The Use of Geographic Information Systems (GIS) in Land Resources Appraisal

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Introduction

Nations, village communities as well as individual land users need to make the best choices among options for the use of land in order to support development without hazard of land degradation, which would endanger sustainable production of food and other rural products. These options of optimal land resources allocation result from complex decision-making processes involving the optimal combination of various kinds of information: information about soils, climates, vegetation, present and potential land uses, location of towns and villages, highways, railroads and waterways, figures on markets, prices, population, health and nutrition. Based on Geographic Information Systems (GIS), computerized Land Information Systems (LIS) 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/LIS systems in linkage with its agro-ecological zoning (AEZ) 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 addressed mainly 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. While good progress has been made in developing GIS/LIS based tools for land resources planning, management and monitoring at different scales, practical difficulties are encountered in making these technologies accessible to the casual user of GIS/LIS in most developing countries. There are problems with lack of data and poor data quality; there are difficulties in training and support for such advanced systems. Because of user need and interest, and the rapid development in computer and systems analysis technology, however, this is an area deserving more attention by GIS/LIS developers.

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Importance of land for sustainable development

Land includes all the natural environmental resources contained on the earth surface: soil, terrain, water, climate and weather. Human welfare and socio-economic development depends on the capability of the land resources to provide food, fuel, timber, fibre and other raw materials, many other products of plants and animals, as well as shelter and recreation.

In many developing countries the land use situation is changing fast. In some, output of food crops has increased with irrigation and management, and the needs for staple foods in both country-side and cities can be satisfied on the internal markets; farmers are able to use land to grow novel products in response to market demand. Economies are becoming larger and more diverse; settlements and industries are growing and more land area is needed for these purposes. In other countries, there may be problems in any or all of these activities. In particular, in most sub-Saharan countries, the intensification of land use to satisfy the ever-increasing demand for food, fuel and shelter by a fast growing population, associated with improper use of the land, is putting severe strains on land resources in various agro-ecological regions. Reserves of fertile lands are continuously diminishing as new production needs are met by opening up new land. Already the needs and growing aspirations of the steadily increasing populations have forced changes in production practices that have imposed excessive demands on fragile lands in humid high forest areas as well as dry savannah zones, resulting in widespread deterioration of the conditions of the productive land areas, undermining in turn their capacity of production.

In the technologically more advanced countries new problems relating to environmental and economic aspects are encountered by land managers dealing with agricultural and rural spaces: problems of pollutants such as acid rains, toxic wastes, soil and groundwater contamination. The issue of climate change due to the greenhouse gases and other atmospheric changes and its possible effects on soil, water and land resources conditions has become a major public concern in all countries of the world.

Pressures on land everywhere and the need to achieve a balance between the exploitation and conservation of the land resources have made rational resources use and management at all levels (world, regional, sub-national, and local) a vital issue.

Global and regional institutions as well as individual countries need to look at the present and future requirements for produce and goods from the available land resources and how to satisfy these requirements considering them against the possibilities and constraints of a sustainable production from these resources. They need to make the best choices among options for the use of land in order to support development without hazard of land degradation, which would endanger sustainable production of food and other rural products.

Rational land use planning and integrated land resources management are essential parts of the solution to sustainable land use and related problems. Knowledge of land resource endowment and its potential under different levels of technology is an essential prerequisite to planning of optimum land use and subsequent sound, long term agricultural and socio-economic development.

Land resources appraisal applications

Making decisions for rational, sustainable land use is becoming increasingly complex as land pressure and the competition for land, and the risk and extent of land degradation problems increase. The information and knowledge required for these decisions should be based on comprehensive and quantified assessments of potentials and development possibilities of the land resources, taking into account the biophysical, environmental, socio-economic factors, as well as the space and time dimensions of sustained land use. The outputs from such assessments are required by a growing variety of clients: land use planners, ecologists, environmentalists, economists, researchers, politicians, agriculture extensionists and land users, corresponding to various areas of applications such as:

- Land suitability and land productivity assessment;
- Land use planning;
- Land degradation assessment;
- Quantification of land resources constraints;
- Land management;
- Agricultural technology transfer;
- Agricultural inputs recommendations;
- Farming systems analysis and development;
- Environmental impact assessment;
- Monitoring land resources development;
- Agro-ecological characterization for research planning;
- Agro-economic zoning for land development and nature conservation;
- Ecosystem research and management.

