PLANNING SUSTAINABLE AGRICULTURE IN THE HUMID TROPICS OF COSTA RICA SUPPORTED BY GIS AND REMOTE SENSING

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ABSTRACT

The planning of a complex rural landscape in the Caribbean humid tropics of Costa Rica was initiated with the reconstruction of a historical land use during a 30 year period using geographic information system (GIS) and remote-sensing. The central point for long term administrative planning process of the area required identification and quantification of changed and preserved areas using change-detection analyses. I created a hierarchical GIS database of agriculture and livestock production. The database can efficiently support daily management decisions using its visual aids. The final products of the GIS analyses performed on the agriculture data are maps, animations and visualizations that increase the understanding of the complex scenario of agricultural production and sustainable management. The benefit of agricultural data gathering such as soil analysis was maximized by the analysis capabilities of the GIS system. Visual displays of soil fertility maps are examples of additional tools supporting the efficient use of resources and priority definition of agriculture practices.

Key words: GIS, Remote Sensing, Visualization, Animation, Agricultural Planning, Sustainable Development.

1. INTRODUCTION

The planning process of sustainable agriculture in the humid tropics implies the harmonic interweaving of very diverse activities such as traditional agriculture plantations, eco-tourism areas, conservation areas of the rich tropical forest remnant; commercial forest plantations, dairy facilities, livestock production, watersheds, riparian vegetation and high yield monoculture among many others. The complexity generated by all these activities usually collapse the traditional methods of planning in rural areas of tropical countries characterized frequently by a low level and availability of technological resources and accurate information. Modern sustainable agriculture implies the combination of entrepreneurial views of the agrarian processes with the principles of sustainable development in the frame of an efficient decision making process. This decision making process in sustainable agricultural production relies for its success in the knowledge of the ecological and environmental variables and in the appropriate balance of the productive inputs. Land use is the common thread that runs through some of the most vital issues facing Central America’s communities today. Concerns like economic growth, natural resources protection, and quality of life are directly affected when a poorly planned process of land use is performed.

A multiple objective planning process including the different dimensions of activities presently done in the Caribbean humid tropics of Costa Rica can be ideally done by using GIS technology supported by Remote Sensing RS data. Local decision makers are then prime candidates to become beneficiaries of information derived from RS and GIS, because the long term support that this technology offers and the critical importance of their work dealing with land use planning on a daily basis (Arnold 2000). In this way, GIS and RS technologies support the decision making process through the correct interpretation of the local association between agriculture and natural resources, providing scientific elements for addressing strategies required for planning sustainable development, supplementing empirical knowledge and administrative decisions funded in the oral tradition (Aspinall 2002, Brooner 2000). These technologies are an appropriate source to obtain critical scientific elements required to support daily planning process and to design the land use of agrarian communities. Geospatial technologies can provide the key information that allows local natural resource managers to place their case-by-case land use decisions within the broader context of the community and region to visualize alternative sustainable futures (Arnold 2000, Beltran and Belmonte2001, Williamson and Goes 2001).

1.1 Objectives

An appropriate planning process of the agrarian system should be the product of combining three main elements: 1 an appropriate understanding of the historical transformation of the land-use. 2 a reliable description of the actual
environmental variables involve in the productive system. A suitable organization tool that store and update the temporal and spatial elements of the planning processes. In this study the previous requirements are satisfied by: 1 reconstructing 30 years of land use from 1973 to 2001. 2 performing change detection analysis with the purpose of identify and quantify land use evolution and its causes. 3 generating a geographic database in which productive elements such a soil variables can be integrated to the decision making process. 4 generating visual tools such as maps an animations that make possible an easy interpretation of the agricultural complexity, increase the knowledge of the productive variables and increase the efficiency of the decision making process.

1.2 Study Area
The study examines the property of EARTH University located at 10° 11’ to 10° 15’ North latitude and 83° 40’ to 83° 55’ West longitude, in the Atlantic coastal plain of Costa Rica, approximately 70 km East of San Jose, the capital city, and 100 km West of the Caribbean shoreline. The land holdings of EARTH equal 3300 ha (approximately 7312 acres), centered within the Caribbean flat lands in a life zone of the Dry/Wet Tropical Forest. This area is a continuation of the Nicaragua basin formed by alluvial and marine deposits and limited by the Caribbean Sea and the Talamanca cordillera. It is also characterized by infrequent small hills arising less than 10 meters above the plain (EARTH 1990).

