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Landscape change by embankment of the flooded savannah *Llanos del Orinoco*: a land unit approach

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Abstract

This work presents an analysis and description of the landscape changes derived from the construction of dikes to control inundation in the flooded savannah of the *Llanos del Orinoco* in Venezuela. Elaboration of the landscape ecological maps (LEMs) was based on a land unit approach. This allowed the land (ecological) units to be defined and described as ecosystems by linking the main ecological processes associated with the savannah ecosystems to the remotely sensed features. Based on this approach, two LEMs were produced from two different spatial data sources: aerial photographs for the 1960 map and Landsat TM for the 1988 map. These LEMs contain the same land units as the ecological ecosystems defined by Sarmiento (1983), where ecological processes are related to water dynamics. An important change process occurred during the period between 1960 and 1988, with dike construction producing a large impact on water management. The dikes and the water management changed the size and distribution of the main land units (ecosystems). These changes are mainly represented by the replacement of the hyper-seasonal savannah unit, which in 1960 occupied more than 45% of the area, by semi-seasonal savannah units, representing more than 50% of the total area in 1988. Almost all the changes observed in the LEM are derived from dike construction. The accumulation of water upstream from the dikes and the drainage pattern downstream determine to a large extent the distribution of the ecological classes in the 1988 LEM. The changes derived from water management not only produce economic benefits, with an increment in secondary production, but also lead to changes (increment/decrement) in the number and abundance of animal habitats, which could affect habitat conservation, and modify many ecological processes as well as the stability of the natural ecosystem.

1. Introduction

Important ecological processes such as plant succession, biodiversity, foraging patterns, predator-prey interactions, dispersal, nutrient dynamics, and the spread of disturbance all have remarkable spatial components, and the relationships between spatial patterns and many ecological processes can be analysed throughout the developments in landscape ecology (Turner and Gardner, 1990). Perception of the landscape can be considered from many points of view, depending on the observation scale as in the Australian 'land system concept' or with emphasis on the vertical (topological) or horizontal (chorological) structure and relations of the landscape (Zonneveld, 1989, 1995, 1998). According to the chorological view, the landscape can be defined as a heterogeneous land area composed of a cluster of interacting ecosystems that are considered as the landscape elements. The relationships between the structure, function and change of these elements are examined (Turner and Gardner, 1990; Forman and Godron, 1986). On the other hand, to understand the ecological processes of the flooded savannah ecosystems, it is necessary to know, and interpret the relationships between structure, function and change within the landscape into the spatial context and dynamics. For this task, a chorological view of the flooded savannah is used, based on the concept of landscape as ecosystem (Zonneveld, 1989, 1995, 1998). The survey and characterisation of the landscape into the different ecosystems of the flooded savannah area units, defined according to the ecological processes, are therefore fundamental to understanding the complexity of the whole system.

In order to analyse the relationships between the spatial patterns and dynamics of the landscape and the ecological processes of the ecosystem, we developed a method to define and recognise the ecological units or land units as ecosystem types, being defined according to the function and vertical structure of each one. If we can identify the ecosystem through a combination of spatial features related to the function, structure and ecological processes of the ecosystem, we can then create an ecological map as a basis from which to embark on an analysis of the landscape.

This study includes two types of relative concept: (1) the basic theory about the ecosystem and all its inherent processes, and (2) the spatial dimension of the ecosystem as land unit. The basic idea of this work is to link, by means of remote sensing analysis, the spatial dimension of the landscape element with the ecosystem processes derived from the vertical structure.

The *Llanos del Orinoco* can be divided according to the age of parent materials, landforms and soil into four principal sub-regions: the piedmont, the high plains, the alluvial overflow plains and the aeolian plains (Sarmiento, 1983; MARNR, 1985; Chacón-Moreno, 1991). The sub-region of alluvial overflow plains or flooded savannahs occupies a vast depression in the central part of the Llanos del Orinoco. The geomorphological dynamics are characterised by many rivers, which transport the Andean sediments, overflow and change their courses during the rainy months. Therefore, the dynamic system effects changes to the geomorphology. The pattern of relief that results from these dynamics is characterised by the presence of a topographic catena, with natural levees or *bancos*, intermediate areas called *bajíos*, and low areas or swamps called *esteros*. The difference in height between *bancos* and *esteros* is approximately 3 meters (Sarmiento *et al*, 1971b; Sarmiento, 1983), although it can be less than 1 meter.

It is interesting to note that the study area was submitted to a management process that produced a landscape change. Consequently, many of the original ecosystems have changed in size, altering the landscape matrix. However, the management process used was mainly geared to increasing one of the natural conditions of the area, *ie*, the *estero* ecosystem, in order to produce large quantities of forage for cattle raising. The increment in the *esteros* has therefore led to a reduction in other areas such as the *bancos* and *bajíos*.

The objectives of this paper were to produce:

- a landscape ecological map (LEM) of the flooded savannah area at regional level, using remote sensing techniques to link data on the main functional ecosystem features with the spatial dimension
- a LEM of the area before the landscape transformation, in order to study the process of change.

The specific tasks or research activities were to:

- define landscape ecological units, based on the ecosystem types of the area and the definition of savannah ecosystems described by Sarmiento (1983, 1990)
- select features linking the ecological processes with structure, using remote sensing data.

The main ecosystem types of the study area have different species compositions, and we therefore expected these differences to be reflected in the remote sensing data. Then a principal research question was: To what extent is the functioning classification used for ecosystem types related to the spectral classification derived from remote sensing?

- elaborate the current LEM through Landsat TM image classification, using the ecosystem definition of flooded savannahs, and combine the spectral result from the classification with previous surveys
- elaborate a LEM of the area prior to management change, through aerial photo interpretation using the ecosystem definition of flooded savannahs
- analyse the landscape ecological changes derived from the land use change.