The need for GIS-based land information systems

The development of these and 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 various application scales. 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 multi-purpose land resources information systems (LIS), which can be used to generate quickly and efficiently various kinds of information according to the requirements of different users. The LIS contains computerized databases, models, decision-support tools and a user interface to facilitate its operation (FAO, 1993b).

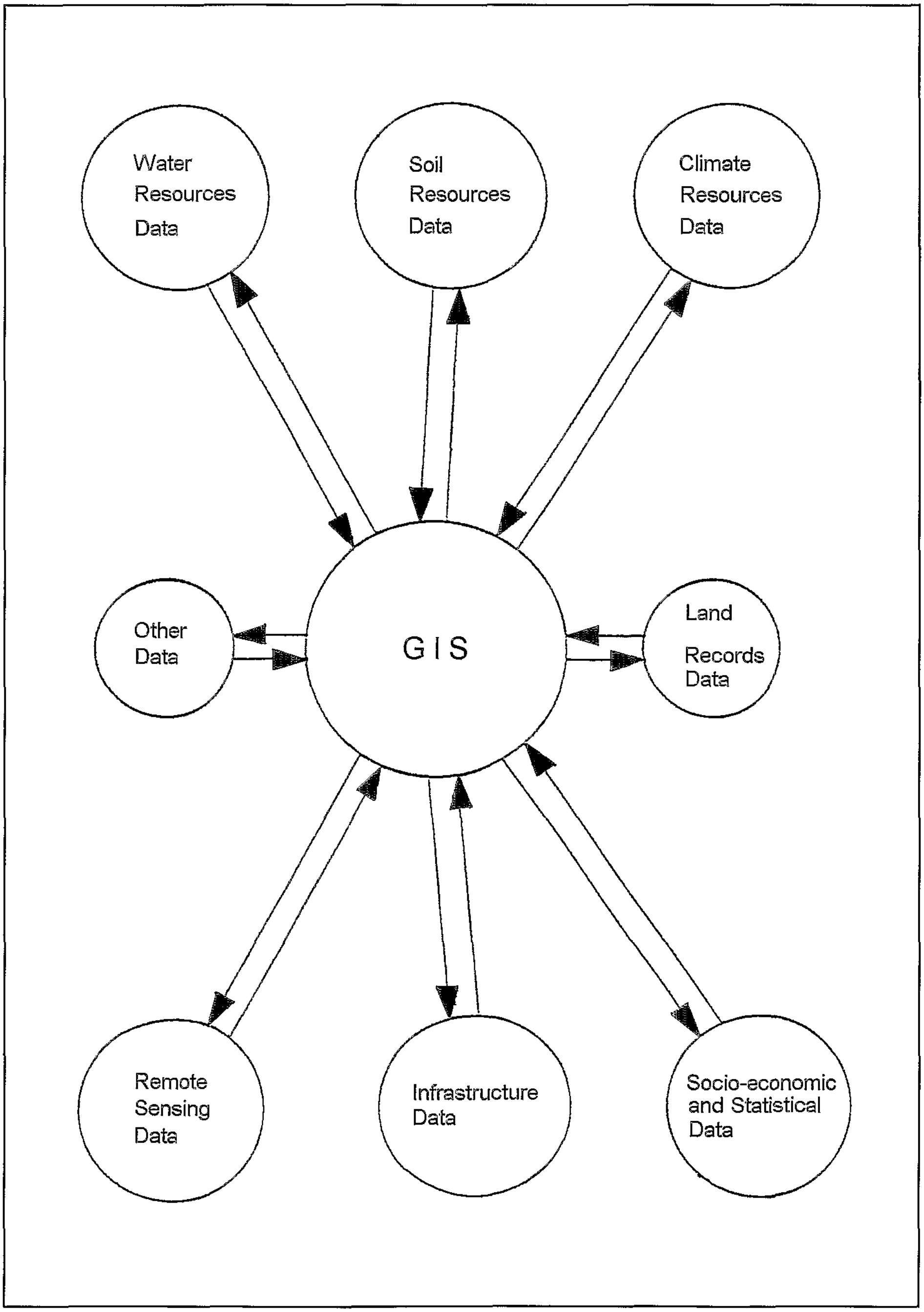

Figure 1. A possible GIS/LIS network configuration.

