Development and Utilization of Agro-Ecological Zones in Indonesia Using GIS

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Abstract

The Center for Soil and Agro-climate Research (CSAR) is actively applying Geographic Information Systems (GIS) technology in conjunction with the Agro-Ecological Zoning based on Soil-Climate Database Management (SDBM). Within this framework, an integrated evaluation methodology for physical land resources information using relational databases and GIS is being developed to facilitate the process of agro-ecological zoning on a reconnaissance (1:250,000) scale. In most of the provinces, the relevant soil and physical land resources data are systematically collected and stored in specifically structured and designed databases. The spatial distribution is recorded using different land resources and topographic base maps. Structural expert system is used in developing models for the agro-ecological zones in each province, which correspond to the area already selected as a link to the land use objectives based on non-spatial physical parameters. GIS operations and techniques are used for enhancing and updating the agro-ecological zoning procedures and presentation of the results. In the future, for detailed zoning, it is suggested that the land characteristics at a semi- detailed or detailed level, farming systems, and socio-economic pattern of farming systems should be incorporated.

Introduction

To achieve adequate and proper land use planning, geographical analysis of the land resources base should be executed intensively. Land resources should be described with their relationship to a geographical notation. All assessment based on good data and agro-ecological criteria will yield land resources potential maps.

Good data have a good structure, which is also systematically put into a format in a database. Indonesia has adopted a land resources database system since 1985, when the first computer system was introduced into the Center for Soil and Agro-climate Research. The land resources database includes a soil database and agro-climate database. Since agro-climatic data were collected after 1992, the soil database shows a better-structured collection than the agro-climate database.

In Indonesia, the introductory use and implementation of Geographic Information Systems (GIS) and Soil-Climate Database Management Systems (SDMS), were initiated more than two decades ago. At the CSAR, such systems were developed from a rudimentary form using a simple computer-assisted cartographic program into a sophisticated analytical system to integrate data from diverse fields. The technologies presently applied enable scientists to store, retrieve and analyze soil and land resources database on geographic coordinates for a wide range of purposes. The increasing demand for accurate geo-referenced data for land evaluation and planning of appropriate land uses providing sustainable benefits required the early application of information technology.

This paper is describing some problems in the development and utilization of agro-ecological zone maps using GIS facilities. Part of this discussion deals with various aspects to solve some of the problems.

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Methodology in AEZ delineation

The first step in Agro-Ecological Zoning, is data input. The input includes delineation of land suitability and base map with land unit polygons. The available land resources data were hardly used due to the limitation in knowledge, hardware and the data structure. Data should be entered systematically in a standard format, which is necessary for adequate performance. Since missing data create problems in performing an analysis, consistency in data format is necessary. Standardization of the data includes standardization of data capture methods. The conditions are related to the land characteristic value.

In the Agro-Ecological Zoning procedures using the GIS, the GIS operations can be divided into several steps. First step is the preparation. Second step involves data processing. The last step consists of GIS application in Agro-Ecological Zoning. In the preparation, the contour maps, hydrological feature maps, roads, settlements, and administrative boundaries have been prepared beforehand by BAKOSURTANAL (National Agency for Survey and Mapping). The GIS is used mostly for rechecking the UTM coordinates, the continuation of the lines and boundaries in adjacent map sheets. Then, in the second step, the GIS operators digitize the agro-ecological components such as landform and interpretative mapping units derived from different sources. The polygons built from these interpretations will be fixed and structured after the field checks. Each polygon represents a unique database in the mapping unit database. The SDBM adjusts the relationship between the database and the mapping units. All the data have been related to other necessary databases such as social economic parameters (Amien, 1997). The attributes defined in the databases can be used for describing the mapping units. AEZ delineation parameters include soil mapping units, elevation range, temperature range, physiographic mapping units, slope range, drainage, isohyet.