2. Flooded savannah and land use change

Areas of flooded savannah in Venezuela have been used for extensive grazing of cattle. These areas have a high biomass production (550 to 800 g/m^2) during the rainy period (González Jiménez, cited by Sarmiento, 1983) but production decreases notably during the dry period. Then, the carrying capacity of the flooded savannah is very low (10 to 15 ha/cattle and 4 ha/cattle in the Mantecal area) (Mata *et al*, 1996). During the 1960s, most of the land was composed of *hatos* (properties of more than 10,000 ha) and the government initiated a political project to promote regional development, with the introduction and intensification of technology in agricultural activities focused on raising cattle (Sarmiento and Monasterio, 1975). In 1971, the project *Módulos de Apure* started in the Mantecal area. This project involved the construction of dikes to control superficial drainage water through gates. The general idea was to store water for producing grass biomass during the dry period and thus increase the carrying capacity of the area (Sarmiento and Monasterio, 1975; López-Hernández and Ojeda, 1996). One of the principal changes was related to the composition of plant communities and the replacement of natural species in the hyper-seasonal savannah by species adapted to wet environments and with greater palatability, such as *Leersia hexandra* and *Hymenachne amplexicaulis* (López-Hernández and Ojeda, 1996). The *Módulos* have produced an increment in the carrying capacity (reaching 2 ha/cattle) of the savannah, with well management to control the level of water (López-Hernández and Ojeda, 1996).

Implementation of the project *Módulos de Apure* favoured an increase in cattle production, aquatic fauna and terrestrial fauna in the wetland region (Tejos *et al*, 1990; Pinowski and Morales, 1981, cited by Pérez and Ojasti, 1996). However, the prolonged retention of water has led to the mosaic of gallery forest, seasonal savannah and hyper-seasonal savannah being replaced by large areas of semi-seasonal savannah, with consequent habitat loss in the ecotones (Ojasti, 1978, cited by Pérez and Ojasti, 1996).

3. Ecological map and ecological unit (land unit) concept

To describe ecological processes in the spatial context, the map unit has to represent the structure and function of the landscape element. Therefore, the landscape can be interpreted as being composed of landscape elements (Forman and Godron, 1986). These landscape elements allow the description of not only the structure but also the associated ecological processes. In terms of landscape ecology, the land unit represents the landscape element where the ecological processes can be spatially analysed (Zonneveld, 1989, 1995, 1998; Forman and Godron, 1986; Turner and Gardner, 1990; Forman, 1995).

The land unit as an ecological spatial unit includes (in the legend) the vertical structure of the ecosystem and the main features related to the ecological processes, such as the internal flux among the components, response to environmental conditions, and balance of energy and mass (Zonneveld, 1995). The ecosystem structure can be linked to the ecological processes. For example, canopy structure determines the distribution of light and water from the top of the canopy to the soil; soil texture can contribute to determining water storage in the soil; and topographic position can also contribute to establishing the water balance and species.

In the study area, the main environmental factor determining species distribution is hydric dynamics, which in turn is controlled by other environmental factors such as geomorphology, soil type, seasonality and land management. The ecosystems derived from these environmental conditions respond by showing different ecological processes. Sarmiento (1983, 1990) defined these ecosystems and described the main associated ecological processes. The spatial definition of the land unit can be expressed as the link and combination of the ecological processes with the ecosystem structure and environmental features.

A landscape ecological map (LEM) can be defined as the graphical representation of the pattern distribution of land units. However, these land units can be expressed in two different ways. First, the LEM can be defined as the sum of the layer forming the ecosystem's structure, *ie*, the overlay of soil, vegetation, animal, water, geology, geomorphology and other spatial information (Figure 1a). Attribute information about the ecological processes, together with non-spatial information, can complement this spatial information.

In the second definition of the LEM, land units are described as the integration of the structure and the ecological processes within and between the land units. In this approach, the land unit can be delineated based either on attributes related to one or more components of the ecosystem structure, or on environmental features that determine ecological processes (Figure 1b). In this integrated approach, complementary information can be used.

In the integrated approach, some of the ecological processes related to the ecosystem can be mapped through correlating these processes with the spectral response of remotely sensed information. With this approach too, we can analyse the ecological processes related to dynamics (temporal dimension) such as phenology, growth and production, the movement of species, and ecological changes. In this work, the integrated approach was used to generate ecological maps based on the previous definitions of ecosystem, ecological processes and environmental variables.

4. Methodology

4.1. Study area

The study area, a large part of the flooded savannah in Venezuela, is located between two large rivers, the Apure and the Arauca, and covers about 16,000 km^2 (see Figure 2). The drainage pattern of the area is formed by several periodic rivers that flow in the direction south-west to north-east, parallel to the Apure and Arauca rivers. The vegetation is herbaceous cover with narrow corridors of gallery forest along the rivers and watercourses.