A Geographic Information System (GIS) is the central element in the configuration of a LIS. GIS's utility derives from a capacity for dynamic functionality based on the following three main qualities:

- The physical computing capacity to manipulate data, including overlay, join, desegregate;
- The related capacity to query the data by formulating hypotheses for testing assumptions, defining potential relationships and developing theoretical constructs;
- 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 natural resources appraisal, planning, management and monitoring.

GIS/LIS is a multidisciplinary undertaking which integrates databases from 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; it is often organized in the form of a network (Fig. 1). Within integrated GIS/LIS remote sensing data support advanced mapping and modelling of soil conditions, such as soil moisture, soil type, soil salinity and soil erosion risks, land cover, land use and vegetation. Due to frequent data collection remote sensing enables rapid and effective monitoring of land use change, which is an essential element of land degradation assessments and a determinant parameter of land use sustainability (FAO, 1990; JRC, 1993).

GIS-based land information systems in FAO

In recent years, FAO has gained valuable experience in the development of such GIS/LIS's to address issues of improved integrated planning and management of land and water resources, based on quantified assessments of resources potentials and limitations and the issue of a rational and efficient use of soils, water and nutrients in biomass production. At the core is FAO's effort in the development of its Agro-ecological Zoning (AEZ) Methodology (FAO, 1978-1981) for land resources appraisal which implements the land evaluation approach of FAO's Framework for Land Evaluation (FAO, 1976). AEZ has two components:

- A computerized land resource database;
- A set of (mainly empirical and heuristic) models in the form of computer programs for PC microcomputers.

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, climate. The models are used to create the land resource database, calculate land suitabilities and land productivity, and to determine optimum land resources allocations. 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 databases into the AEZ model and vice versa. Modelling results are transferred to GIS for further processing and presentation.

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.

FAO AEZ/GIS studies address a wide range of real-world issues; improved land use planning (China, Kenya, Mozambique), formulation of population policies (Malaysia, Philippines, China), national agricultural development (Kenya, Bangladesh), agricultural research planning and management (Bangladesh and Indonesia), natural resource management (Brazil), technology targeting (Bangladesh) and disaster preparedness (Philippines and Bangladesh) (FAO, 1994).

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. Current development efforts have a much greater focus on application at the farming systems level. Table 1 provides an overview of the various scales at which AEZ/GIS studies have been performed.

However, this list of applications is by no means exhaustive. In reality, 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:

- *What if* I could modify one or more land resource characteristics? (e.g., by terracing, drainage, fertilizer application, liming) or,

- *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.

Different applications interpret and aggregate these data in different ways to suit their specific purposes. In general, applications are concerned with the spatial variability of suitabilities and constraints, and how these change under different production scenarios (i.e., different *what if...?* questions). Using this information analysts can identify opportunities for, and evaluate impacts of, increased land productivity, land improvement investments, and the introduction of new production technologies and commodities.

Table 1. AEZ/GIS studies by scale of application.

Planning Level	Sample Applications	User
1:5,000,000 Global and Regional	Grassland and livestock potential of West Africa	ILCA (International Livestock Center for Africa), Ethiopia
	Population supporting capacity of the developing world	FAO, UNFPA (United Nations Fund for Population Activities)
1:1,000,000-1:5,000,000 Regional and Large Nation	Population supporting capacity, land use allocation, national resources planning	State Land Administration, China, Provincial Land Bureau, Heilongjiang
1:1,000,000 National and Sub-National	Agricultural development planning; crops, livestock, fuelwood	Government of Kenya, Government of Mozambique
1:500,000 Small Nation and Sub-National	Population supporting capacity	Government of Philippines, Government of Malaysia
1:250,000	Land degradation risk assessment	Federal Land Resources Department, Nigeria
1:125,000	Fertilizer recommendations and technology targeting.	Extension Service, Bangladesh
Local level		
1:20,000 Northern Ethiopian Rift Valley	Irrigation suitability assessment	Government of Ethiopia
20,000 ha Marakina Watershed	Forest suitability assessment	Bureau of Forest Development, Philippines
1:10,000 village Communities	Support to farm planning and development	Government of Oman

In the following, four examples are presented to illustrate the recent application of GIS/LIS in FAO at the global and national levels:

1. **AT2010 Study**: Estimation of arable lands and future land reserves.