For convenience, the GIS software selected for the AEZ implementation for each BPTP/LPTP/IPTP is a vector-based GIS (such as MapInfo). It was converted from ARC/INFO format that allows polygon-based data handling and high quality map production. To facilitate the use of the natural resources information for regional planners, a user interface was established through a PC-based version of the Microsoft-Office. Because of the emphasis placed in AEZ on data collection and database structures, the application of expert system procedures is only the first approximation of an integrated system and it requires substantial enhancing and validation.
Data input procedures are as follows:

1. Digitized and computer-assisted plotting of maps, change of scales and projections
2. Overlying of different types of maps to construct new maps. Climatic inventory maps on soil/landform/ physiographic maps to generate AEZ delineation
3. Various calculations based on statistics, summarized spatial data by AEZ
4. Automatic classification or evaluation of land resources, such as suitability assessment or productivity assessment according to specified purposes and rules
5. By linking the database of the evaluation procedures, it is possible to import data generated by map overlay into the procedures.

The classification of each mapping unit (zone) was derived from expert system decisions (Amien, 1991). The data are represented as map legend. The data for the classification can be derived from different sources. Comprehensive databases have been established at CSAR. Data bases have been arranged into program packages such as Soil Data Processing for Land Evaluation (SDPLE) after LREP II Project implementation. The data output can be used for ALES (Rossiter, 1992) and other kinds of application programs for "matching procedures", provided that the land use requirements and the land qualities have been structured. The standard procedures for input have been designed.

Analytical tools for agricultural applications

Computer technology has played a large role in agro-technology transfer and land evaluation. The role of computer technology in database management, simulation, geographic information systems, and expert systems gained a wide acceptance during the last decade (Jones *et al.*, 1986). Expert system belongs to the field of artificial intelligence. The name refers to the use of computers to solve problems in ways that would be natural to humans (Waterman, 1986). An expert system can be considered as a computing system that uses organized knowledge about a specific field to solve a problem. The system can be developed for many uses such as for diagnostics, classification, decision-making, tutoring, and retrieving information. Although traditional computer programing techniques have been used to solve these types of problems, there is a major difference. In traditional programing, the problem-solving logic and knowledge are integrated into the program code and become hidden from all but the programers. In an expert system, the knowledge remains separate and easily accessible to the users, the human experts, and the programers. This feature of expert system allows application developers to focus on knowledge presentation (Jones *et al.*, 1986).

The most innovative part of an expert system is the ease with which a variety of information can be represented and used in decision-making. This information ranges from quantitative information, including statistical relationships such as regression equations and physical and chemical laws, to less precise general rules of thumb or hunches that have been developed through hard-gained experience in the field. The first type of information is referred to as "algorithmic" and the second as "heuristic". The latter type of information can now be preserved and utilized in a more systematic way (Yost *et al.*, 1986).

Production rules or frames can represent the knowledge base of an expert system. Descriptive types of knowledge such as hierarchical classification are best represented by frames, while more "heuristic" types are better represented by rules. An expert system operates on a knowledge base of production rules, searching through the rules in an organized way to arrive at a conclusion. In a rule-based expert system, there are two primary approaches: data-driven or forward chaining and hypothesis-driven or backward chaining (Waterman, 1986).

Expert system can also be connected to databases through external programs. This is particularly useful in making decisions or recommendations when only limited data are available from the user. By having access to a database, the expert system can infer site conditions from available data by considering, for example, the geographic location.

The expert system for crop suitability analysis and agricultural system selection described here has been developed in view of the scarcity of soil and climate data in Indonesia (Amien, 1986). Although the conditions applied to reach conclusions are descriptive characteristics of soil taxonomy, the system is based on production rules rather than frames.

The expert system tries to provide recommendations on appropriate agricultural systems based on land characteristics such as slope, soil texture, acidity, and drainage. Given such factors as steep slope, very coarse soil texture or deep peat, or very low pH as limitations, the system will give recommendations on different agricultural systems including rice, annual upland crops, permanent crops, and forestry.

If the crop suitability assessment mode is selected, the system will require additional data on moisture and temperature regimes. Options will be given for a wide range of cereals, root crops, grain legumes, fiber crops, oil crops, beverage crops, vegetables, fruit crops and cash crops such as sugarcane, tobacco, rubber and pepper, based on the soil and climatic conditions of the land. If the land is only suitable for forestry, ranges of timber species and other tree species are also provided. Inadequate or excessive water regime or extreme temperatures generally limits crop suitability.