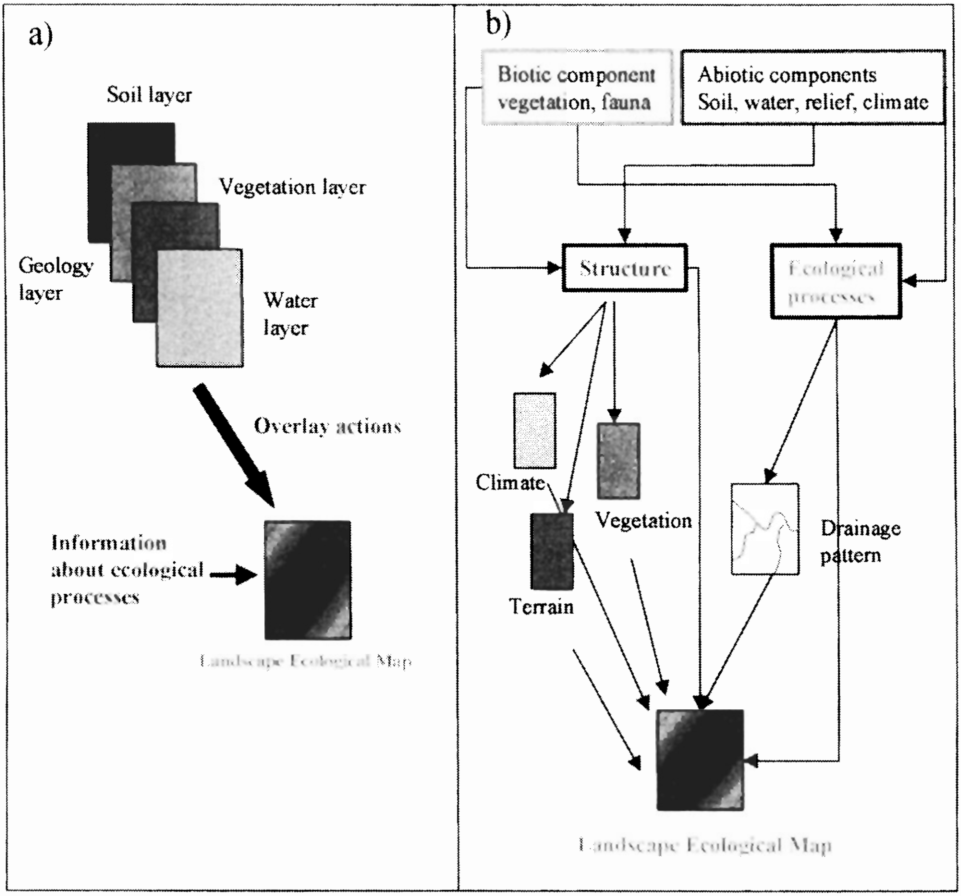


Figure 1 Representative schemes of two different approaches to define and elaborate landscape ecological maps (LEMs): (A) overlay procedure to obtain ecological map from thematical maps; (B) integrated procedure relating ecological processes to landscape structure.

The geomorphological units derived from the river dynamics (*bancos*, *bajíos* and *esteros*) present different soil features. The *bancos* are the natural levees along the borders of the streams and main rivers, with sandy soils predominant from alluvial deposits. The *bajíos* are the larger areas, where silty alluvium predominates. The *esteros* correspond to the lowest part of the catena, with a predominance of clay texture. These geomorphological features produce a differentiation in the distribution and accumulation of water in the soil during the year. This differentiation coupled with water dynamics leads to the distribution of species.

Four principal ecosystems are present in the flooded savannahs:

1. gallery forest, which occurs on the banks and forms narrow strips along the rivers;
2. seasonal savannah, which also occurs on the banks;
3. hyper-seasonal savannah (the most widespread ecosystem in this low region), which occupies the wide silty extensions between successive banks; and
4. semi-seasonal savannah, which occupies the lowest lands, which remain under water (1 m or more) during the rainy season and slowly dry out through the dry season.

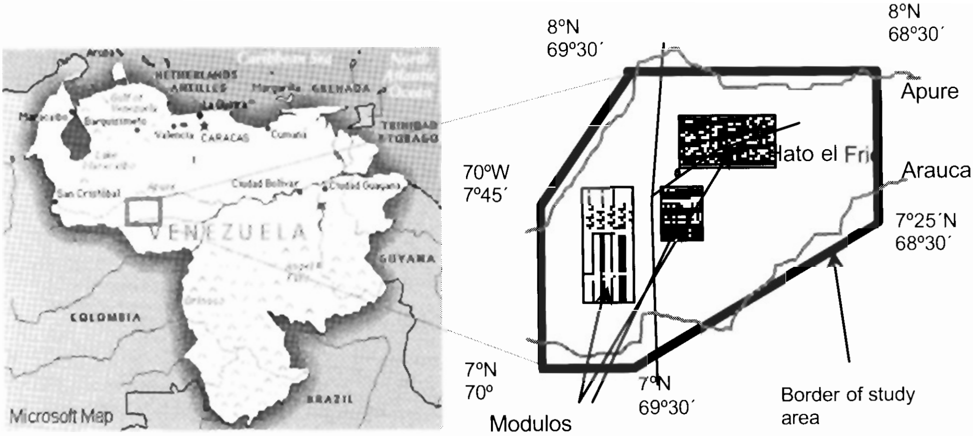


Figure 2 Geographical ocation of the flooded savannah area in Venezuela (the three rectangles are the main management areas for controlling water).

4.2. Data sources

Two different data sources were used to elaborate the ecological maps. For the current LEM, the primary data source was a Landsat TM image of January 1988 (middle of dry period; spatial resolution 30 x 30 m; covering a width of 185 km), which covered the whole study area in the Llanos del Orinoco. Topographic maps were used to geo-reference the image and complement the spatial information. To produce the LEM of the area before dike construction, 268 aerial photographs (January 1960; scale 1:60,000) were interpreted.

Descriptions of the vegetation communities and other ecosystem features were obtained from the species and environment parameters sampled in 58 sites in Hato El Frío (Chacón-Moreno *et al,* in preparation) and earlier species lists and surveys (Sarmiento, 1983; Sarmiento *et al,* 1971a, 1971b; Silva *et al*, 1971; Monasterio *et al*, 1971; Ramia, 1959; Castroviejo and López, 1985).

4.3. Data processing

All the image processing, digitising and spatial analysis were carried out using a geographical information system (ILWIS: Integrated Land and Water Information System). The Landsat TM image did not present any radiometric problems, and the geo-referencing was based on topographic maps of the area. The image was processed to obtain a false-colour composite (FCC), following the standard procedure. Based on the FCC and the definition and analysis of land units, a supervised image classification was made. This was filtered to eliminate the smallest pixel clusters and noise. After concluding the image processing, resampling was carried out to correct the geographical distortion of the rastered objects. All these procedures were based on the methods and techniques of image processing and GIS described in Shrestha (1991), Bronsveld and Shrestha (1993), Sabins (1987), Meijerink *et al* (1994), Aronoff (1993), Valenzuela (1992) and ILWIS (1997).

As for the aerial photographs, these were interpreted following the standard procedure that is very well described and summarised by Zonneveld in Küchler and Zonneveld (1988) and Zonneveld (1995). The interpretation of the 268 photographs produced a map, which was digitised using ILWIS. The interpretation was based on the integrated approach, combining the features of terrain, vegetation and water dynamics from the land unit definition.