2.METHODS

2.1 Field data collection
A common constrain for the incorporation of GIS and RS technology into the planning process of rural communities in developing countries is the intrinsic cost that the data and the technology has. In order to overcome this problem, this study was centered in the acquisition of low cost data accessible to anyone and its processing through widespread computer programs. On June 2002 a field trip was made for acquisition of the data sets: maps and aerial photographs from the geographic institutes of Costa Rica. A field reconnaissance of the study area was made to obtain data for training in the classification process (Russo 2002). On May 2003 a second field trip to the study area was made with the purpose of perform a ground truthing exercise to assess the accuracy of the interpretation of the aerial photographs and to obtain detailed information concerning the lots distribution within the cropping parcels as a second level of information for the database.

2.2 Data preprocessing
Black and white aerial photographs for the study area were obtained for the years 1973, 1981, 1992, and 1998 from the National Geographic Institute of Costa Rica. The 1992 photo is the first registered using a topographic map of the study area from 1990 as source for ground control points (GCPs). A 1992 photo was used to register the other images selecting not less than twenty GCPs surrounding the study area. At least four of them were selected as close as possible to each one of the corners of the photo in order to maximize the likelihood of a good match. The images were then warped using a linear transformation, nearest neighborhood intensity interpolation and a pixel re-sampling size of 1 m (ERDAS 1995, Frazier and Page 2000). The resulting images have an approximate ground pixel size from 1.05 to 2.54 m (Table 1).

Polygons of the aerial photographs were then digitized directly onto the scanned, registered aerial photograph using the ESRI ArcView 3.2 Software, and then annotated with attribute information corresponding to the 10 land use classes: Bamboo (BB) Banana (BN) Crops (CP) Mixed vegetation (MX), Campus (CS), Floodplain (FP), Forest (FR), Grass (GR) Riparian (RP), and Road (RD). Land use maps were then prepared for each date studied (Jensen 2000, Frazier and Page 2000).

2.3 Landsat imagery acquisition and classification
A Landsat data file radiometrically and geometrically corrected was obtained from the U.S. Geological Survey (USGS) in standard National Land Archive Processing System Data Format (NDF). Subsets of the Landsat ETM+ for June 15th 2001, covering the study area were created drawing in them the boundaries of the EARTH University property as area of interest (AOI). This subset was used to perform supervised and unsupervised classification serving as auxiliary source of information starting with 15 classes, and then reduced to a final number of 10 matching the categories of the aerial photographs. A final on screen classification of the AOI was performed generating a vector file from the 2001 image being compared with the maps generated from the aerial photographs. An assessment of the accuracy of the classification was performed visiting 40 different points of the property during the ground truthing exercise in May 2003, comparing the land use observed in the ground for each polygon with that obtained from the classification, correcting also the polygons boundaries where it was required.
2.4 Change detection analysis
Contingency tables were prepared comparing data between each year analyzed. Also from the years previous to the creation of the EARTH University campus with data from years after the creation of the University, generating maps to elucidate the contrast between areas exposed to active transformation with areas remaining under the same land use. Finally with the purpose of achieving a better understanding of the data, the different interactions between the ten categories were clustered within six summary categories attending the interest of this study in the interaction between agriculture, livestock and natural forest. The clustered categories were: Lost crop, Lost forest, Stable, Transition to forest, Transition to crop, others.

2.5 Soil maps
As starting point for a planning process an intensive soil sampling was conducted for the study area during 1992. Including three fourths of the property 276 samples were processed for 10 different chemical characteristics and 5 physical variables. The results of this sampling were presented in several papers maps displaying the geographical locations of the soil samples with the found value for the chemical and physical variables analyzed. For the soil conditions of the area, intensive soil analysis were not executed in the previous years being the dataset used in this project the only reliable source of information that includes the whole area for the period previous to 1992 (Sancho et al. 1989, EARTH, 1990). This fact makes this dataset an important source of historical data and a baseline for soil studies of the area. Considering the value of this dataset, an important effort was made in incorporate the paper data into a digital format that can be used as a new layer within the GIS.

