus for actual implementation of land-use plans through reconciliation of conflicting interests;

· the harmonization of the work of national institutions that deal with elements of land characterization, evaluation and rural physical planning.

In summary, EEZ is a tool for natural resources management that has the following parameters:

· a time frame of 5 to 25 years;

· a landscape or catchment area spatial focus;

· multiple beneficiaries;

· a technology that embraces all elements of a natural resources system with maximum concern for on- and off site environmental effects;

· a target of intergenerational social equity;

· a participatory approach, and

· an incorporation of multiple policies.

Proposed step-by-step zoning procedure

The following step-by-step procedure has been proposed for an EEZ exercise of the Amazon Region (Sombroek, 1994):

Step 1: Collection of maps and spatial information and entry into GIS

Step 2: Pre-zoning activities

A Delineation of natural land units and thematic analysis of their various natural resources

· climatic conditions;

· landform characteristics;

· soil conditions;

· land hydrology;

· vegetation;

· biodiversity values;

· current land uses;

· incidence of pests and diseases;

· near-surface mineral reserves and mining activities;

· river hydrology;

· population density;

· land ownership, formal or traditional.

B Determination of the bio physical land qualities and limitations, for each natural land unit distinguished.

C Identification of agro-ecologically viable land utilization types, and determination of their bio physical requirements in contact with stokeholders.

D Characterization of the socio-economic conditions and perspectives for each physiographic subregion or municipality, and for areas already demarcated for specific use.

Step 3: Zoning sensu-strictu

A Systematic comparison, through a process of matching and weighing, of the bio physical qualities of each identified natural land unit with the requirements of each envisaged land utilization type.

B Modification of the physico-biological rating through comparison with the prevailing socio-economic conditions.

Step 4: Post-Zoning

A A process of land-use negotiations among the various potential stakeholders on the basis of the objective inventory and evaluation of the natural resources conditions and their matching with land utilization alternatives, leading to a consensus on the future use of the various units of land.

B Implementation of the agreed future use or non-use of the land: preprojects for legislation, political decisions; legal, administrative and institutional execution; demarcation on the ground, inspection and control of adherence to the decisions.

In a sense, EEZ can be seen as an advanced application of AEZ, in which an expanded multi-layered AEZ database, including socio-economic data layers, is used.

Glossary

Agro-ecological cell (AEC). An area or point with a unique combination of land, soil, and climatic characteristics. The AEC is the basic processing unit for physical analysis in an AEZ study.

Agro-ecological zone. A land resource mapping unit, defined in terms of climate, landform and soils, and/or land cover, and having a specific range of potentials and constraints for land use.

Agro-ecological zoning (AEZ). The division of an area of land into smaller units, which have similar characteristics related to land suitability, potential production and environmental impact.

Agronomically attainable yield. The maximum yield that can be achieved by a given crop cultivar in a given area, taking account of climatic, soil and other physical or biological constraints.

Cropping pattern. The yearly sequence and spatial arrangement of crops or of crops and fallow on a given area.

Cropping system. A system, comprising soil, crop, weeds, pathogen and insect subsystems, that transforms solar energy, water, nutrients, labour and other inputs into food, feed, fuel or fibre. The cropping system is a subsystem of a farm system.

Database. An organized, integrated collection of data stored so as to be capable of use by relevant applications with data being accessed by different, logical paths. In theory the data are application independent.

Ecological-economic zoning. A kind of zoning which integrates physical land resources elements with socio-economic factors and a wider range of land uses in zone definitions.

Ecotype. A crop cultivar adapted to a particular range of climatic or soil conditions.

Edaphic requirement. A requirement of the crop for a particular condition or range of conditions in the soil environment.

Evapotranspiration. The combined loss of water from a given area over a specified period of time by evaporation from the soil surface and by transpira- tion by plants.

Farming System. A decision making unit, comprising a farm household, cropping and livestock systems, that produces crop and animal products for consumption and sale.

Geographical Information System (GIS). A system for capturing, storing, checking, integrating, manipulating, analyzing and displaying data which is spatially referenced to the earth.

Growing Period. The period of the year when both moisture and temperature conditions are suitable for crop production (see Text Box 2, p.8 for definition of types of growing period and growing period components).

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 intercrops relative to their sole crop yields.

Land Utilization Type (LUT). A use of land defined in terms of a product, or products, the inputs and operations required to produce these products, and the socio-economic setting in which production is carried out.

Land evaluation. The assessment of land performance when used for a specified purpose.

Land Quality. A complex attribute of land which acts in a distinct way in its influence on the suitability of land for a specified use.

Land Characteristic. A property of the land that can be measured or estimated.

Land. An area of the Earth's surface. In the context of land evaluation, land includes all properties of the surface, soil and climate, together with any resident plant and animal communities.

Length of growing period (LGP). The continuous period of the year when precipitation exceeds half of Penman evapotranspiration plus a period required to evapotranspire an assumed soil moisture reserve and when mean daily temperature exceeds 6.5 °C.

Model. A simplified representation of a limited part of reality with related elements .

Multi-criteria decision analysis (MCDA). A set of techniques used to solve problems which involve several objectives being considered simultaneously. In the context of integrated land use planning and management, MCDA techniques are applied to analyse various land use scenarios considering simultaneously several objectives such as maximizing revenues from crop and livestock production, minimizing costs of production and environmental damage from erosion.

Phenological requirement. A crop requirement for certain environmental conditions to occur at times which are related to the crop growth cycle.

Population supporting capacity. Assessment of the number of people a given area can support, based on the nutritional output of the crop and livestock production systems.

Potential yield. The maximum yield that can be achieved by a given crop cultivar in a given area, based on radiation and temperature.

Production system. A particular series of activities (the management system) carried out to produce a defined set of commodities or benefits (produces).

Resource management domains. Regions designated for identical treatments, i.e. land development plans, nature conservation programmes, and classified on the basis of ecological-economic zoning.

Soil type. A specific unit of soil with definable ranges of characteristics. May correspond to the lowest hierarchical unit of a soil classification system, including specification of phase.

Soil mapping unit. An area of land delineated on a map. A soil mapping unit may consist either of a single soil type, or of multiple soil types occurring as a complex or association.

Stakeholder. An individual, community, government or NGO which has a traditional, current or future right to take decisions on land.

Sustainable land use. Use of the land that does not progressively degrade its productive capacity for a defined purpose.

Thermal regime. The amount of heat available during the growing period. Thermal regime can be defined either in terms of temperature or degree days.

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