2. **District Planning**: Land use allocations best satisfying specified development objectives.

3. **Climate Change**: Assessing the likely impacts on agricultural production.

4. **Vegetation and Land Cover Mapping**.

Example 1. AT2010 Land Resources projection

In the AT2010 study an attempt was made to project how much new land may be brought into crop production by the year 2010 (FAO, 1993a). The first step was to estimate the potential arable land or extent of land with crop potentials. The foundation of the evaluation consists of FAO GIS global land resource inventory for the developing world, based on the FAO/UNESCO Soil Map of the World (scale 1:5,000,000), which combine information on soil, landform and climate resources (temperature and length of growing period (LGP)) to characterize land in terms of agro-ecological zones. The land resource inventory is composed of thousand of agro-ecological cells which are pieces of land of varying size with homogeneous soil, landform and climate attributes. The database contains information on land suitability, soil fertility constraints and, to a limited extent, land cover/land use.

Each agro-ecological cell with given soil, terrain and LGP characteristics was tested on the computer for its suitability for growing each of 30 crops under three levels of technology: e.g. low, intermediate and high. The resulting yields for each cell, crop and technology alternative were then compared with those obtainable under the same technology and LGP characteristics on land without soil and terrain constraints (termed the maximum constraint free yield-MCFY). Any agro-ecological cell so tested is classified as suitable for rainfed crop production if at least one of the crops could be grown under any one of the three technology alternatives with a yield of 20% or more of the MCFY for that technology. If more than one crop meet this criterion, the amount of land is classified as suitable as determined on the basis of the crop which utilized the greatest part of the land in the cell. The extent occupied by that crop defined the extent of arable land. Any piece of land not meeting this criterion is classified as not suitable. The land classified as suitable is further classified into three suitability classes as follows: very suitable (at least 80% of MCFY); suitable (40 to 80% of MCFY); marginally suitable (20 to 40%). Plate 13 presents a map of potential rainfed arable land for Africa.

Example 2. District Planning: Making land use choices

In this study, a detailed country methodology has been developed for the determination of land resources and land use potentials of individual districts in Kenya for purposes of policy formulation and development planning (6).

The main components of the data required to compile the Kenya computerized land resource inventory include:

- Soil map (soil type, texture, phase, slope etc.) at 1:1,000,000 scale;
- Climate map, consisting of:
    - temperature regimes,
    - length of growing period (water availability),
    - rainfall pattern (form and variability of length of growing period - LGP).
- Administrative area map;

- Irrigation schemes and production;
- Non-food crop areas and production;
- Other land uses, including:
    - forest areas,
    - national parks and reserves,
    - urban areas, industrial and mining areas,
- Population distribution;
- Present crop mix, acreage and inputs.

The various layers were digitized and the digitized data were converted to a grid cell or raster database. Each pixel is one square kilometre (100 ha).

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 analyze 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. In this case 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.

The study produced numerous map outputs, including physical resources maps (landform, soil, climate, land resources), potential crop suitability maps, as well as maps of potential population supporting capacities and maps of optimal land resources allocations by district and for the whole of the country.

Figure 2 shows a map of suitability for rainfed production of cowpea at the intermediate level of inputs. Potential crop suitability is assessed by matching the land (soil, landform and climate) attributes described in the land resources inventory with the requirements of the crop expressed in terms of the land attributes.

Example 3. Climate change and its effects on global agricultural potential

Changes in climate will alter agricultural potential in various agro-ecological regions of the world. An increase in the atmospheric concentration of carbon dioxide will result in an increase in potential agricultural productivity and enhance the efficiency of water use by various crops. The effects of global warming will also tend to expand the agro-ecological potential poleward and into higher altitudes. These positive benefits, however, will be constrained by altered temperature conditions, precipitation, and evaporation patterns. In the long term, these changes in agricultural potential and climate patterns will significantly alter the ability of future generations to produce food, other agricultural products, and fuel-wood.