3. RESULTS

3.1 GIS database
The geographical database built in this study includes the digital files in vector and raster format of the land-use cover maps for the EARTH University property for the years 1973, 1981, 1992, 1998 and 2001 (Figure 1), joined with attribute data for each one of the areas of land-use found. Also it includes a secondary level of information concerning with the spatial distribution of the administrative sub units of the property. This database was also developed including attribute data for each particular subplot allowing the creation of individual maps for each one of the administrative units (Figure 1).

Figure 1. Land use cover for study area for 1973, 1992, and 2001

These cropping areas are divided into seven different subunits where Banana plantations neither Bamboo areas are included (Figure 2). The name for this sub unit was kept from the original spanish name used within the property. Just two of the areas account for pasture under livestock operations holding 37 sub parcels or “Lotes” the remaining five units are under cropping activities divided into 89 sub parcels. This sublevel of the database includes areal information for each one of the sub parcels that the units have, as well as attribute information mostly for the perennial crops. The assessment of the accuracy for the land use classification was 92.5% which allowed confidence in using the database created.
3.2 Land use and change analysis

Individual maps displaying the land use cover composition are showed in figure 2. Only four categories: BN, GR, FR and RP out of the ten were consistent through the 30 years considered. They account for more than 72% of the land cover of the property for the year 1992, and 82% for the year 2001 in which a total of nine categories (the highest number for a year) were presented.

![Figure 2. Agriculture parcels map (left), and subparcels example map (right).](image)

The importance of those categories are also showed in the earliest period studied, 1973, when they accounted for more than 94% of the land cover of the study area. Before and after 1992 GR was the one showing the major number of hectares changed as well as the one being majority substituted by others in the land cover of the study area. However it is the period after 1992 when it lost the most of its participation in the land cover remaining in 2001 only around 330 hectares of the previous 990 ha (Figure 3).

On the other hand CP has suffered major transformation not only increasing its area from the one held previously to 1992, but also because, after 1992 more than 77.5% had been relocated through the study area. FP was mostly relevant as a kind of cover in the period after 1992. However they were posterior replaced principally by BN and FR. Interesting is the transformation of the RP, increasing 57% of the area that previously held after 1992 besides of its contributions with others categories in the same period. The consolidation of a major road inside the property occurred after 1992, being more than 24 hectares directly under its influence. In general the property has suffered a major number of land use changes in the period posterior to 1992, when 58 changes were found, against the 30 accounted for the previous years.

![Figure 3. Distribution of the land use for EARTH Property.](image)
The maps presented in figure 4 depict compact unchanged areas before 1992 concentrated in three main sectors. After 1992 the process of land use change in the middle zone as well as in the southern region offers a view of stable land use areas more scattered and isolated.

Figure 4. Changed and unchanged landuse areas before and after 1992.

The increase of areas exposed to flooding events from 1973 through 1992 can be associated with the natural occurrence of this events located mainly in the area limited by the Parismina river. The sudden interruption of this category and its later transformation around 1992 into the categories BN, FR, and BB can be explained from a clear human intervention in a process of reclamation of this area and its later incorporation into the productive process of the property. The same active human intervention within the landscape can be associated with the evolution of the category RP.

Considering the period of almost 30 years of this study it is possible to recognize that FR replaced GR as the primary land use of the property and identify the period around 1992 as the intersecting point when the dominance was changed (Figure 3). These results are in agreement with the results of Russo and Soto 2000 for the Atlantic zone of Costa Rica where they found more than 100% of increase in the areas covered by pastures in the years previous to 1992.

Observing the high cover that the above categories present into the study area it is possible to affirm that the others categories acts as secondary covers (especially CP and BN) or even transitions within the dynamic GR to FR. Supporting this affirmation appear the land use change from the category MX to FR, placing MX as a transitory state between GR and FR categories. It is also possible to support the previous conclusion studying the areas grouped under the category Transition to Forest, which are the second more relevant categories after those considered as Stable or Unchanged. This category is the summary group for all those process of change from the natural succession of forest until long-term abandoned areas, including changing process with potential of become forest if aging and mature process allowed.