Furthermore, the system is capable of suggesting cropping patterns when provided with input data on water supply. Although not always accurate, water supply can be inferred from drainage and the number of consecutive months with rainfall above 100 mm. Recommendations on P and K fertilizer application are given based on soil clay mineralogy. Information on soil is also the basis for recommending other soil management options such as organic manuring and appropriate time and method of soil tillage. The system also provides cautions on problem soils such as potentially acid sulfate soils and soils with alkaline pH.

Often the user does not have adequate data to feed the system. In this case, the system calls upon "heuristic" information gained from experiences in the field. The system tries to infer most of the input data by asking simple questions on specific soil and land characteristics. Approximate soil acidity is inferred from native vegetation, moisture regime from soil drainage and consecutive dry months in which rainfall is less than 60 cm. Because the system is designed for tropical regions, the soil temperature regime is inferred from elevation of the land. At an elevation less than 750 m the regime is referred to as "isohyperthermic" and between 750 and 2,000 m as "isomesic". A more complicated inference is involved in determining soil clay mineralogy.

Database development and GIS

Renewable natural resources that directly affect agriculture can be roughly divided based on their relative stability. Edaphic resources consisting of terrain and soil that are unlikely to change within a lifetime, followed by aerial resources are the most stable resources. In the field of agriculture, the dominant aerial variable will be climate. Although the weather changes dynamically within a month or season, climate changes over a longer period of time, probably within 30-50 years. Biological resources that consist of plants, microbes, and animals are more dynamic. Pest populations and diseases often fluctuate seasonally, depending on the availability of food resources. The most dynamic resource is human resource that can move freely at any time (Amien, 1997).

Because of the dynamic features and stability of the resources, inventory, characterization, delineation, and analysis must be carried out in a systematic way. Natural characteristics such as climate, terrain, and soil should be put in one file or map, separated from anthropogenic characteristics that can change in a relatively short period of time. Anthropogenic-related features such as land use involve interaction of soil, plants and human or infrastructure such as roads, bridges and ports that can be built within a year. Otherwise, we have to prepare a new map probably every 2 or 5 years. With the development of computer technology such as GIS, this information can now be put into different layers that can be easily overlaid for analysis.

The ability of plant and animals to convert solar energy, water, and nutrients through photosynthesis into starch, sugar, fiber, and other components is determined by the conditions of the environment. With an agro-ecological approach, environmental conditions are delineated and analyzed to select a sustainable form of agriculture that is technically sound, economically feasible, and environmentally safe. The agro-ecological approach sets two levels of hierarchy in resources management domain, each with different inputs and outputs. The first aims at national level planning with expected outputs of production systems and crop choices. This hierarchy is related to resources allocation and should be the first activity to be carried out. The end-users of the outputs in this analysis will be policy-makers and planners.

The climate information required for this purpose includes moisture and temperature regimes along with slope, elevation, texture, acidity, and drainage of the soil. In the current method of resources survey and mapping, this information can be obtained from exploration or reconnaissance surveys. A combination of temperature and moisture regimes stratifies the environment into classes in which particular crops can be suitable.

In the second hierarchy, the agro-ecological approach is expected to provide information on crop management such as selected cultivars, cropping patterns, and time of planting as well as soil management such as fertilization and water supply or irrigation. More information on soil and climate is required to analyze the expected outputs that can be obtained from semi-detailed or detailed reconnaissance surveys as presented in Table 1. If more detailed information is available, prediction of crop yield can be expected and economic analysis for particular crops and soil management can be carried out to evaluate the suitability of the selected farming systems. This requires information on cost of production and market value of the produce based on different market scenarios.