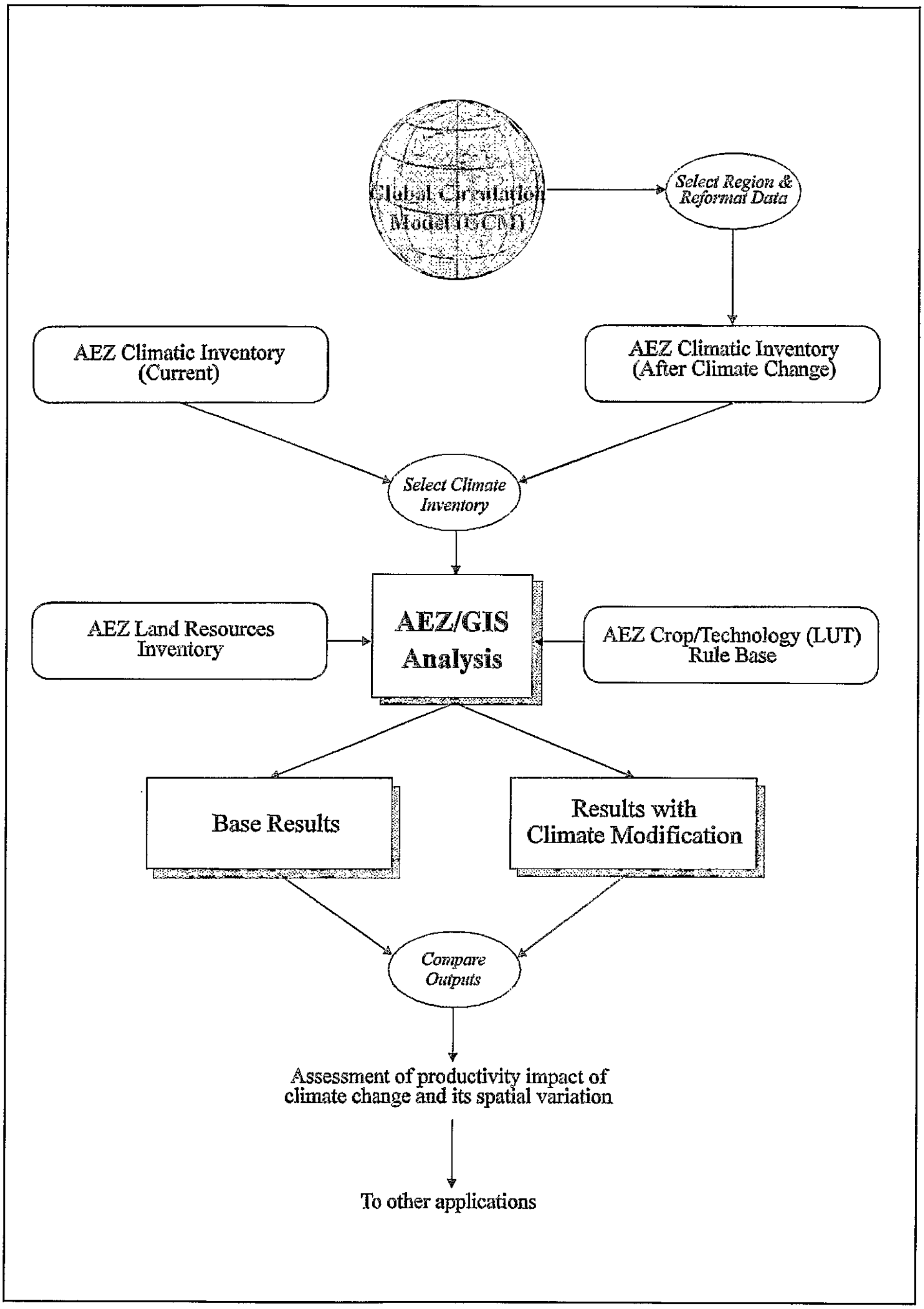

Figure 2. Generalized land suitability for rainfed production of cowpea at intermediate level of inputs.