Although the origins and types of remote sensing information were very different, definition of the land units followed the same criteria, and in some aspects the results can be compared. However, the information about the size and number of units is not comparable. Using GIS, the spatial information was analysed to obtain the final LEMs, and the spatial information about land unit pattern distribution (size, area, number) was also analysed.

The accuracy of the maps was checked by field sampling in Hato El Frío. For the current map, areas with dikes were used to confirm the ecological units. The accuracy of the 1960 LEM was checked against field areas that had not been submitted to management. Some marginal areas in the north of the 1960 LEM could not be included or compared with the LEM derived from the Landsat TM image because some aerial photographs were missing.

5. Results and discussion

5.1. Land unit and ecosystem link

Using the integrated approach, structure and dynamics were combined with remote sensing data in order to produce maps. Although the land units defined for the two LEMs were the same, the way of delineating the units was different for each map. How to link ecosystem structure and ecological processes with remote sensing patterns from two different sources? First of all, the structure and ecological processes of each ecosystem had to be defined and described. Then, the structure parameters or ecological conditions that could be described through remote sensing parameters were selected. Finally, this key was used to interpret the photographs or process the image.

Sarmiento (1983, 1990) described the components and main ecological processes of the three savannah ecosystems and the gallery forest. Table 1 presents the main features of each ecosystem and the links with the remote sensing data. Using the parameters described in this table and the description of the ecological processes, the land units could be defined and delineated to elaborate the LEMs.

The criteria for defining land units were based on particular aspects of the features presented in Table 1. Some structure features were clearly associated with remote sensing features, but other criteria had to be used to define land units presenting similar structure features that could not be differentiated in the remote sensing data. The different criteria associated with the environmental conditions or particular ecological processes were then used to complement the delineation.

Vegetation as a structure criterion allows the differentiation between forest and herb cover; then the gallery forest can be defined from the texture and red colour in the aerial photographs and satellite images, respectively. Now the herbaceous vegetation communities (savannah ecosystems) can be differentiated based on environmental features such as the topographic position exposed in the aerial photographs. Through this characteristic, we can define levees (*bancos*), the intermediate position (*bajíos*) and the lowest position (*esteros*). However, the criteria are different for image data, and the environmental parameters cannot be used. For image data, the ecological conditions relate to the phenological state, and production during the dry period can be used to differentiate the ecosystems. As during this period the seasonal savannah does not present green vegetation and part of the soil is not covered by vegetation, the areas reflect the dry soil condition (cyan colour).

Table 1 Main features of the structure, ecological processes and environmental parameters associated with the four principal ecosystems in the flooded savannah area in Venezuela. Also key to main characteristics in the remote sensing data (aerial photographs and satellite image) associated with each ecosystem and such ecological processes and structure as presented

Ecosystem	Main structural components	Main ecological processes	Environmental parameters	Associated remote sensing features
Gallery forest	Tree vegetation, high tree density	Semi-seasonal and evergreen phenological state; water dependency; large radical system	River levee, watercourse, sandy soils	Photos: coarse texture, dark tones, high topographic position Image: FCC red colour
Seasonal savannah (*banco*)	Herbs (grasses and non-grasses) and shrubs	Seasonal phenological state associated with seasonal climate; one stress period with soil water deficit (3 months); fire presence; little vegetation cover in the dry period	River levee and higher topographic areas; no flooded areas; sandy soils	Photos: fine-smooth texture, light tones, higher position Image: brown and white areas during dry period
Hyper-seasonal savannah (*bajío*)	Herbs (grasses and non-grasses) and few shrubs; earthworm mounds; large areas between watercourses	Marked seasonal phenology; two stress periods: one for soil water deficit and one for soil water excess; fire presence	Approximately four flooded months; intermediate topographic position; silty soils	Photos: light grey tones, fine texture, intermediate position, large and homogeneous areas Image: greenish-brown colour in dry period
Semi-seasonal savannah (*estero*)	Grasses and sedge cover, no shrubs; little species diversity; homogeneous areas; smooth relief; lowest topographic position	No soil water deficit during the year; flooded stress during four months; physiological responses to the flooding; high productivity for grazing	Lowest topographic position; soil water availability during the dry seasonal period; all areas flooded during rainy period; presence of flooding gradient; clay soils	Photos: medium grey tones, smooth texture, some areas with heterogeneous drainage pattern; some areas with mirror reflection; can differentiate two or three types Image: red-orange light colour (non-flooding areas in dry period); red-brown dark colour (flooding areas in dry period)

Besides, the hyper-seasonal savannah has a certain quantity of water in the soil during this period and the vegetation is not completely dry, so the colour is different from that of the seasonal or semi-seasonal ecosystem.

As regards the semi-seasonal savannah, soil water availability during the dry period enables the vegetation to grow at a high rate, including the (C4) vegetation type with a high metabolic rate, which can be differentiated in the image by the red-orange colour. However, the areas of the semi-seasonal ecosystem that remain inundated can be differentiated by the dark colour or mirror reflection in the water. All these features relating to vegetation phenology and production are ecological processes. See figures 3 and 4.

5.2 Land unit description

The land units presented in the legend with figures 3 and 4 can be described as follows:

Gallery forest

This is an ecosystem dominated by evergreen and semi-deciduous trees, with a high diversity. The area is submitted to periodic inundation and a slight gradient from the bottom of the watercourse to the high position of the bank can be observed. The main species relating to this ecosystem are: *Duguetia riberensis, Nectandra pichurini, Chomelia polyantha, Copaifera officinalis* and *Covvoloba obtusifolia* (Castroviejo and López, 1985; Sarmiento *et al*. 1971).

Seasonal savannah (banco)

This ecosystem is located on the higher topographic position, closer to the watercourses. The vegetation is herbaceous, with some shrubs and a few trees. It contains the highest number of species in relation to the other herbaceous ecosystems of the area. Referring to the vegetation data described in Chacón-Moreno (in preparation), the number of species over 20 sites was 141, the most common species being *Panicum laxum, Paspalum chaffanjonii* and *Axonopus purpusii*.