Table 1 Expected outputs and minimum data requirement on different scales of land resources information

Expected outputs	Data input requirement		Mapping level	Scale	Minimum area delineated (ha)
	Climate	Soil			
Production systems/ Crop choices	(monthly data) moisture and temperature regimes	slope, texture, acidity, drainage, elevation	exploration/ reconnaissance	1: 1,000,000 1: 250,000	4,000 250
Crop management/ Soil management	(weekly data) rainfall, temperature, solar radiation	slope, texture, acidity, drainage, elevation, mineralogy, nutrients, organic C, CEC, aluminum, cat clay	detailed reconnaissance/ semi-detailed	1: 100,000 1: 50,000	40 10
Yield prediction	(daily data) rainfall, temperature, solar radiation	mineralogy, nutrients, organic C, CEC, aluminum, cat clay	detailed	1: 25,000 1: 10,000	2.5 0.5

Note: Economic analysis for different production systems, crop choices, and management strategies can be carried out at each Hierarchy level.

Soil resources and relevant climate data previously presented only in written hard-copy form and spatially distributed on maps are nowadays stored in digital format. A major push to the automation of data storage and handling of land resources data was given with the execution of the Land Resources Evaluation and Planning project started in 1985. Major incentives to computerization and implementation of a versatile GIS in those projects were manifold, such as the need for standardization of methodology. It also includes the magnitude and complexity of data, integration of soil and other physical environmental data in a computerized evaluation methodology and last but not least a better quantification of land resources.

The approach adopted by the AEZ/SDBM project consisted of developing a systematic descriptive legend for mapping soil and land resources to be adopted at a national level in each province, that would be sufficiently "open" and "adaptable" to be employed for land resources inventories on various scales. A detailed (computer) coding system for the description of the physical environmental data and soil parameters was developed based on experiences of previously conducted surveys and widely used standard methodologies. For the storage of collected data, several databases were developed using formats adapted to the specific requirements of the characteristics described (Hof *et al.*, 1994). Proper linkage between these databases is ensured through specially developed interfaces for making up the Soil Database Management System. Major components of this system include the site and soil horizon database and the database on soil sample analyses, both describing "point" or non-spatial information while geo-referencing or spatial distribution is achieved by a "land unit" or "mapping unit" database. The software used in the AEZ/SDBM project in which the PC-operated database programs are combined consists of standard software packages such as "Dbase".

AEZ application and future development

In more than four provinces, attempts were made to construct an agro-ecological zone map on a reconnaissance scale (1:250,000). The objectives of agro-ecological zoning in Indonesia are to describe geographically areas which fulfill the requirements of a group of commodities. The BPPT/IPPT/LPPT in many provinces conduct project activities in their provinces to promote the development of an agro-ecological zone, which will contribute to agricultural development in the area.

As the Agro-Ecological Zoning activities were initiated in the early 1990s, well-documented GIS and SIS (soil information system) on a reconnaissance scale (1:250,000) were developed for several provinces of Indonesia (Sumatra and Java). Unless the capability of each province needs to be further refined, the first phase of the program is to introduce the system. The second phase in the development of a national program to further strengthen the database, processes and skills for agro-ecological zoning and land resources evaluation and planning will be started after the completion of the AEZ format. There are many projects which are based on the achievements of former projects and aim at strengthening institutional capability in collection, collation, evaluation, presentation and management of land resources data. Analysis and application of the various resources data to the process of physical planning are major objectives. Special attention is given to these objectives by concentrating on different selected priority areas in Indonesia. Key organizations are the executing agencies of the Center for Agro-Social and Economic Research for the projects. The projects are coordinated by AARD (Agency for Agricultural Research and Development). In particular, many projects related to GIS were coordinated by BAKOSURTANAL, which will be further strengthened as the national center for geographical land resources information and will be responsible in particular for the provision of base materials such as digital topographic maps, aerial photographs and satellite imagery for the respective priority areas.

Data used for AEZ secondary data source, were supplied by BPS (National Agency for Statistics) and other agencies. The National Land Cadastral Agency (BPN) is responsible for land use and vegetation mapping while the CSAR is in charge of soil mapping. Main data users are mostly the provincial planners, including BPTP/LPTP/IPTP. They are supported by the Directorate General of Regional Planning (BANGDA) or KANWIL (Regional Office at Province level).