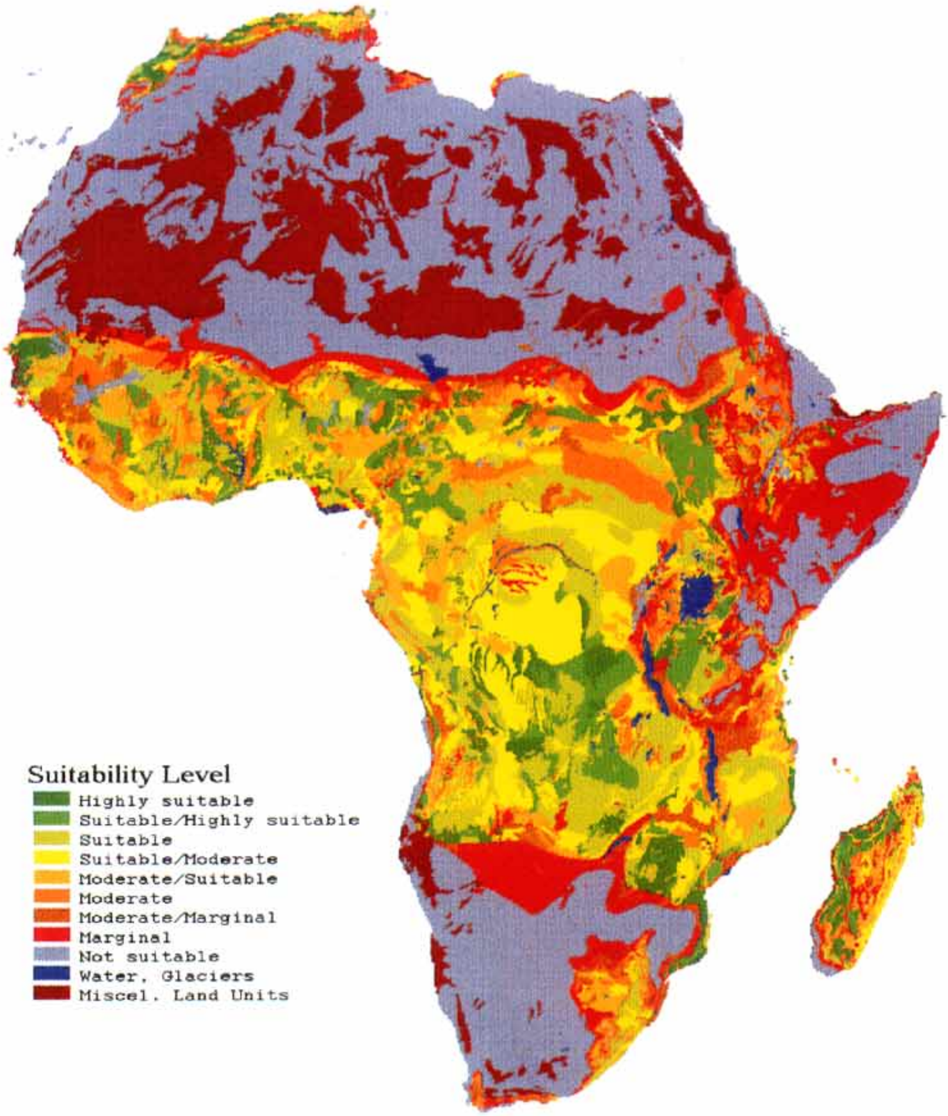

Plate 13. Africa, potential rainfed arable land. Average suitability of mapping unit (p. 550).