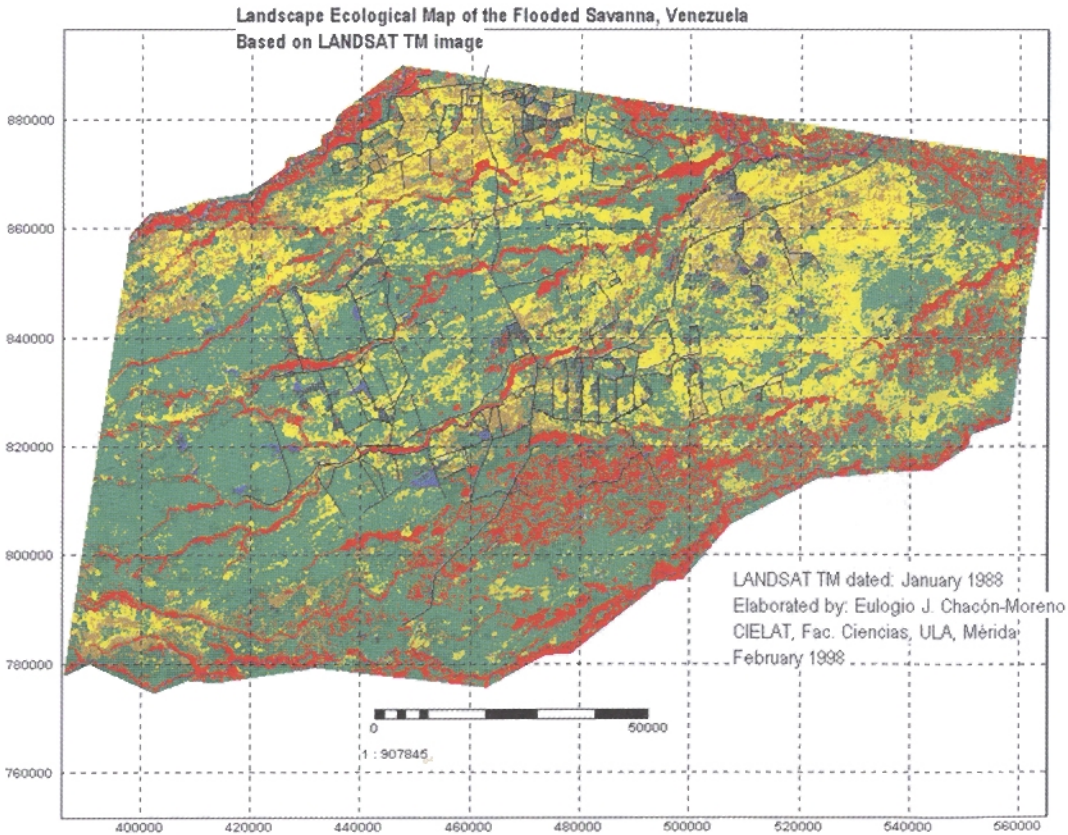
Hyper-seasonal savannah (bajío)

This ecosystem is located on the intermediate topographic position and occupies a large expanse under natural conditions. After dike construction, however, the areas of hyper-seasonal savannah were replaced by semi-seasonal savannahs, which still have water available in the soil during the dry period. The vegetation is herbaceous, with a few low shrubs but almost no trees. The number of species is quite high, but not higher than found in the seasonal ecosystem. According to the vegetation data (Chacón-Moreno, in preparation) for the study area of El Frío, the number of species collected for this ecosystem was 118 over 18 sites, the species most frequently encountered being: *Panicum laxum, Leersia hexandra, Ipomoea fistulosa, Mimosa pigra, Hydrolea spinosa* and *Hyptis lappacea*. Only the first two species are the most dominant grasses.

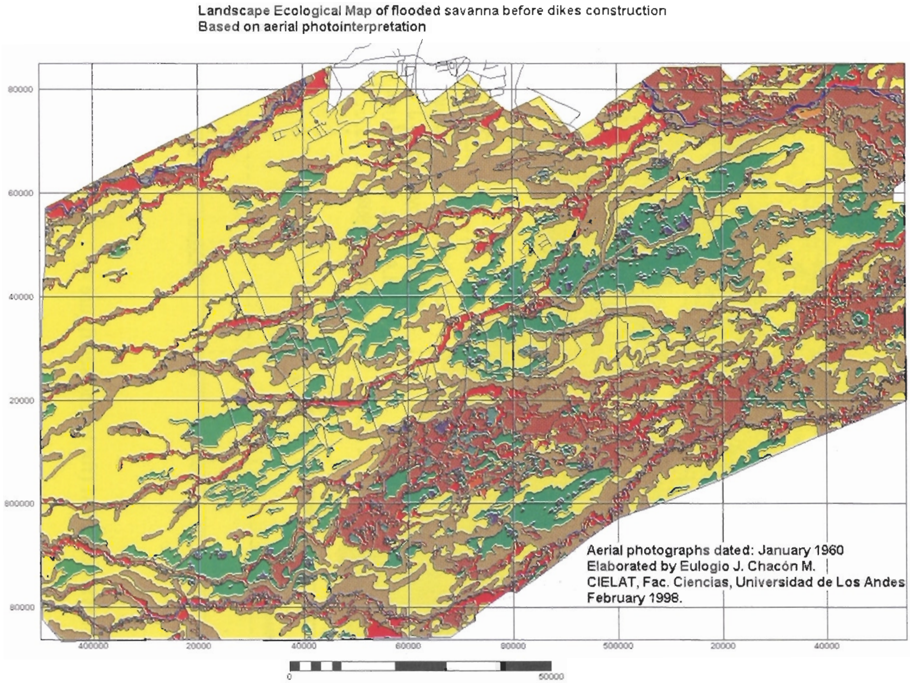
Semi-seasonal savannahs (esteros)

These ecosystems are located in the lowest topographic position, where the soil has bad drainage and the texture is mainly clay. Availability/quantity of water in the soil during the dry period determines three different subtypes:

1. *Semi-seasonal savannah non-saturated* (contains water during the dry period but is not the saturated type of savannah). The vegetation cover of this subtype is dominated by grasses



E. Chacon Moreno Figure 3 Current flooded savannah LEM (for legend see figure 4)



For these ecological maps, a simple legend is presented with colour code and names of units.