### 3.3 Soil sampling maps

As an example of the importance that the historical map information took once it was incorporated within the GIS system, this section shortly describes two examples of the kind of analysis that can be performed using the soil data. Spatial analyses using the GIS capabilities were performed studying the point pattern distribution of the sampling locations. Density analysis using the kernel function with a 25 meters cell and 250 meters ratio was performed over the 277 points locations. Areas of high point density were then compared with landuse of the property in 1992 defining how the land use categories were represented within the original sampling.

Thiessen polygons of the sampling locations were created (Figure 5). The produced file was then clipped with the shape property file seeking to limit the polygons size within the study area. Polygon areas were subject of statistical analysis obtaining central tendency measures. Maps classifying the polygons by areas were prepared following the criterion that polygons with less than 10 hectares represent better the soil conditions than those with higher values (Sancho, et al. 1989).

The final analysis consisted in the interpolation of the point data, generating surfaces that can be classified by levels of fertility (Figure 6). This paper presents the surface map for just one of the variables now available within the data set. The
visualization of the dataset allows an easy understanding of the potentialities of the soil as source of fertility. But also it serves as an indicator of the areas in which decisions should be taken. Advance analysis within the GIS system allows the interaction of this variables with other layers present within the system in a process of data interrogation.

Figure 5. a. Thiessen polygons. b. polygons grouped by their area

Figure 6. Distribution of levels of potassium and Calcium.
CONCLUSIONS AND FURTHER RESEARCH QUESTIONS

There are several examples of the potential application that the database developed in this study may have in the planning process of agriculture and livestock activities using the framework of sustainable development. The cases where a database of forest stands in the Caribbean zone is used to monitor the availability and location of seed production for further forest plantations (Castro and Rueda, 1998) and the methodologies developed and applied by Bouman and Jensen 2000 to integrate into the land-use database biophysical and socio-economical variables to address policy in applicable sustainability issues as: technological change, biocide limitation and soil nutrition depletion among others, are some of the next-step-uses for databases as the one generated here.

One of the most interesting and immediate applications, can be the integration of the GIS database within the administrative process of the cropping areas including banana, with the purpose to enhance the decision making process. With this idea, yield maps can be generated from the different subplots with the purpose of identify areas that have relative low production compared with the potential of the plantation. This information suggests a decision support system for complex areas where process of rotation, association and substitution can replace an intense monoculture system (Stoorvogel et al. 2000).

In this way, the soil sampling analysis is a clear example of the importance that the GIS dataset has as analytical tool. In large areas the cost benefit of a given practice such as fertilization or irrigation can be assessed before hand using the soil variables contained within the dataset. GIS becomes not just the repository for data but also a right hand tool to evaluate critical decisions in an environmental and economical frame.

The visual capabilities of the GIS data set allows the creation of maps, animations and models that may increase the speed in which complex information is transmitted to the final users. This is an important capability that produces priceless benefits in the agriculture activity in which low educative levels are frequently found among the decision makers. Also the database developed through this study evidence the important support in the process of identification and sub-classification of the different elements of the forest cover. This particular land use can be further implemented as a second level within the dataset in a similar way that the one created for the cropping and pastures units

REFERENCES


AUTHOR'S BIOGRAPHY

Mario Giraldo a Colombian national is currently enrolled as PhD student in the Geography Department at University of Georgia USA. He has a MSc from the same department in 2003 and a BSc from a state Colombia University in 1996. His areas of interest include the applications of GIS modeling and remote sensing to study: rural landscape, water, mountain geography, food and coffee. As an agriculture engineer from Colombia, he worked for the National Coffee Growers Federation planning sustainable coffee production in the Andes of Colombia. His earliest years as researcher were dedicated to the study of the biodiversity within coffee plantations at the National Coffee Research Center CENICAFFE and to teaching agro ecology in various State Universities. His publications include peer review papers in the Journal of the Plant Pathology Association of Colombia and in the Journal Cenicafe. He has done several presentations before national and international annual meetings such as: ASCOLFI, Cenicafe, AAG, and ISRSE. Current projects includes: A change detection analysis from 1992 to 2001 for the Coastal counties of Georgia US, a Web base animation and cartographic visualization of Land use maps, Mountain landscape fragmentation and rural isolation in the mountains of Colombia and GIS modeling and 3D visualization of the hydrological cycle.