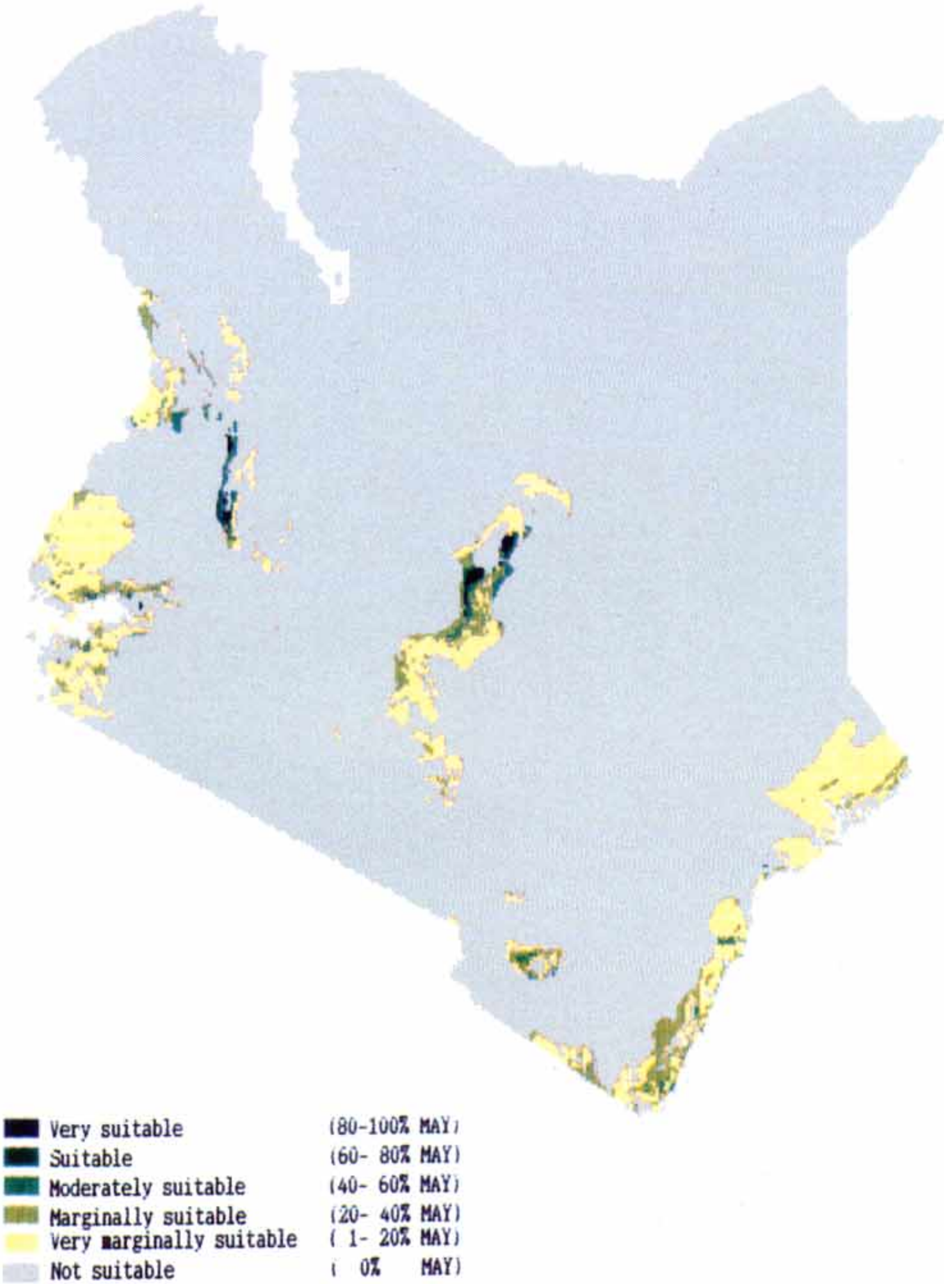

Plate 14. Generalized land suitability for rainnfed production of cowpea at intermediatelevel of inputs (p. 553).

New scenarios of climate change can be expected in the next few years that will incorporate realistic land cover models, ocean-atmosphere interaction and improved modelling of the water cycle. This next generation of Global Climate Models (GCM) scenarios should provide greater insight into critical variables for agriculture such as the frequency of extreme episodes (drought and heat), rainfall erosivity, and solar radiation.

In December 1993, a project to study the possible effects of climate change on global agricultural potential was launched in FAO. It is a collaborative undertaking which involves FAO; the United Nations Environment Programme (UNEP); the Environmental Climate Change Unit (ECU), Oxford University, UK; the International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria; and various national institutions such as the Kenya Agricultural Research Institute (KARI) and the Bangladesh Agricultural Research Council (BARC), under FAO technical supervision.

The project intends to assess the AEZ methodology and various other current models of land resources appraisal and use the results to develop a single refined methodology that includes many of these climate related factors that have yet to be addressed. In this application, however, climate is the agent of change. An overview of the analytical approach is shown in Plate 14. Differences between potential productivity (or environmental degradation) estimates using (a) the base climate data and (b) the predicted (changed) climate data, provide measures of impact for the agricultural sector. Of particular importance, are not just changes in production levels but also in the spatial distribution of production - both of which are obtained from the AEZ/GIS analysis. In future, this refined methodology and its application to existing databases will allow scientists and policy makers to define present conditions and enable them to identify future agricultural scenarios on a national, regional, and global scale. As part of this project, this refined methodology will also be applied and tested using expanded databases for Kenya and Bangladesh. Final results are expected early 1995 for the Kenya study and later in 1995 in the case of Bangladesh. It is anticipated that the methodology will serve as the basis for a second project that will focus on developing a global database that includes a larger number of country studies.