- Gallery forest
- Hyper-seasonal savannah = *bajío*
- Seasonal savannah = *banco*
- Semi-seasonal savannah flooded
- Semi-seasonal savannah water-saturated
- Semi-seasonal savannah non-saturated

} = ***estero*** (the last three units)

E. Chacon Moreno : Figure 4 Flooded savannah LEM of 1960 (before dike construction) and sedges. *Leersia hexandra, Ipomoea fistulosa* and *Hymenachne amplexicaulis* are the main dominant species.

2. *Semi-seasonal savannah water-saturated* (soil saturated with water but not flooded). This subtype is dominated by the same species as found in (1), but in different proportions. Here *Hymenachne amplexicaulis* accounts for a greater proportion of cover than *Leersia hexandra*.
3. *Semi-seasonal savannah flooded.* In this third subtype, the water-level is (a few centimetres) above the soil surface during the dry period, and the dominant species are sedges and aquatic plants.

5.3. Landscape change analysis

The information derived from the 1960 and 1988 LEMs of the flooded savannah was analysed to compare the spatial parameters relating to the number of polygons per land unit in each map, the total area per map, and the rate of change for each ecological unit between 1960 and 1988.

As the original data sources for the two ecological maps were different, only certain aspects were comparable. For example, the total areas represented by each ecological class in both maps could be compared, whereas the numbers of polygons or patches per unit could not. Photo interpretation for the 1960 LEM generated continuous and homogeneous areas with few patches, and the scale or spatial resolution (1:60,000) gave an interpretation resolution of around 36 ha. However, the Landsat image gave a spatial resolution of approximately 0.09 ha, with the landscape derived from image processing thus showing smaller patches or polygons.

Another important observation is both maps do not exactly cover the same area, the differences occurring especially at the borders of the study area. Some aerial photographs were missing for the northern part of the 1960 LEM, while because of the image orientation some areas on the northern side (east corner) and western side (north corner) of the 1988 LEM are missing. Therefore, the total area observed for the 1960 LEM was 15,369.53 km^2 and the area for the 1988 LEM was 14,530.17 km^2 (difference of about 830 km^2), but the total area common to both maps is only 13,682.29 km^2 .

To carry out the change analysis, we used the total area common to both maps as the reference total area. In Figure 5, the total area and the area percentage per ecological class are presented for the two maps. Figure 5a shows the distribution of areas per class for the 1960 LEM. Almost half the total area is covered by the hyper-seasonal savannah class (*ie*, the characteristic units for flooded savannah), because it is related to the two seasonal climatic periods. Seasonal savannah is the second class in respect to cover percentage, with more than 26%; gallery forest and semi-seasonal savannah non-saturated cover around 12% each. We can see that the class with water availability during the year and no stress caused by hydric deficit represents only a few areas, and the other classes of semi-seasonal savannah have a cover percentage of less than 1%.

Figure 5b shows the percentage cover distribution of ecological classes in the 1988 LEM. The changes in cover distribution have been considerable as a consequence of dike construction, which led to a greater accumulation of water during the dry period and the continuous availability of water in some areas throughout the year. The majority of the area is covered by semi-seasonal savannah non-saturated, representing more than 40%. The other semi-seasonal savannah classes presented in 1960 now have less than 1% cover, with 12% and 2% for the water-saturated and flooded semi-seasonal classes, respectively. On the other hand, the area of the main class in 1960, the hyper-seasonal savannah, has decreased from almost half the total area to 21.17%. The proportion of seasonal savannah has also decreased, although gallery forest accounts for around the same as in 1960. An important observation is that the semi-seasonal savannah classes in 1988 represent more than 54% of the total area, which is the result of the water accumulation attributable to the dikes.

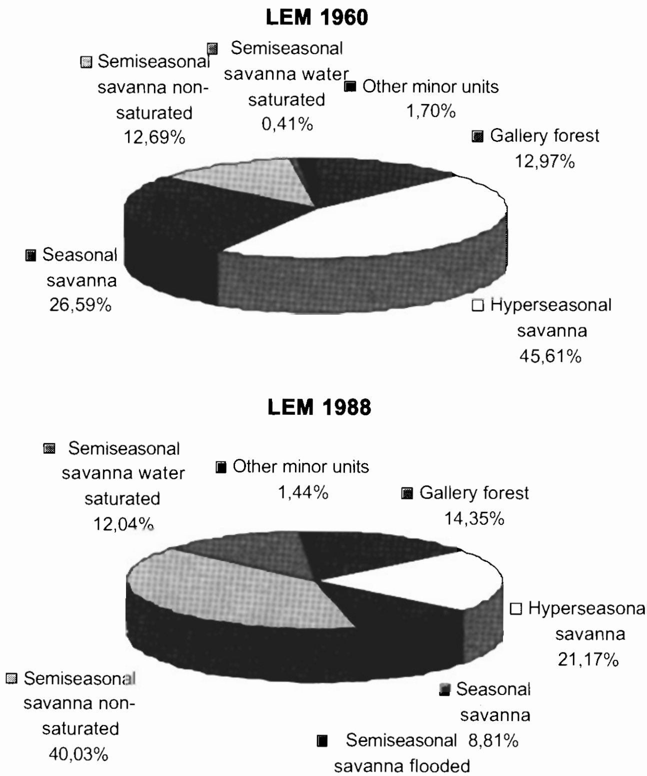


Figure 5 Percentage of area per ecological classes of the Landscape Ecological Maps of the Flooded Savannah in 1960 (a) and 1988 (b).