Drawing on the experiences gained in the AEZ project, existing database programs for storage and retrieval of "point" data were significantly enhanced, resulting in the supply of a detailed description of land and soil parameters at a semi-detailed level. Simultaneously, updating of the existing computer coding system ensured comprehensive and efficient handling of data. Actual mapping procedures were streamlined with the amended procedures described in the 1993 edition of the USDA - Soil Survey Manual. The non-spatial "point" data are basically stored in the following databases: the Site and Soil Horizon Database, the Soil Sample Analysis Database, the Mapping Unit and Climate Database (rainfall/meteorological station base). To facilitate data presentation, software had been developed for standard format output for reporting. Interface procedures and programs linking the non-spatial data with application modules such as computerized land evaluation systems are being developed.

The application of land and soil resources information for practical purposes requires the development of special interpretation procedures of relevant physical and environmental parameters for a particular use. In addition to the information gathered in a soil survey, information on the physical environment has to be considered as well as economic and social conditions. In 1983, within the framework of a FAO project, a Land Evaluation Computer System based on qualitative land evaluation procedures was developed for surveys executed at reconnaissance level. This was at the time a tremendous step forward in automation of the extensive rating tables and cumbersome matching procedures for agricultural suitability classification that had been hitherto employed. The number of parameters used was limited and determined by detailed survey results on a 1:250,000 scale. The LREP-I project adopted the existing computer land evaluation system and made it available for PCs, although proper validation of applied ratings and evaluation results were not included in the original project design. However, the change of scale to semi-detailed, the increase in the detail of the surveys, as shown in the LREP-II project context, required considerable updating and remodeling of the available software to the current conditions and parameters. For the AEZ project, an alternative based on the same FAO concept was found in the Proceedings of the Regional Workshop on Agro-Ecological Zone Methodology and Application (AEZIA/AEZ in Asia). In Indonesia, the system is a structured Expert System Shell allowing the evaluator or user to generate land use options. Furthermore, in the LREP II projects, the evaluation models use user-defined land characteristics, land qualities and land use requirements. There is, in theory, no limit to the complexity (and simplicity) of the models constructed, in terms of detail of the data or in terms of the number of variables that can be used. Consequently the system is scale-independent and sufficiently versatile to accommodate the various planning objectives and conditions in each province.

The mapping and physical planning are executed on a semi-detailed scale: 1:50,000. Compared with the reconnaissance scale employed in the AEZ project, substantial enhancement of the data structure and detail in mapping as well as higher emphasis on the evaluation procedures were required at this level. Practically, adjustment in data composition and processing at a more detailed level (farm level) is necessary.

Basic procedures adopted in land evaluation exercises based on the FAO Framework for Land Evaluation as applied in the AEZ project, consist of assessing the suitability of land for a given use, which can be achieved based on matching land use requirements determined by the planning objectives and the so-called land qualities with associated land characteristics. The latter are measurable physical environmental parameters, if only a "physical" suitability classification is executed and they form the basis for the evaluation of the "supply side" of the matching. The spatial entities to be evaluated in the case of AEZ in semi-detailed study areas, consist of mapping units which represent relatively uniform areas of land in terms of land form but compound in individual soil bodies (so-called "land unit"). The actual steps in the evaluation procedures structured by the ALES program consist of the selection and definition of appropriate Land Utilization Types and associated relevant Land Use Requirements. Subsequently a selection is made of diagnostic Land Qualities and Land Characteristics, which forms the basis of the "evaluation model". The semi-detailed scale of planning and mapping leads to a relatively low level of generalization, which results in the construction of "evaluation models" (FAO, 1991) associated with priority areas.