Example 4. Vegetation and land cover mapping

The lack of reliable and quantitative and qualitative information on vegetation cover and land use at national and regional levels in Africa has been a major constraint on the planning and implementation of measures for increased food production and food security, the sustainable management and conservation of natural resources and environmental monitoring. The UNCED Agenda 21 emphasizes the need for reliable information upon which to base decisions concerning the environment and development.

To fill this serious data gap FAO has designed an umbrella AFRICOVER project.

The objective of the project is two-fold:

- To produce a vegetation cover/land cover map, digital databases including coverages on topography, roads, drainage at a variable scale of 1:100,000, 1:250,000, 1:1,200,000 and 1:1,000,000, depending on country size, for the whole African continent and,

- To strengthen national and sub-regional capacities for mapping vegetation and land cover and monitoring change in Africa.

The project intends to use advanced techniques of Integrated Geographic Information System (IGIS) to store, analyze and interpret the huge amount of data, which the project will generate. IGIS integrates remote sensing and GIS technologies to efficiently manipulate satellite and other type of map data in a GIS environment.

Conclusion

FAO's future activities in GIS based systems of land resources appraisal will probably be determined by two essential factors:

- The ever-increasing demand by member countries of multi-purpose computerized land resource information systems as a means of dealing with emerging problems of land and environmental resources planning, management and conservation;

- The dramatic growth in the capabilities of GIS as a tool capable of integrating various kinds and increasingly large amounts of data at progressively reduced costs. This includes the large amount of data generated through remote sensing.

Accordingly, the trend is to further develop integrated modular systems capable of handling a wide range of 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.

However, there are a number of technical and organizational constraints which need to be removed for an effective application of LIS/GIS in land resources analysis:

- Overcome the still severe limitations in the capability of current LIS/GIS technology in the development of computer based tool for analyzing real life problems involving the integration of physical, socio-economic and political considerations in a holistic manner in decision-making, as they occur in complex land management and sustainability issues at farm level, which require a multi-disciplinary research effort. Newly evolving object-oriented design combined with multi-objective optimization and multi-criteria decision support systems could offer appropriate solutions to this problem.

- Overcome data availability and data quality limitations at all scales through cooperative arrangements between the various specialized national and international institutions dealing with the establishment and maintenance of the different kinds of databases required in multidisciplinary land resources applications. Definitions of common data exchange formats and protocols need to be established.

- Overcome the constraints to LIS/GIS use in developing countries. In many of these countries, lack of data and poor data quality remains serious drawbacks to the application of computer based systems of land and water resources management. Lack of trained personnel to apply the systems in solving practical problems is another constraint, which often causes the available systems to be under-utilized and sometimes not used at all. In terms of computer technology there are severe communications problems to be overcome in many developing country environments and the potential benefits have to be compared to the costs. In some countries the telephone network, which is the main means for establishing linkages between computers, is not reliable. A separate satellite-based system might then be called for. This can cost several thousand dollars per node to supply with very high rental costs for the satellite link. Most land resources data does not change rapidly. The benefits and costs of on-line communications and update facilities versus off-line solutions must be compared, therefore.

Computing technology, hardware and software is changing rapidly, particularly with GIS software, new products are announced almost every year which makes it very difficult to make any recommendations as to software purchase, or indeed what is possible. The user must keep abreast of current developments by studying the specialist press. Also, local support and maintenance is often of variable quality. Digital information technology is developing faster than research and agricultural organizations in developing countries can keep pace with it.

In summary, while good progress has been made in developing planning tools for district level evaluation, practical difficulties are encountered in making these technologies available to the casual AEZ/GIS user. There are difficulties in training and support for such advanced applications, in providing the software tools, and in performing optimization analysis on the type of PC platforms generally in use. Because of user interest, and the rapid developments in computer and system analysis technology, however, this is an area deserving more attention by AEZ/GIS funders and developers.

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