In the 1960 LEM, the four main land units (gallery forest, hyper-seasonal savannah, seasonal savannah and semi-seasonal savannah non-saturated) represent more than 97% of the total area. To understand the process of change between 1960 and 1988, a diagram is presented for each of the ecological classes mentioned, showing the percentage and area of change. In each diagram, arrows indicate the direction of change. The full arrow shows the main change.

The first diagram (Figure 6) shows the percentage and area of change for the hyper-seasonal savannah class in relation to the other main classes in the 1988 LEM. The hyper-seasonal savannah class is the land unit covering an area of more than 45% in the 1960 LEM. The values and percentages are related to the total area of the land unit in 1960. The main change is to non-saturated semi-seasonal savannah, which is the next land unit in a soil wetness gradient. The increase in water-level by repressing and managing water during the dry season accounts for the change in the soil wetness conditions; therefore, the plant communities have changed and the hyper-seasonal savannah ecosystem has turned into semi-seasonal savannah.

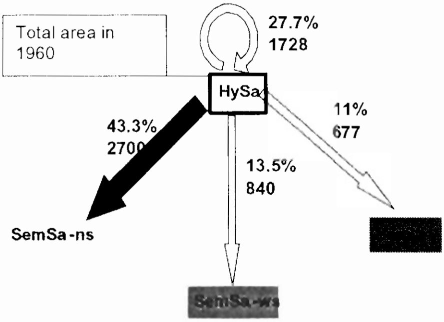


Figure 6

Change of hyper-seasonal class in 1960 LEM to other classes in 1988 LEM (HySa: hyper-seasonal savannah; SemSa-ns: semi-seasonal savannah non-saturated; SemSa-ws: semi-seasonal savannah water-saturated; SeaSa: seasonal savannah).

For the same reason, the areas closer to the bottom have turned from hyper-seasonal savannah into water-saturated semi-seasonal savannah. In Figure 6, also the change from hyper-seasonal to seasonal savannah can be observed. We may think that, due to the accumulation of water, change to this kind of ecosystem is impossible. However, management using dikes to control the water produces an inverse effect in the areas downstream of the dike. This is because when the water is repressed, it produces a drainage area on the other side of the dike, making areas drier. The soil wetness conditions change to non-flooded areas at any period of the year; therefore the soil conditions allow and create the establishment of the seasonal savannah ecosystem.

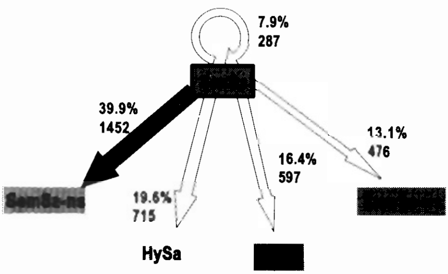


Figure 7

Change of seasonal savannah class in 1960 LEM to other classes in 1988 LEM (HySa: hyper-seasonal savannah; SemSa-ns: semi-seasonal savannah non-saturated; SemSa-ws: semi-seasonal savannah water-saturated; SeaSa: seasonal savannah; GaFo: gallery forest).

Figure 7 shows the diagram of landscape ecological change from seasonal savannah in the 1960 LEM to other ecological classes in the 1988 LEM. In this figure, seasonal savannah changes mainly to non-saturated semi-seasonal savannah (as observed in Figure 6). However, the percentage of change is not larger than 40%. The explanation for the change is similar to that described for the hyper-seasonal savannah. Another important change is from seasonal to hyper-seasonal savannah. This can be observed in lower areas where water conditions change from water availability during the wet period into flood conditions, hence establishing the hyper-seasonal savannah ecosystem. Important is the change from seasonal savannah to new areas under the gallery forest ecosystem (more than 16% of the seasonal savannah transformed into forest). This type of ecosystem probably originated in areas with good drainage where now, with a greater quantity of water, the establishment of forest becomes possible. The dike construction produced conditions of water availability throughout the year but without flooding, and the decrease in water and consequent dry conditions downstream also has created favourable environmental conditions for forest (Van Os, 2000). The figure also shows that an important percentage of seasonal savannah has changed to water-saturated semi-seasonal savannah. This could be because these higher areas (*bancos*) are closer to the dike upstream, where water accumulation is high and thus larger areas could be covered by water.

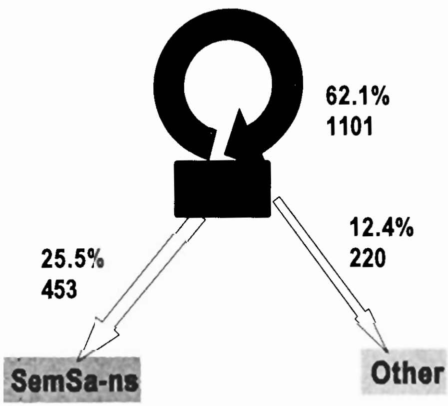


Figure 8

Change of gallery forest class in 1960 LEM to other classes in 1988 LEM (SemSa-ns: semi-seasonal savannah non-saturated; GaFo: gallery forest).

Figure 8 shows the transformation of the gallery forest ecological class into other classes in the 1988 LEM. This figure illustrates a different way of change (*cf* Figure 7). Gallery forest does not change to other ecological classes; it remains largely unchanged. Dike construction does not affect forest conditions there. However, 25.5% of the preliminary gallery forest in 1960 changed to non-flooded semi-seasonal savannah, and another 12.4% of the gallery forest changed to other classes. It is possible that the areas of gallery forest closer to the dikes and in specific zones upstream were inundated because of the dike construction, and that this made the forest vegetation disappear from these areas. It is the inverse of the phenomenon that occurred downstream, where the hydric conditions contributed to the establishment of forest. On the other hand, the estimation/definition of gallery forests differs between the two maps, because in the 1988 LEM the gallery forest class corresponds to a unique type of class, whereas the gallery forest ecological unit in the 1960 LEM is the combination of three different classes: gallery forest, gallery forest matrix with savannah areas, and gallery forest matrix with agricultural areas. To estimate the area of gallery forest for the 1960 LEM, we used a discrimination of 100% gallery forest and 66% for the other two gallery forest matrix classes.