For the semi-detailed data, the actual "matching" or "suitability rating" in the ALES program (Rossiter, 1992) is performed primarily on non-spatial (point) data imported from the various databases such as the SSH, SSA and Soil Series database. Distribution is obtained through the "mapping unit" database depicting area arrangement and surface size of each mapping unit component. The physical evaluation results for the selected type of land use are typified by suitability ratings, by indicating major limiting factors, for each mapping unit (component). For further implementation of AEZ, the concept of Resources Management Domain can be applied as an option as in the case of large-scale evaluation in Alternative Slash and Burn Area (Nugroho *et al.*, 1998). The scaling factors for evaluation should be considered (Amien, 1997). A particular issue is the comparison of land and physical constraints on the different types of land use. Physical land evaluation does not provide an inherent common scale of measure as the severity of the physical constraints may depend on the land uses. However economic evaluation is a suitable way to compare potentials of land and land uses.

The ALES program provides also all the structures needed for this type of evaluation and classifies the evaluation units into land suitability classes corresponding to the FAO Framework for Land Evaluation. The economic evaluation, incidentally, generalizes the individual mapping unit component potentials into a single suitability class for each spatial entity or mapping unit due to the common scale.

Non-GIS evaluation system based on non-spatial data can be linked to a GIS in various ways. The general procedure involves the construction of a base map showing the evaluation (mapping/land) unit polygons each with a unique identifier. In the AEZ project, this procedure is performed using ARC/INFO facilities. The evaluation units are defined in the Expert System (Land Use) with the same identifiers and the land characteristics required by the expert model are entered into the database. Expert System (Land Use Option) performs the evaluation without reference to the location of the mapping units by only considering the in situ characteristics. The evaluation results are than exported as an overlay of GIS.

The latest version of SDPLE (Soil Data Processing for Land Evaluation) was made available by converting the data into attribute data for ArcView (ESRI). The system is a professional-level geographic research tool for micro- and personal computers and facilitates spatial analysis by the use of a large number of program modules. Combining the evaluation programs such as ALES with GIS programs such as IDRISI/ArcView generates a versatile and powerful analytical tool for validating and enhancing interactively the land evaluation models developed. Evaluation results of expert models are used to reclassify IDRISI raster images or ArcView polygon attributes representing map or evaluation units. The interface enables also to construct single-factor maps of any land characteristic and land quality for any given Land Utilization Type (LUT). All kinds of GIS operations such as reclassifying, overlaying, grouping, etc. are then available to the user. Improving the expert models for each priority area is generally achieved by using only limited data of a typical sample area. Once the model is improved and optimized to fulfill the needs of the land evaluator (planner), the data of the entire area can be evaluated. Exporting the final evaluation results as attribute tables to polygons in ARC/INFO is the next procedural step in putting together the projected GIS with required land and soil resources information for each AEZ priority area involved.

The background for promoting the area for a given LUT, is the expectation that the potential of the local land resources, which can support the development of the area for a given land use type, is high. It is necessary to determine the real potential of the area. A land evaluation procedure is a tool to figure out the land resources potential. Based on this requirement, the AEZ (semi-detailed level) can provide the appropriate data related to land evaluation, by conducting soil surveys. Furthermore, the BBPT/IPPT/LPPT and BAPPEDA (regional Planning Bureau) will supply detailed planning for implementation in the priority area of each province based on the results of land evaluation.

Conclusion

1. Indonesia is actively implementing Geographic Information Systems (GIS) technology in conjunction with Soil-Climate Database Management (SDBM) in AEZ Mapping.
2. In the execution of the AEZ project, CSAR is involved in the development of facilities for an integrated evaluation methodology for physical land resources information using relational databases and GIS within the process of physical planning at different levels from reconnaissance (scale 1:250,000) to semi-detailed (1:50,000) scale and farming level.
3. Relevant soil and physical land resources data for land evaluation purposes in various areas of some provinces over the Indonesian archipelago are systematically collected and stored in specially structured and designed databases, which are expected to be integrated.
4. The geographical information of each mapping unit is obtained from aerial photograph interpretation and secondary data such as topographic base maps, and soil surveys. The information is used for basic data for Expert System (Land Use) and Automated Land Evaluation System (ALES) as a tool for providing the basic data for land use and regional planning.
5. GIS operations and techniques are used for enhancing and updating the evaluation procedures and presentation of the results.

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