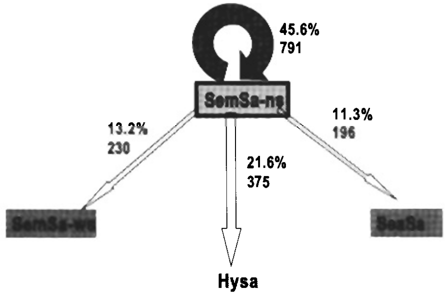


Figure 9
Change of semi-seasonal savannah class nono-saturated in 1960 LEM to other classes in 1988 LEM (HySa: hyper-seasonal savannah; SemSa-ns: SemSa-ws: semi-seasonal savannah water-saturated; SeaSa: seasonal savannah).

Figure 9 shows the process of change from the non-saturated semi-seasonal savannah ecological unit of 1960 to the 1988 ecological classes. The first observation is that almost half (45.6%) of the non-saturated semi-seasonal savannah class does not change. However, change does occur in two directions: for 13.2% to wetter areas as the water-saturated semi-seasonal savannah class, but also to drier areas as hyper-seasonal and seasonal savannahs. In the first case, the change to wet areas occurred because the level of water increased through the dike construction; in the second case, the change could be because some areas became drier when the dike interrupted the water flow to these areas. The percentage of change to drier areas in relation to the total area is 4%, which is lower in relation to the change from drier areas (hyper-seasonal and seasonal savannah) to wet areas (semi-seasonal savannahs).

The 1988 (current) LEM presents a landscape ecological unit distribution where the semi-seasonal savannah ecosystems, as a product of water management, represent the major area, and the hyper-seasonal savannah is the second class in respect to percentage of area covered. The technique used to produce the 1988 LEM was a simple supervised classification of Landsat TM, where the spectral features were related to ecological processes, *eg,* the productivity represented in the green vegetation and the tone derived by water accumulation (inundation).

The 1960 LEM presents a distribution of ecological units, where the hyper-seasonal savannah and seasonal savannah together cover more than 70% (45% and 26%, respectively). Elaboration of the map was based on the interpretation of aerial photographs, and photo characteristics were linked to ecological processes associated with vegetation growth and the inundation of certain areas.

When the two LEMs are compared in relation to the percentage of cover and the direction of change, we find that the main change observed is from the hyper-seasonal savannah and seasonal savannah classes to the non-saturated semi-seasonal savannah. This is because of the accumulation of water during the dry period caused by the dike construction. An important change can be observed from hyper-seasonal savannah in the direction of seasonal savannah, as a product of the drainage in the areas downstream of the dike, where the soil water conditions have become drier.

6. Conclusions

Based on the land unit concept, an approach was developed to link the ecological processes associated with the main ecological ecosystems and the spatial definition and distribution of these ecological units. Ecological processes such as soil wetness conditions and vegetation responses to these conditions were used to define and associate remote sensing features in order to identify, for two different dates, those land units where an important water management process had produced great changes in the study area.

From the conceptual point of view, the definition and characterisation of the land (ecological) units with use of the ecosystem concept and linking the remote sensing features with ecological processes, is an important step forward. With this approach, changes in a landscape can be compared using different mechanisms of spatial data capture, because the focal points of description are the ecological processes and not the physical features, which can be very different in relation to the data sources.

The main features of remote sensing data relating to water conditions (an ecological process) were used to define and characterise the ecological units. These main remote sensing features were also related to the pattern of vegetation growth, *ie*, greenness to separate hyper-seasonal savannah from semi-seasonal savannah, and texture to separate forest vegetation from other vegetation types.

From the point of view of grass production and forage utilisation, the change (from a less productive ecosystem or one with a stress period caused by dry soil conditions during the dry period, to an ecosystem with a continuous period of growth because water is continuously available throughout the year) favours secondary production, as represented by cattle and wild life.

The flooded savannah in Venezuela is an area used mainly for extensive cattle raising, where the water-deficit conditions owing to seasonality determine the carrying capacity of the landscape to support the primary production of forage. The embankment of the landscape contributes to increase the carrying capacity for forage production; consequently, the number of animals (cattle) supported by the landscape is increased too. From the human point of view, the increment in secondary production brings great economic benefit, which can improve the quality of life of the peasant (*llanero*) in the Llanos. Also, the landscape change and the growth of the semi-seasonal savannah ecosystem contribute to the increase in number and size of animal habitats, especially for wild species such as large numbers of birds, crocodiles, big mammals (*chigüire*) and many others. This increasing number of animal species contributes to promoting adventure and ecological tourism, and to generating more employment. However, the landscape change also leads to a reduction in the area of other ecosystems, *eg*, the hyper-seasonal savannah, which can in turn lead to a reduction in habitats for animals such as the deer (*Venado caramerudo)*, ant-eater (*Oso palmero*) and American lion (*Puma*), as well as a reduction in the numbers of plant species and vegetation types associated with this savannah ecosystem. It is difficult to conclude that the changes benefit habitat conservation because many other vegetation species and wild life could disappear; also many ecological processes are changed and the stability of the natural ecosystem could be modified.

The two landscape ecological maps resulting from the integrated approach represent two completely different stages. One stage represents almost-natural conditions, where the dynamics of the ecosystems are not greatly modified by human actions (represented by extensive grazing). The second stage represents a landscape ecological unit distribution derived from intensive water management, where the ecological conditions, especially those related to duration of flooding, have been changed by dike construction. These two maps can be compared in terms of area per ecological class but not in terms of patch numbers per class.

This study, from the spatial point of view, will not only allow the ecological processes associated with each ecosystem or land unit to be integrated in a general model, but also allow the changes in species distribution and abundance derived from the landscape change to be described. With this model of species distribution and abundance associated with the land units described in the maps, we can predict the rate of change and also monitor the influence of the embankment on the associated ecological processes.

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